Boosted W/Z/H bosons in physics analyses at CMS

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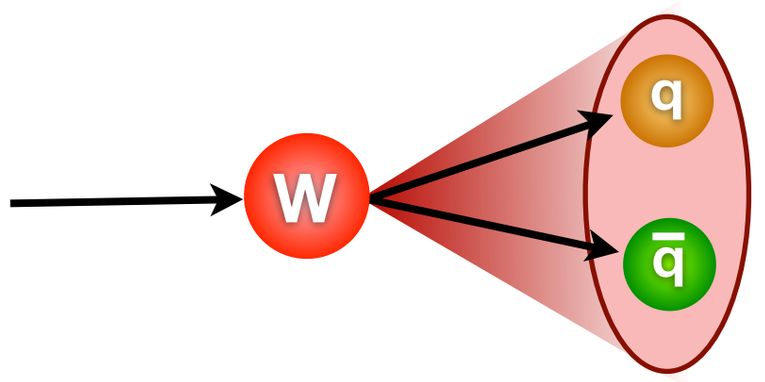
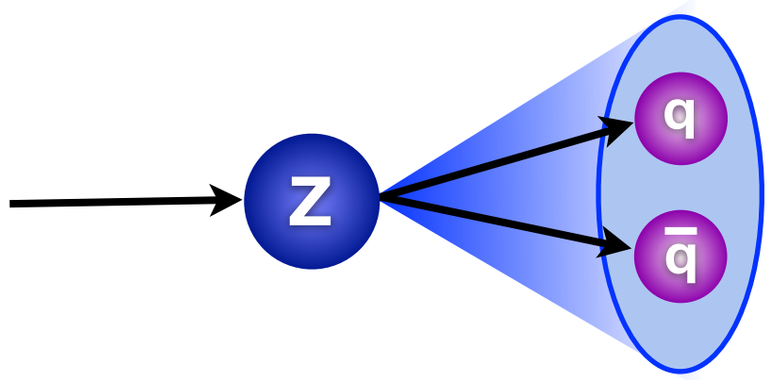
On behalf of the CMS Collaboration

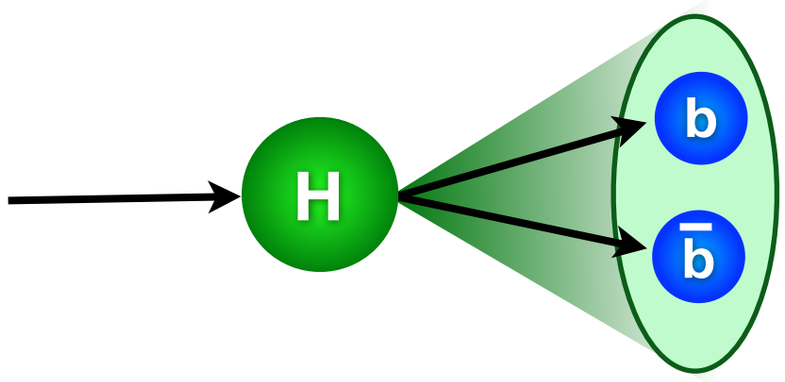
BOOST 2015 - Chicago

Introduction

- Searches with boosted bosons → decay products merged into a single jet (V jets)
- Techniques used to identify these objects will be discussed in detail in other talks this week (ex. Gregor, Caterina, Julien)
  - Only a quick summary today
- V jets occur in many BSM models, some of which have dedicated CMS talks at BOOST (VV resonances - Andreas, V+MET - Kristian), therefore I will concentrate on top partner models which produce a very rich phenomenology containing boosted V

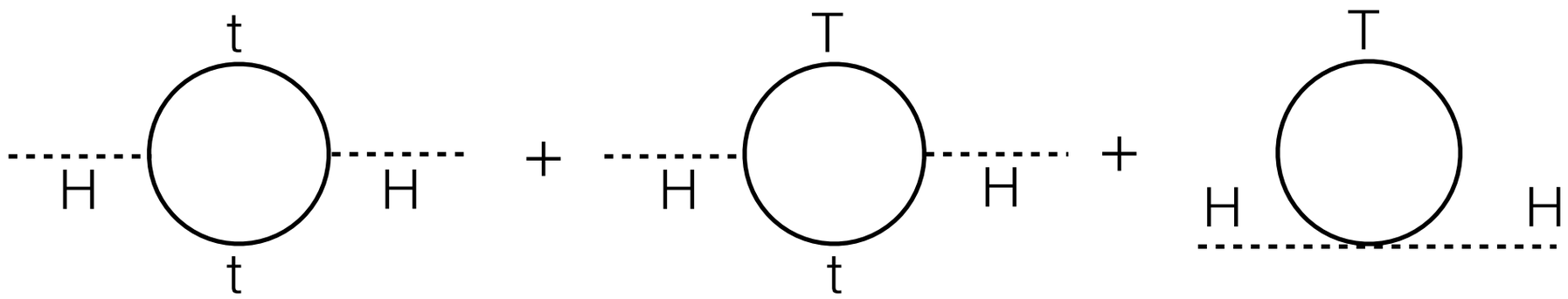






Motivation

- An abundance of models have been built to address naturalness (Little Higgs, Composite Higgs, extra dimensions, etc.)
- Many of these models consider heavy top partners in order to cancel the quadratically divergent contribution to the Higgs mass from top loops



- 4th generation chiral quarks highly disfavored by experiment, but vector-like quarks still allowed and motivated
- Vector-like top partner
  - Left handed and right handed charged currents
  - Acquire mass through mass term unlike other quarks which acquire mass through Yukawa couplings

Okada, Panizzi "LHC signatures of vector-like quarks" arxiv:1207.5607v3

- Heavy top partner decay → standard model quark + W/Z/H boson
  - Rich phenomenology with boosted V jets!

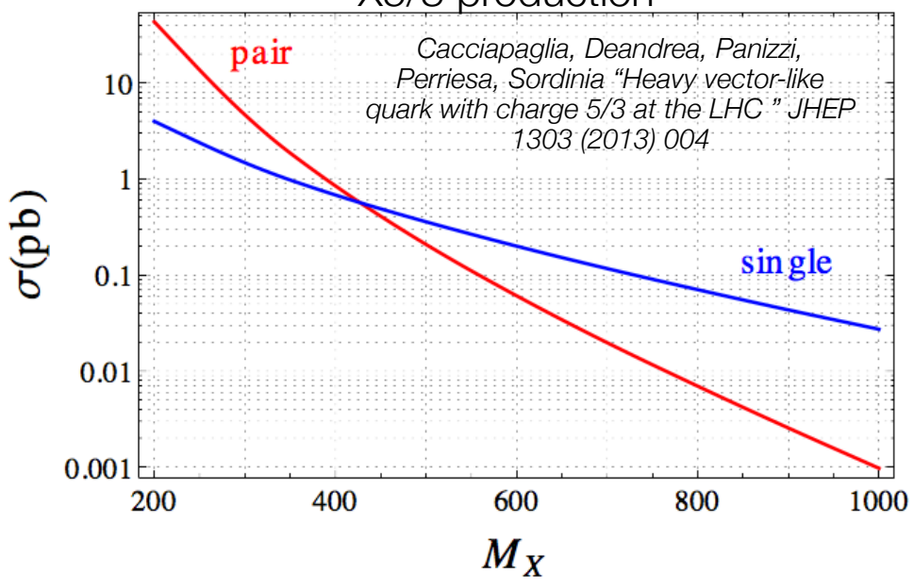
Vector-like quark phenomenology

- VLQ top partners (minimal scenario)
  - Mass eigenstates $T_{2/3}$, $B_{-1/3}$, $X_{5/3}$,$Y_{-4/3}$
  - Isospin singlet, doublet, or triplet
- Production
  - Pair production
    - Focus of most run 1 analyses
  - Single production
    - Dominant at large mass (model dependent)
    - Increasingly important in run 2
- Decay
  - SM quark + SM boson
    - Preferentially decay to 3rd generation quarks (t,b)
    - Decay to light quarks constrained - could still have a sizable branching fraction
  - If mass hierarchal allows, could also decay to VLQ + SM boson

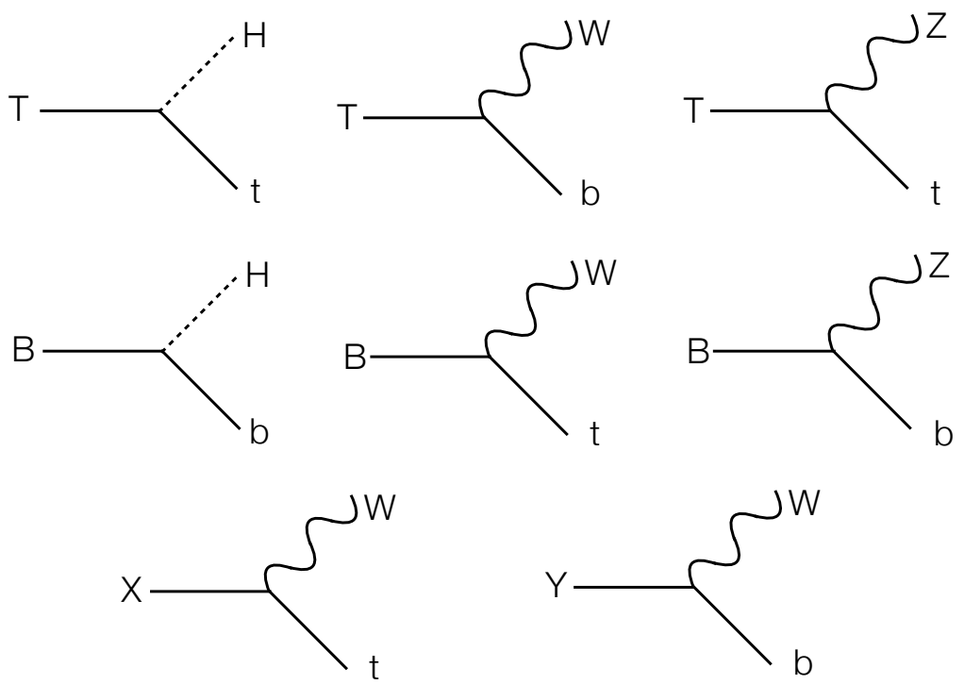
M. Buchkremer "Model independent analysis of heavy vector-like top partners" Moriond 2014 arXiv:1405.2586v1

$T_{\frac{2}{3}}$	$B_{-\frac{1}{3}}$	$\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \end{pmatrix}$	$\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\begin{pmatrix} B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$	$\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$

X5/3 production



Cacciapaglia, Deandrea, Panizzi, Perriesa, Sordinia "Heavy vector-like quark with charge 5/3 at the LHC " JHEP 1303 (2013) 004



Example VLQ final states

Diagram based on talk by Luca Panizzi at "Workshop on Vector-like Quarks 2014, DESY"

$T_{2/3}$ pair production

W^+j	W^-j	W^+j	$W^-\bar{b}$	W^+j	Zj	W^+j	$Z\bar{t}$	W^+j	Hj	W^+j	$H\bar{t}$
W^+b	W^-j	W^+b	$W^-\bar{b}$	W^+b	Zj	W^+b	$Z\bar{t}$	W^+b	Hj	W^+b	$H\bar{t}$
Zj	W^-j	Zj	$W^-\bar{b}$	Zj	Zj	Zj	$Z\bar{t}$	Zj	Hj	Zj	$H\bar{t}$
Zt	W^-j	Zt	$W^-\bar{b}$	Zt	Zj	Zt	$Z\bar{t}$	Zt	Hj	Zt	$H\bar{t}$
Hj	W^-j	Hj	$W^-\bar{b}$	Hj	Zj	Hj	$Z\bar{t}$	Hj	Hj	Hj	$H\bar{t}$
Ht	W^-j	Ht	$W^-\bar{b}$	Ht	Zj	Ht	$Z\bar{t}$	Ht	Hj	Ht	$H\bar{t}$

$B_{-1/3}$ pair production

W^-j	W^+j	W^-j	$W^+\bar{t}$	W^-j	Zj	W^-j	$Z\bar{b}$	W^-j	Hj	W^-j	$H\bar{b}$
W^-t	W^+j	W^-t	$W^+\bar{t}$	W^-t	Zj	W^-t	$Z\bar{b}$	W^-t	Hj	W^-t	$H\bar{b}$
Zj	W^+j	Zj	$W^+\bar{t}$	Zj	Zj	Zj	$Z\bar{b}$	Zj	Hj	Zj	$H\bar{b}$
Zb	W^+j	Zb	$W^+\bar{t}$	Zb	Zj	Zb	$Z\bar{b}$	Zb	Hj	Zb	$H\bar{b}$
Hj	W^+j	Hj	$W^+\bar{t}$	Hj	Zj	Hj	$Z\bar{b}$	Hj	Hj	Hj	$H\bar{b}$
Hb	W^+j	Hb	$W^+\bar{t}$	Hb	Zj	Hb	$Z\bar{b}$	Hb	Hj	Hb	$H\bar{b}$

$X_{5/3}$ pair production

W^+j	W^-j	W^+j	$W^-\bar{t}$
W^+t	W^-j	W^+t	$W^-\bar{t}$

$Y_{-4/3}$ pair production

W^-j	W^+j	W^-j	$W^+\bar{b}$
W^-b	W^+j	W^-b	$W^+\bar{b}$

Single $T_{2/3}$ production with t

$W^+j + tj$

$W^+b + tj$

$Zj + tj$

$Zt + tj$

$Hj + tj$

$Ht + tj$

Single $B_{-1/3}$ production with t

$W^-j + tj$

$W^-t + tj$

$Zj + tj$

$Zb + tj$

$Hj + tj$

$Hb + tj$

Single $X_{5/3}$ production with t

$W^+j + tj$

$W^+t + tj$

Single $Y_{-4/3}$ production with t

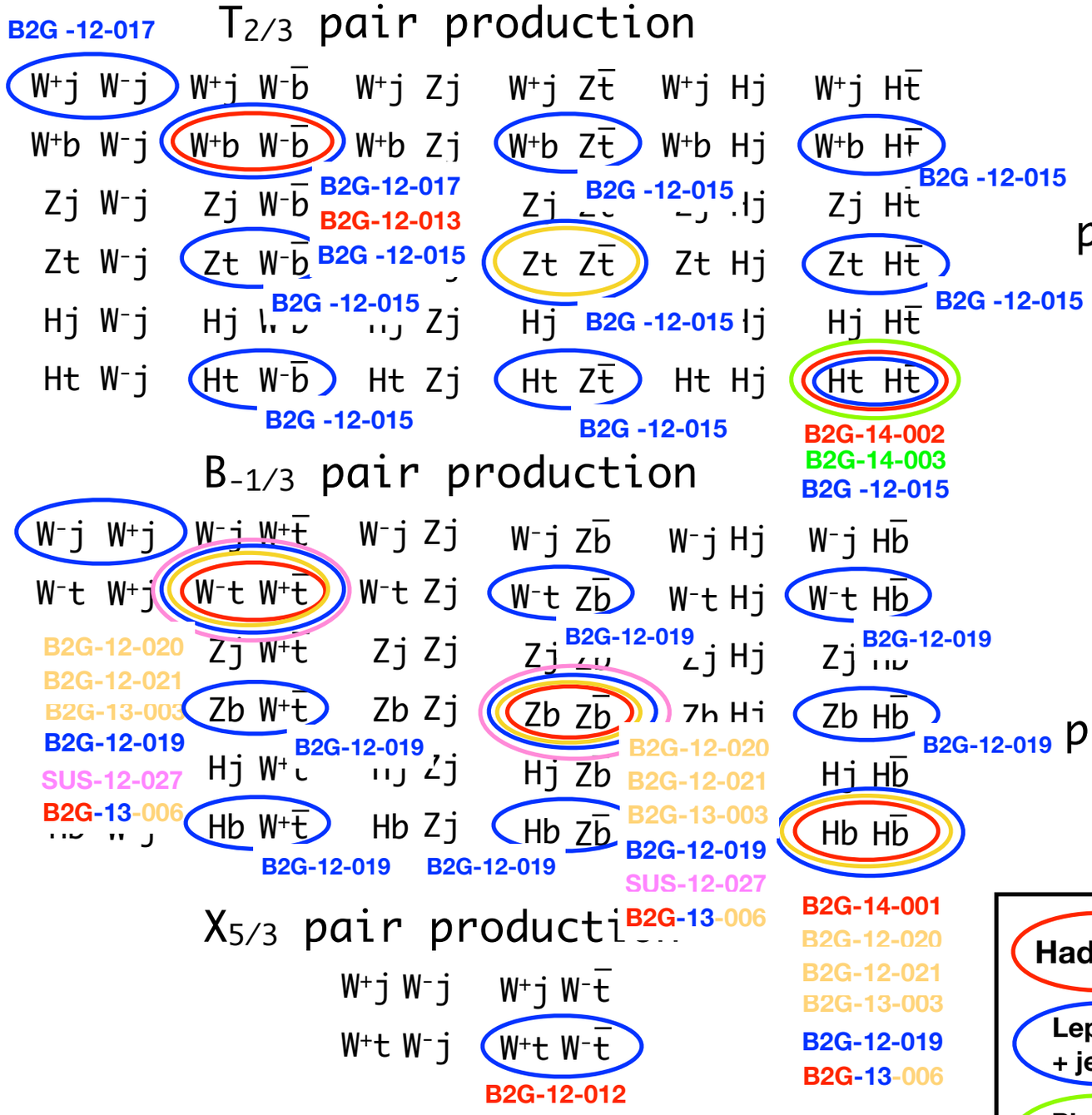
$W^-j + tj$

$W^-b + tj$

Single $T_{2/3}/B_{-1/3}/X_{5/3}/Y_{-4/3}$ production with b/j/V

Dedicated searches at CMS

Diagram based on talk by Luca Panizzi at "Workshop on Vector-like Quarks 2014, DESY"



Single $T_{2/3}$ production with t

$W^+j + tj$

$W^+b + tj$

$Zj + tj$

$Zt + tj$

$Hj + tj$

$Ht + tj$

Single $B_{-1/3}$ production with t

$W^-j + tj$

$W^-t + tj$

$Zj + tj$

$Zb + tj$

$Hj + tj$

$Hb + tj$

Single $X_{5/3}$ production with t

$W^+j + tj$

$W^+t + tj$

Single $Y_{-4/3}$ production with t

$W^-j + tj$

$W^-b + tj$

Hadronic

Lepton + jets

Photons + jets

Multi lepton

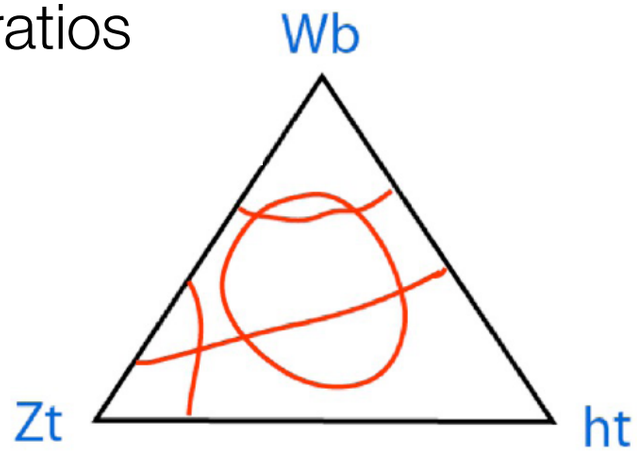
Single $T_{2/3}/B_{-1/3}/X_{5/3}/Y_{-4/3}$ production with b/j/V

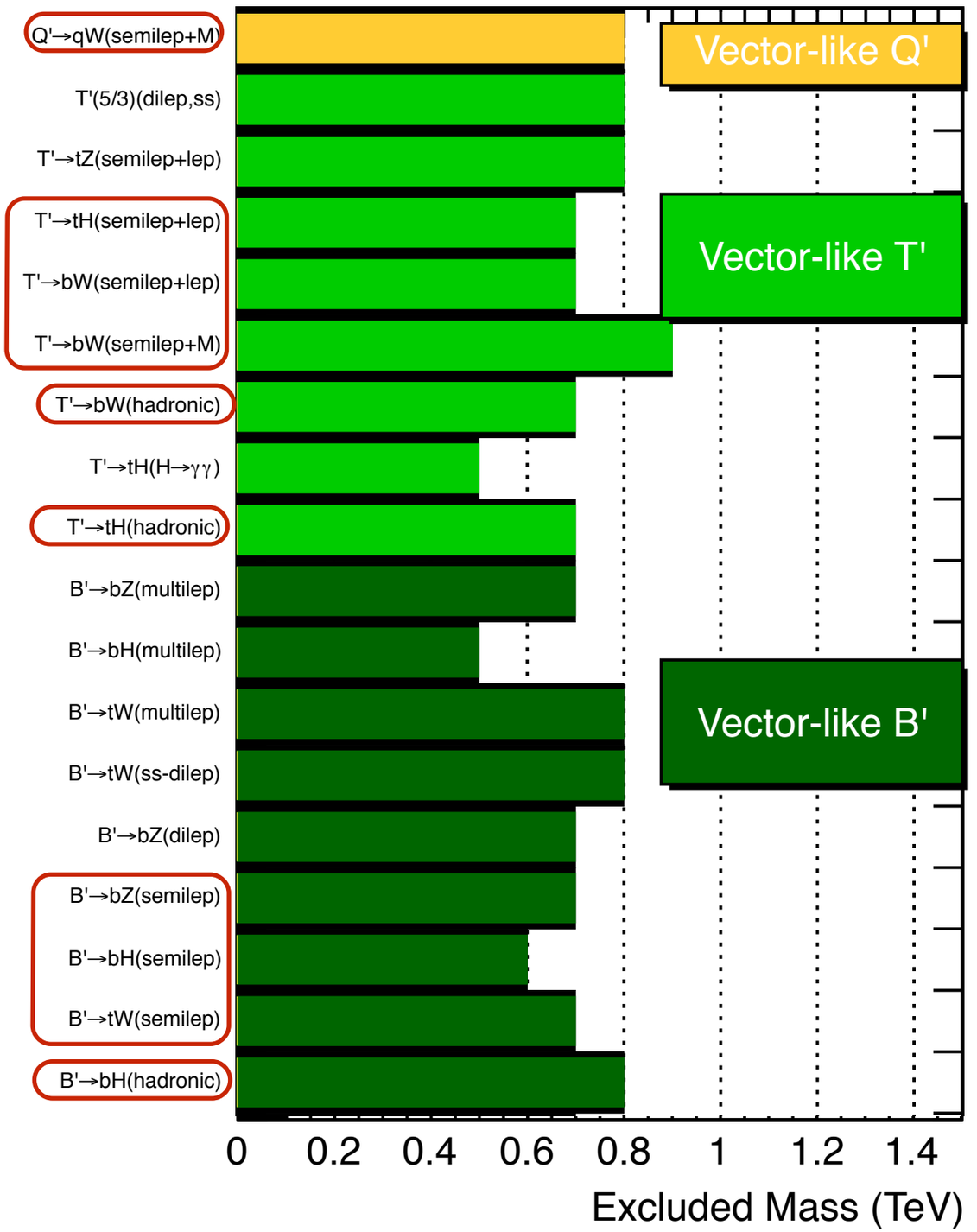
Note: This list of analyses is definitely incomplete

Run 1 VLQ searches at CMS

- Assume pair production and assume decay to third generation
  - BR(Wb)+BR(tZ)+BR(tH)=1
- Analyses utilizing boosted V jets
  - BB → bHbH (all-hadronic)
  - BB → all decays (lepton + jets)
  - *BB legacy combination*
  - TT → tHtH (all-hadronic)
  - TT → bWbW (all-hadronic)
  - TT → bWbW (lepton + jets)
  - TT → all decays (leptons + jets)
  - *TT legacy combination*
- Exclusions with triangle diagram - 3 varying branching ratios

M. E. Peskin
SEARCH workshop
U of Maryland
March 2012

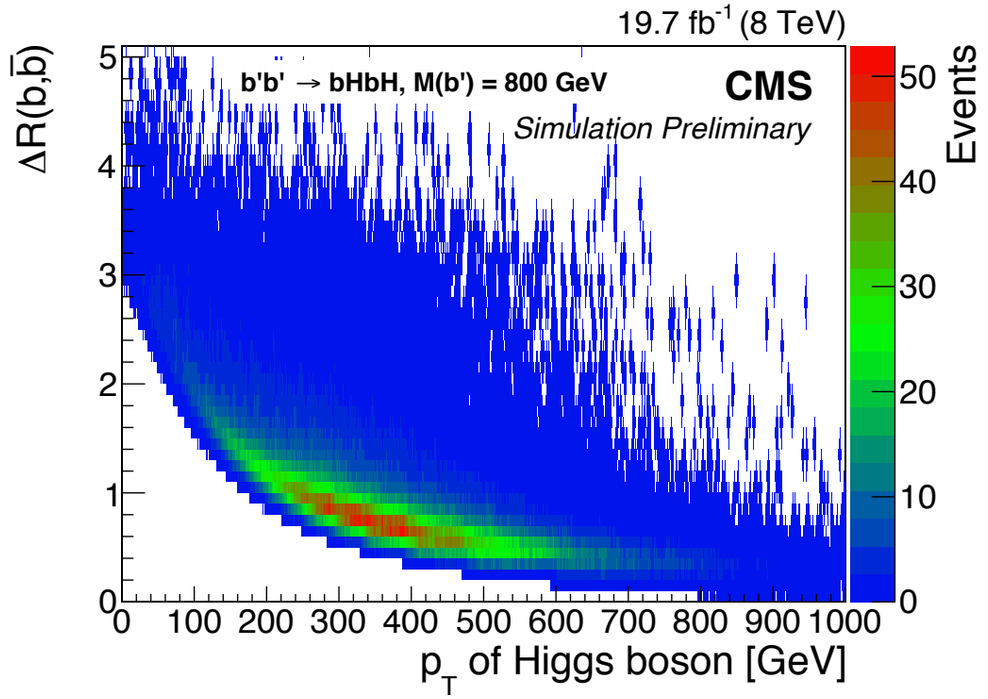


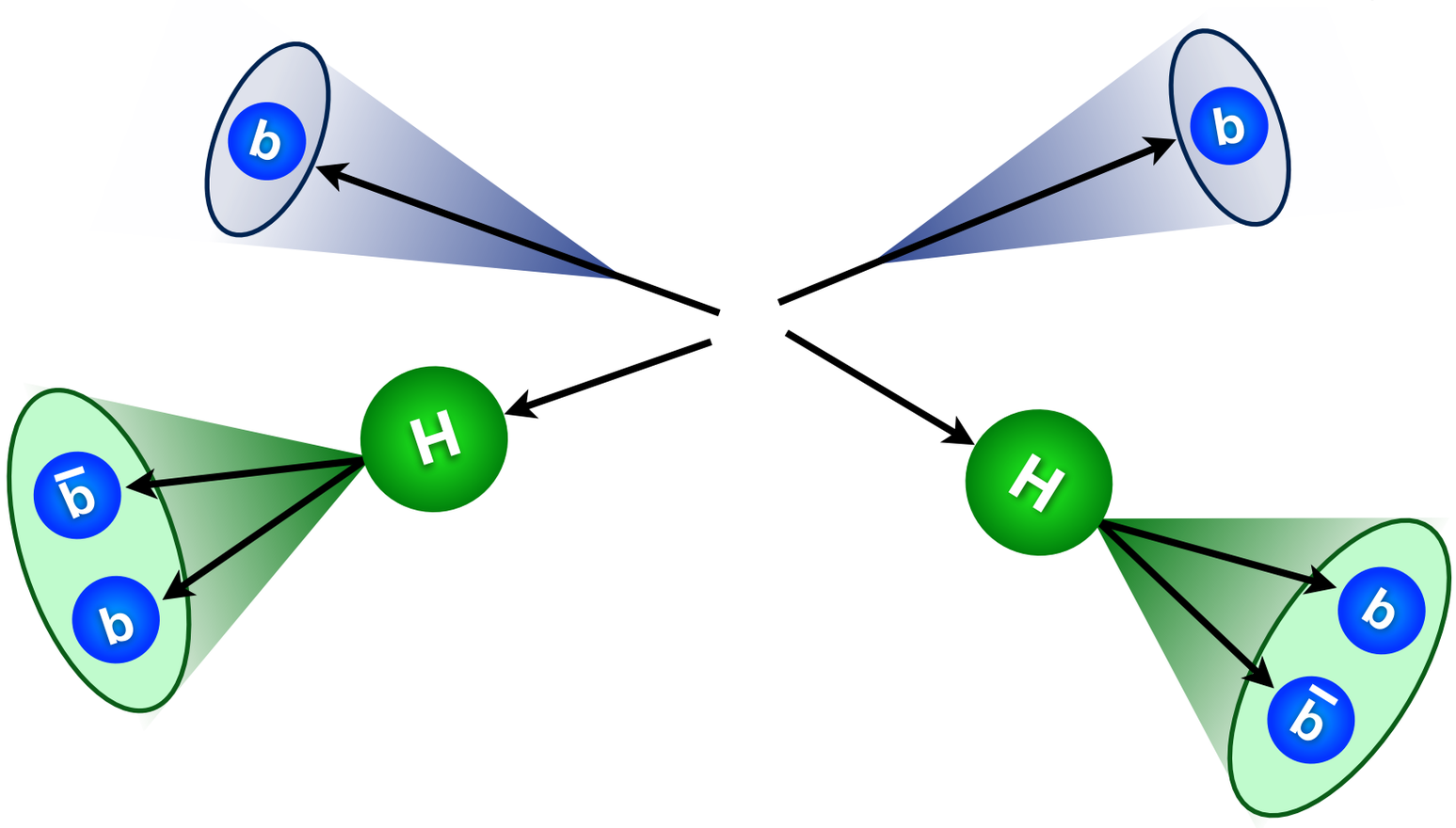


$B_{-1/3}\bar{B}_{-1/3} \rightarrow bH\bar{b}H$ all-hadronic

CMS B2G-14-001

- Search for pair produced $B_{-1/3}$ (labeled b' in B2G-14-001)
- Optimized for the bH decay channel
- Consider hadronic decays of the H
- Utilize b-tagging and H-tagging





$BB \rightarrow bHbH$ analysis strategy

CMS B2G-14-001

- HT>750 trigger
- Selection
  - HT > 950 (scalar sum of all AK5 jet p_T)
  - At least 1 b-tagged AK5 jet
  - At least 1 H-tagged CA8 jet
  - ΔR(b jet, Higgs-tagged jet) > 1.2
- Categorize events with 1 b-tag and >1 b-tag
- Search performed using HT distribution

b-tag =
AK5 jet (p_T>80) tagged with the combined secondary vertex algorithm medium operating point (CSVM)

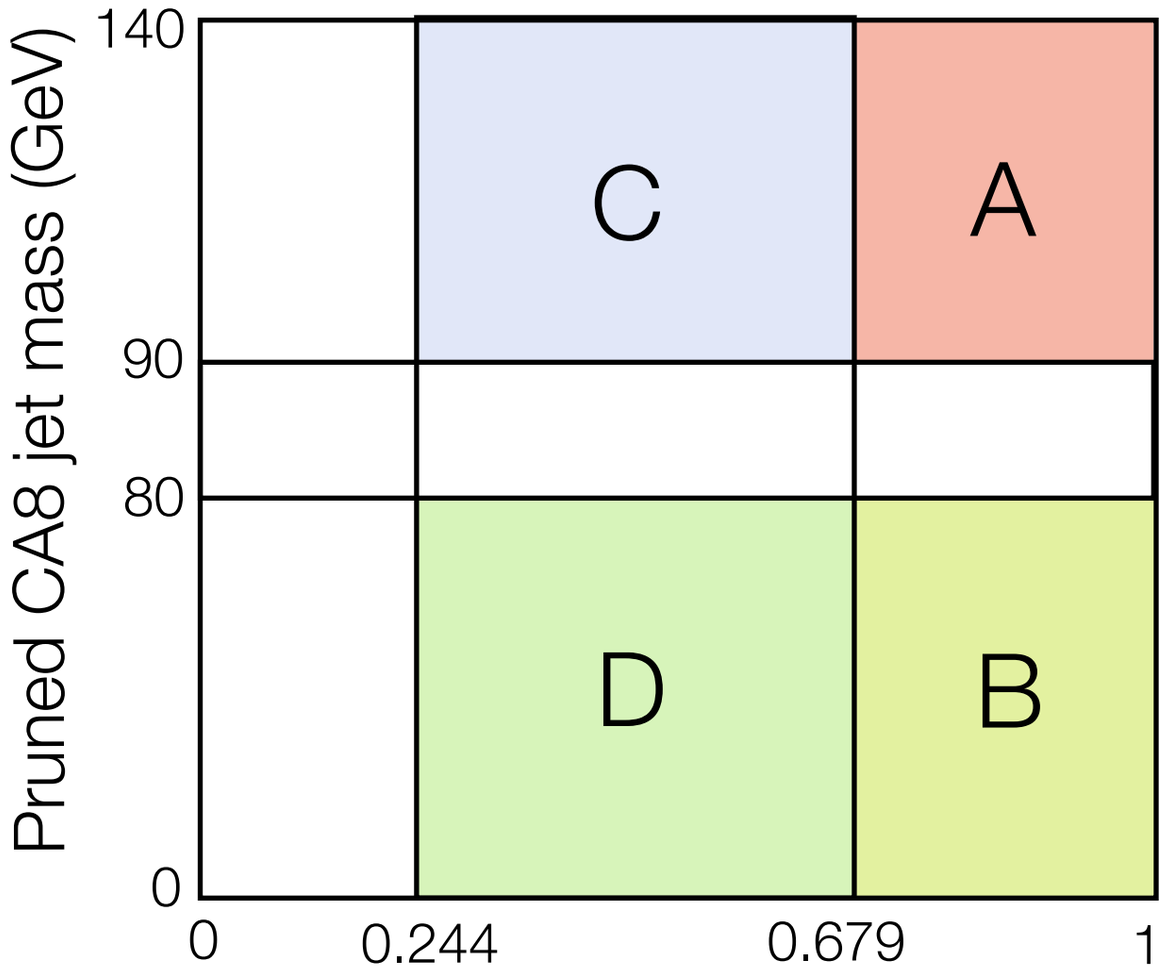
H-tag =
CA8 jet (p_T>300)
$90<m_{prune}<140$
$\tau_2/\tau_1 <0.5$
double subjet btag* (CSVM)

*subjets required to have $\Delta R>0.3$ separation in order to remove correlations from shared tracks

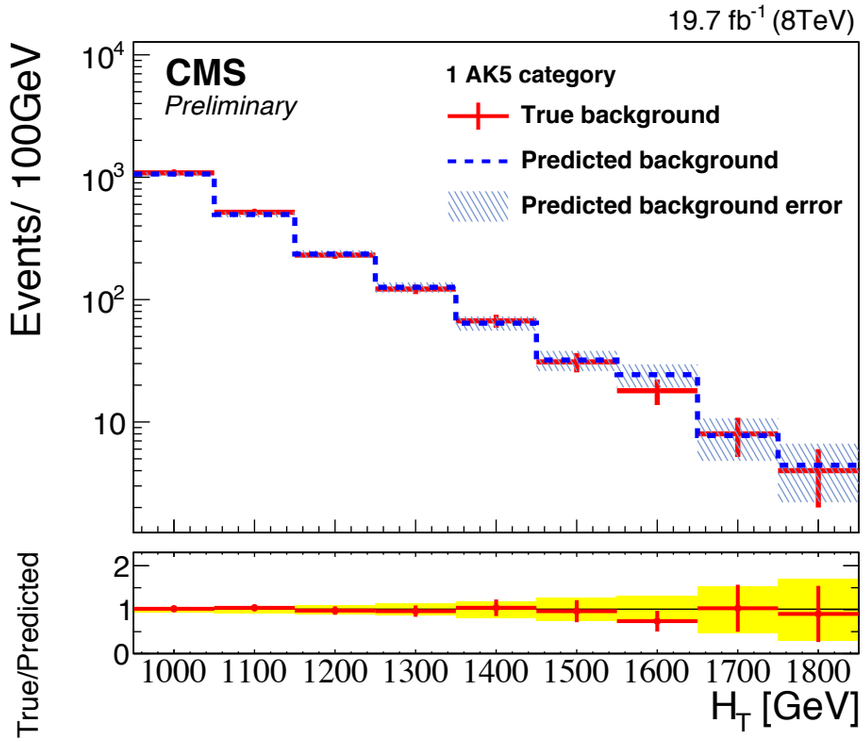
$BB \rightarrow bHbH$ multijet background estimation

CMS B2G-14-001

- ABCD method
- A = signal = events with at least 1 H-tagged jet
- B = events with at least one jet with a double b-tag but pruned mass < 80 GeV
- C = events with at least one jet with pruned mass in the H mass window and subjet b-discriminant [0.244,0.679]
- D = events with at least one jet with two subjets which each have b-discriminant [0.244,0.679] and pruned jet mass < 80 GeV



$$N_A = N_B \times \frac{N_C}{N_D}$$



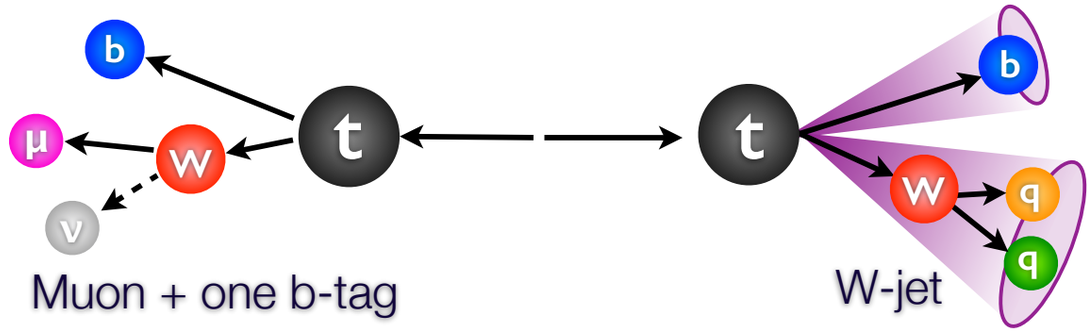
Substructure tagging systematics

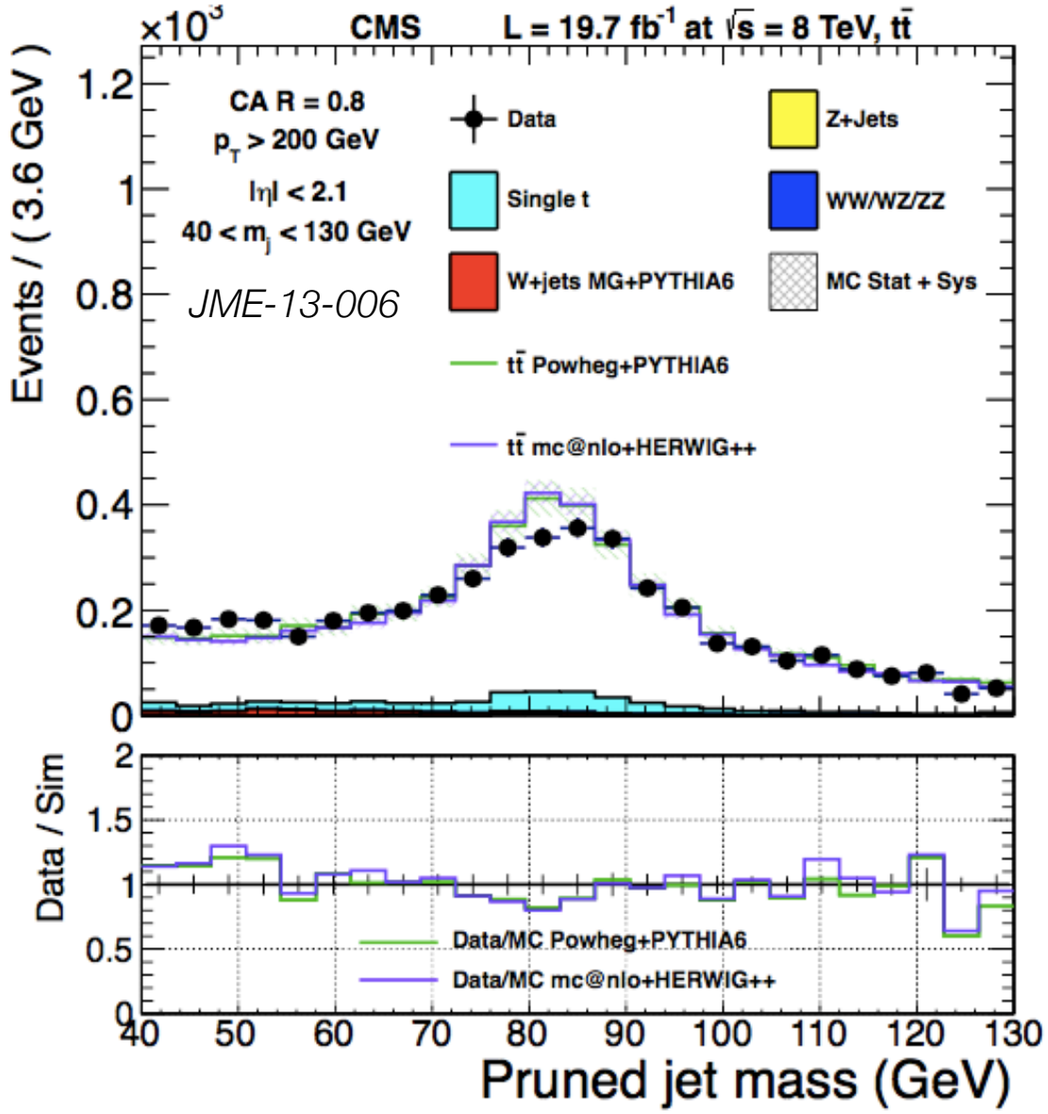
CMS B2G-14-001

- Obtain a sample of very pure boosted W's in semileptonic ttbar events

- Use the W-jet to measure scale factors for pruned jet mass and N-subjettiness

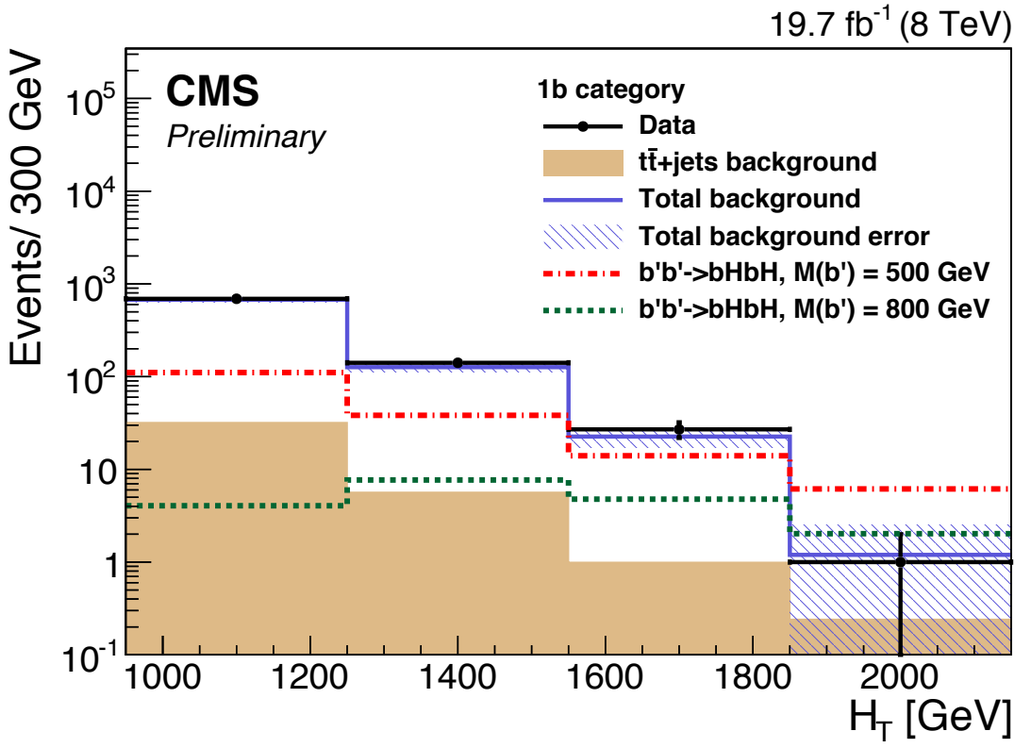
- Apply these scale factors to H-jets
  - Assign additional systematic uncertainty to account for the difference in the quark fragmentation in H → bb and W→ qq

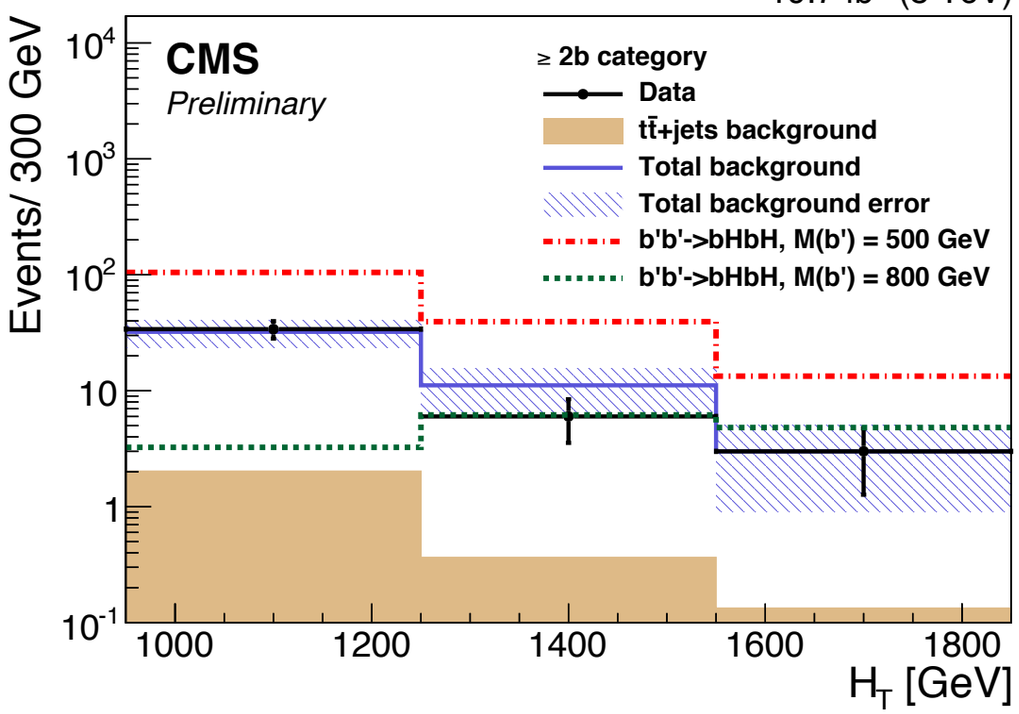


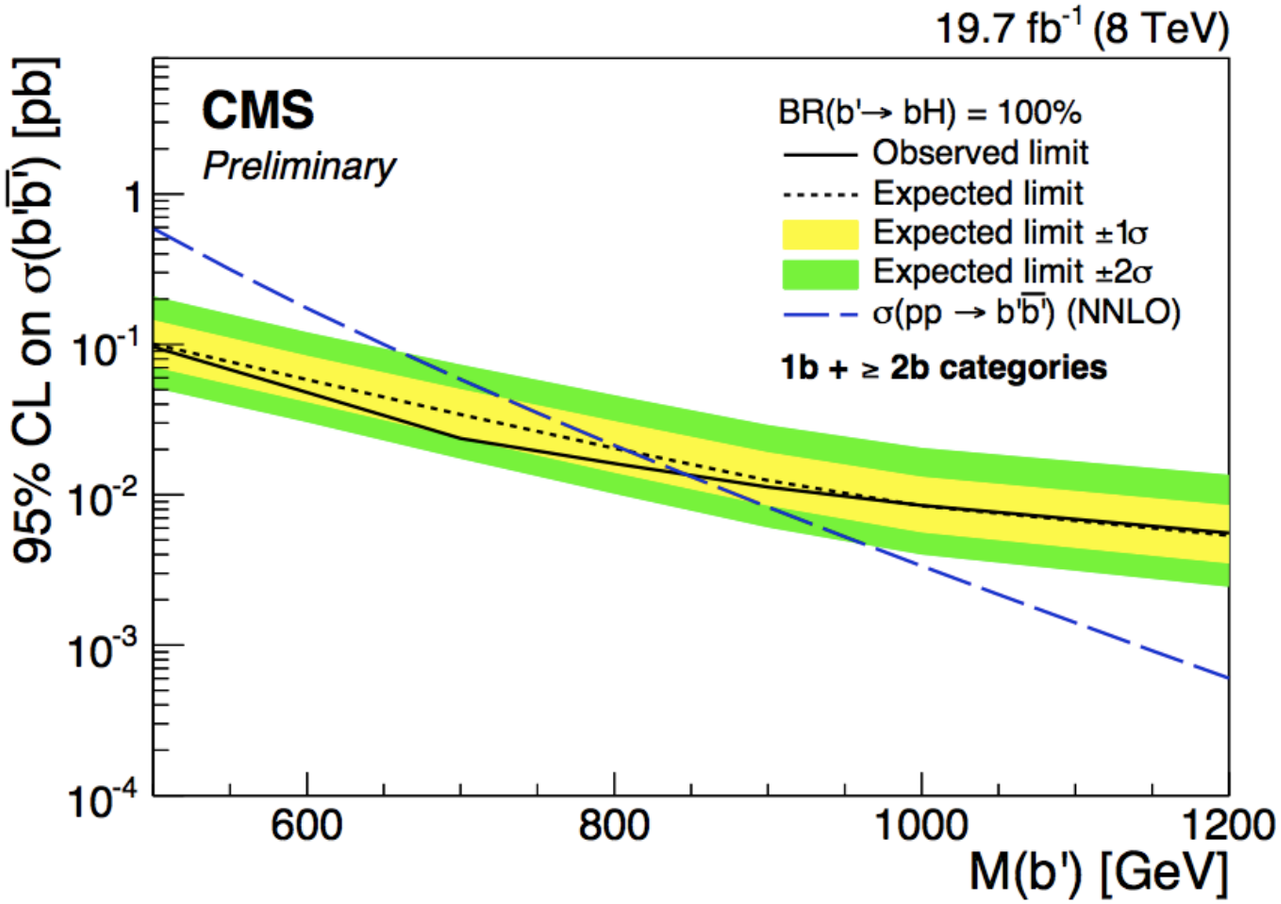


$BB \rightarrow bHbH$ results

CMS B2G-14-001







No significant excess of events found. B excluded at 95% CL below a mass of 846 GeV (expected 811 GeV).

$B_{-1/3}\bar{B}_{-1/3}$ - all decays (single lepton)

CMS B2G-12-019

- Search for pair produced $B_{-1/3}$ with exactly 1 lepton + jets
  - BB → tWtW, tWbH, tWbZ, bZbZ, bZbH, bHbH
- Selection
  - Exactly one isolated lepton
  - At least 4 AK5 jets
  - 1 b-tagged AK5 jet
  - Centrality > 0.4 (jet $\sum p_T/\sum E$)
  - MET > 20 GeV

V-tag =
CA8 jet (p_T>200)
50<m_{prune}<150
subjet mass drop < 0.4

- Categorize events based on the number of V tags
- Search in ST (scalar sum jet p_T + lepton p_T + MET)

BB single lepton results

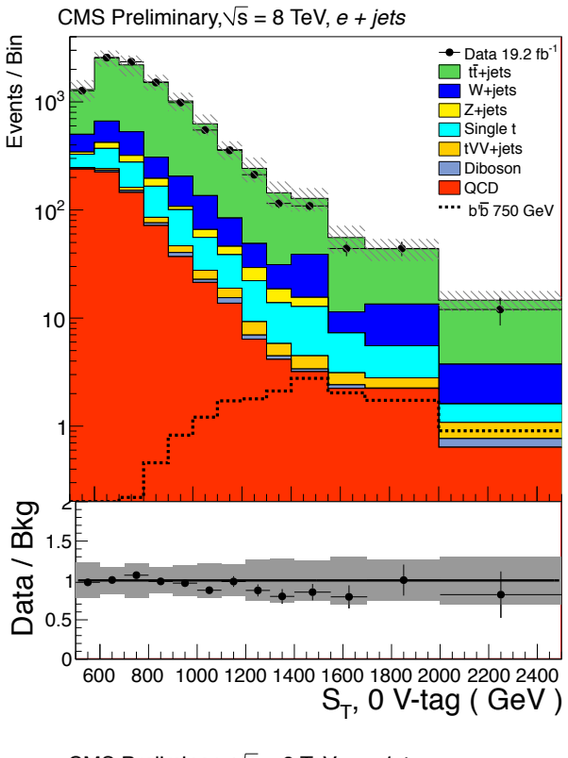
CMS B2G-12-019

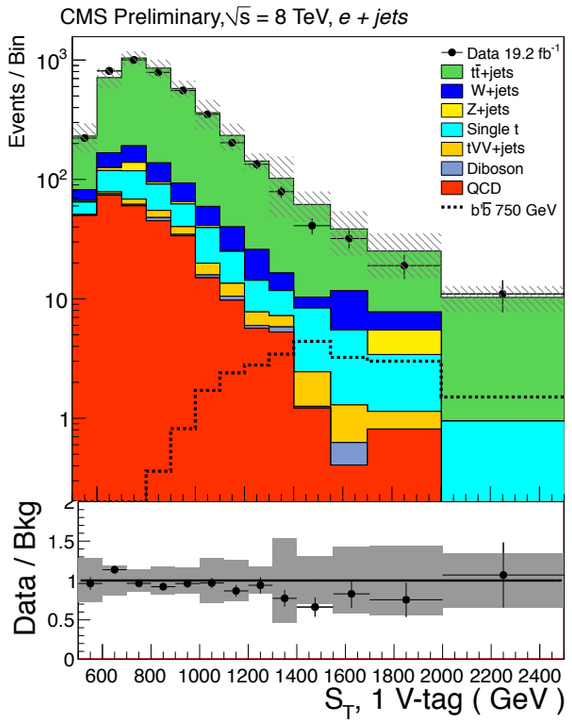
0 V tags

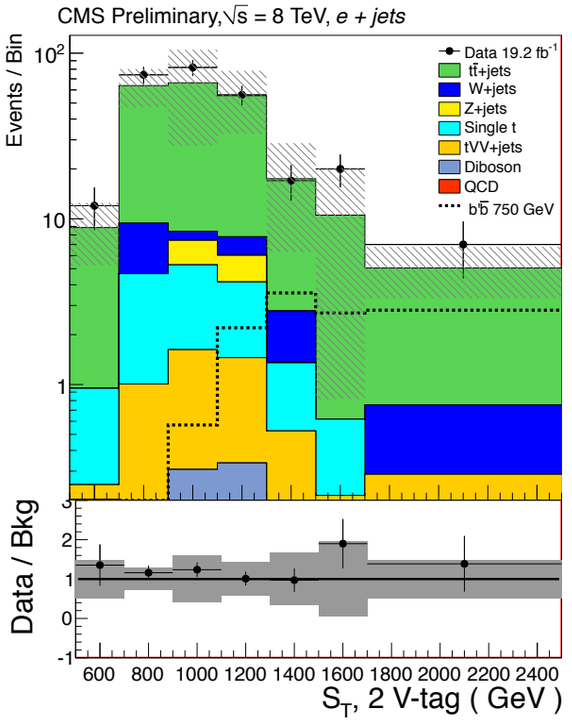
1 V tags

2 V tags

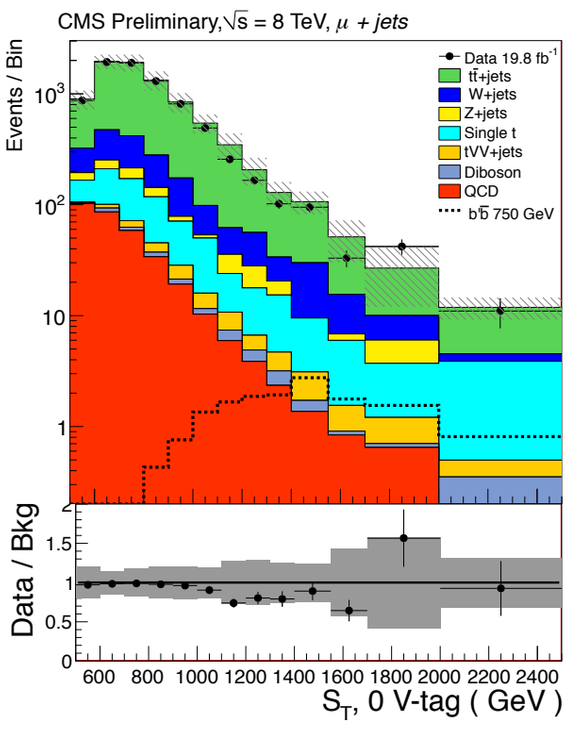
e + jets

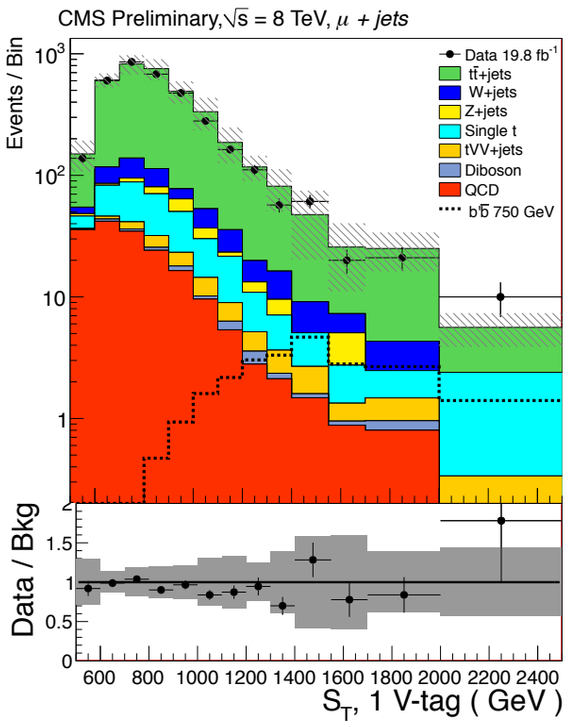


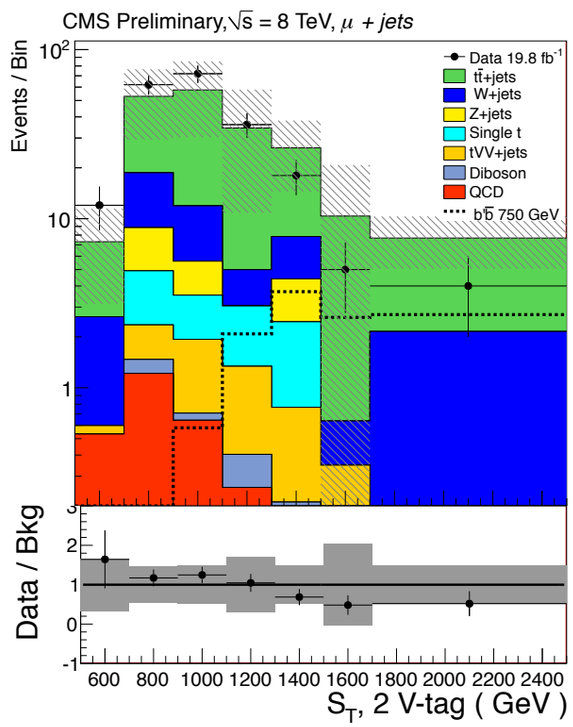




μ + jets

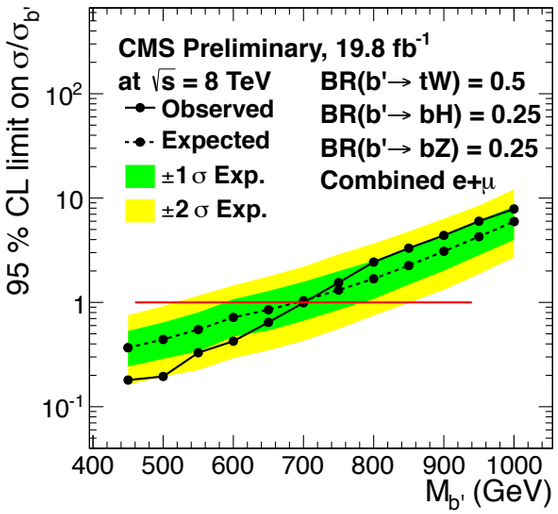


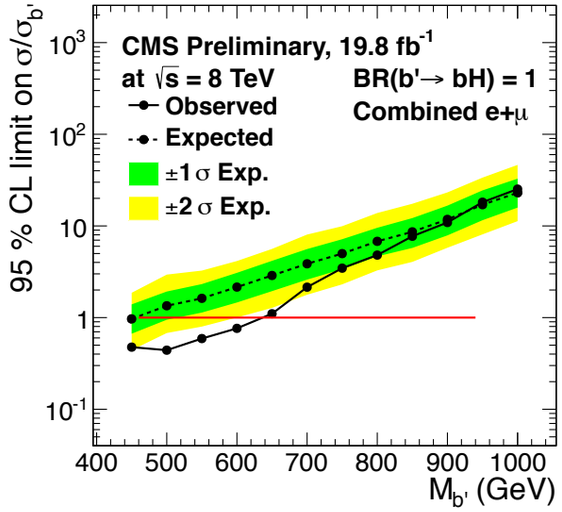


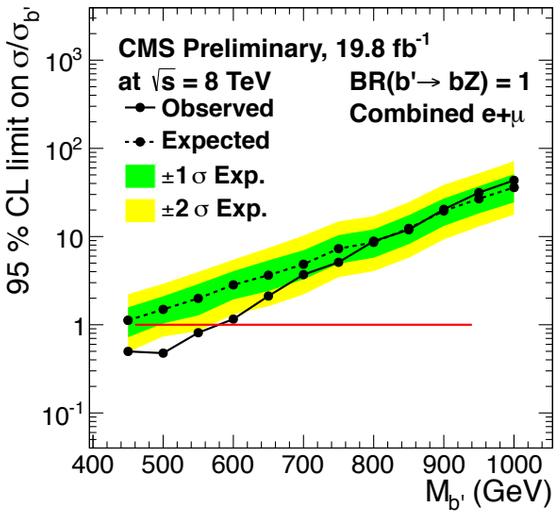


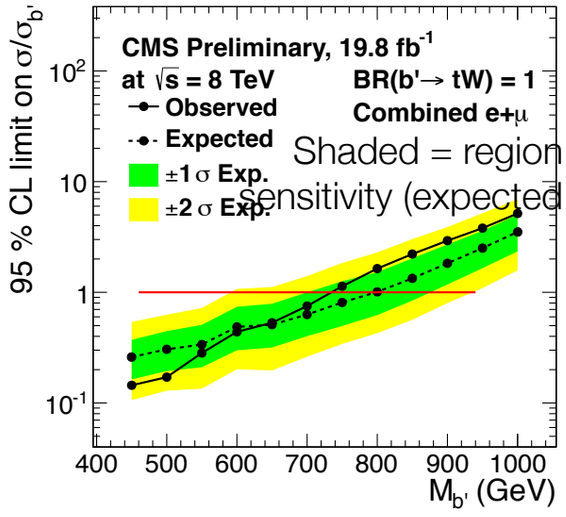
BB single lepton limits

CMS B2G-12-019







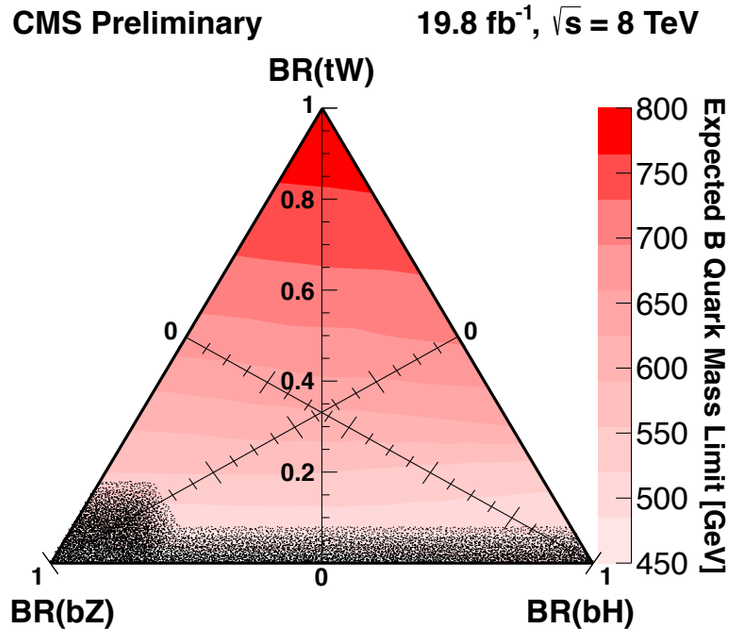


Shaded = region of small sensitivity (expected limit < 500)

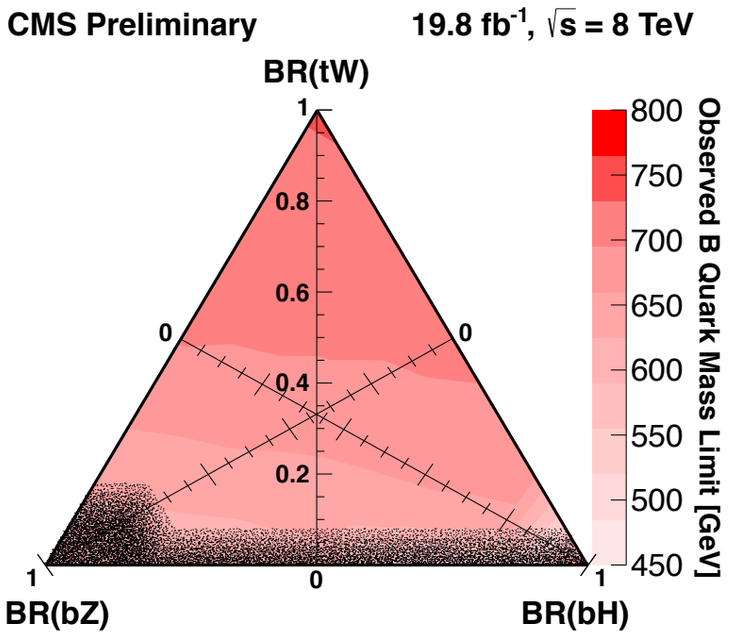
No significant excess of events found.
B excluded at 95% CL below 582-732 GeV
(depending on the branching ratio)

This analysis is most sensitive to the b` → tW decay
(more boosted V ⇒ better signal/background)

Expected



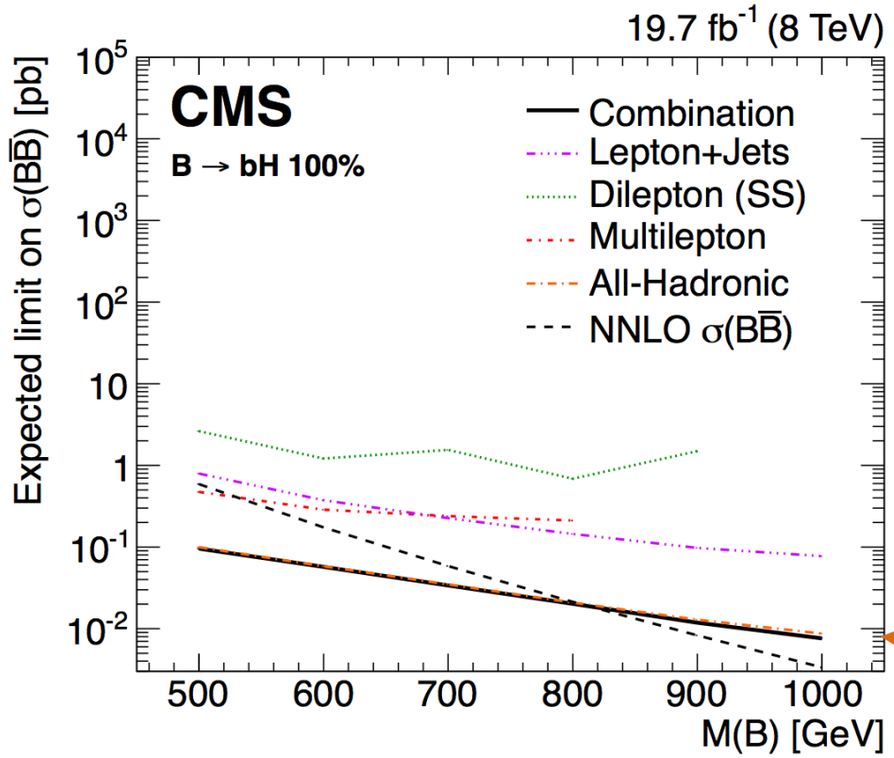
Observed



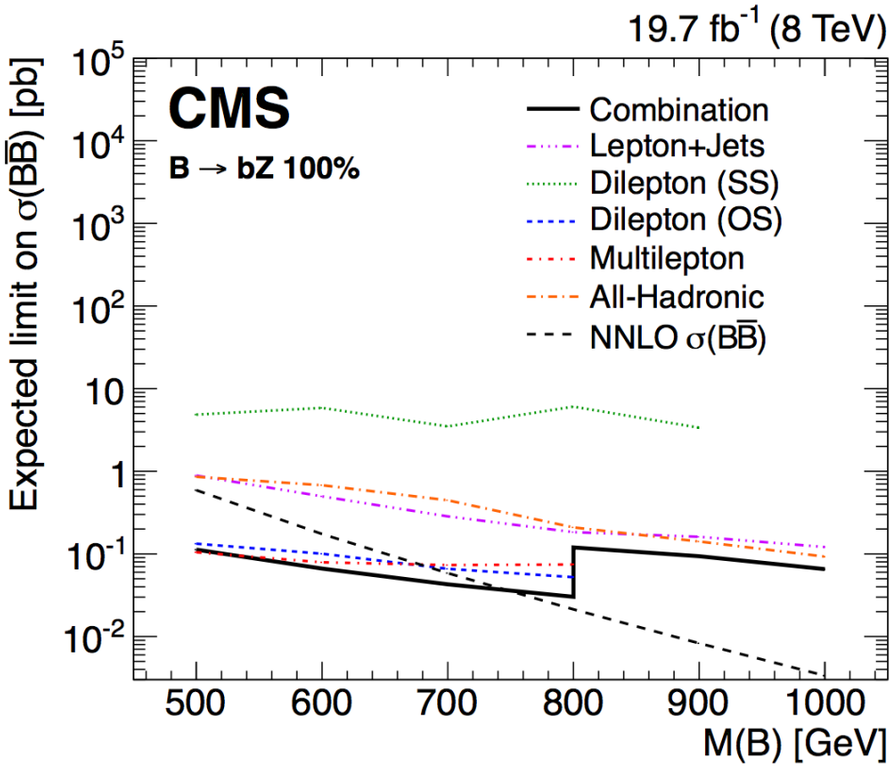
BB legacy combination

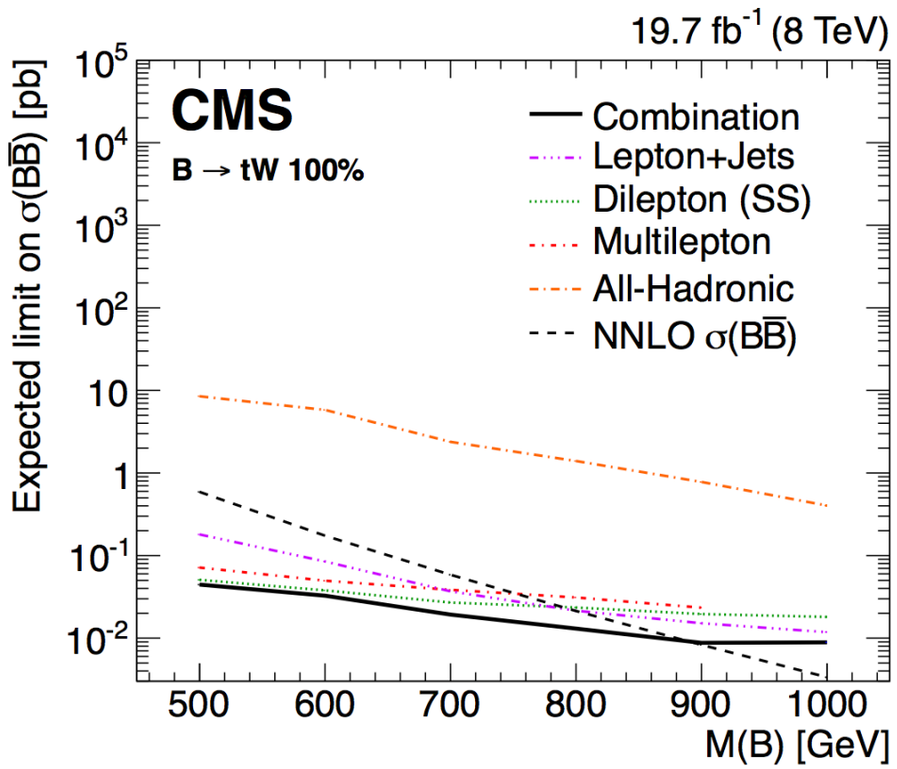
CMS B2G-13-006

- Combine all BB analyses
  - Lepton + jets
  - Same sign lepton pair
  - Opposite sign lepton pair
  - Multilepton
  - All-hadronic (T → bH)



Utilizes Higgs tagging





Utilizes V tagging

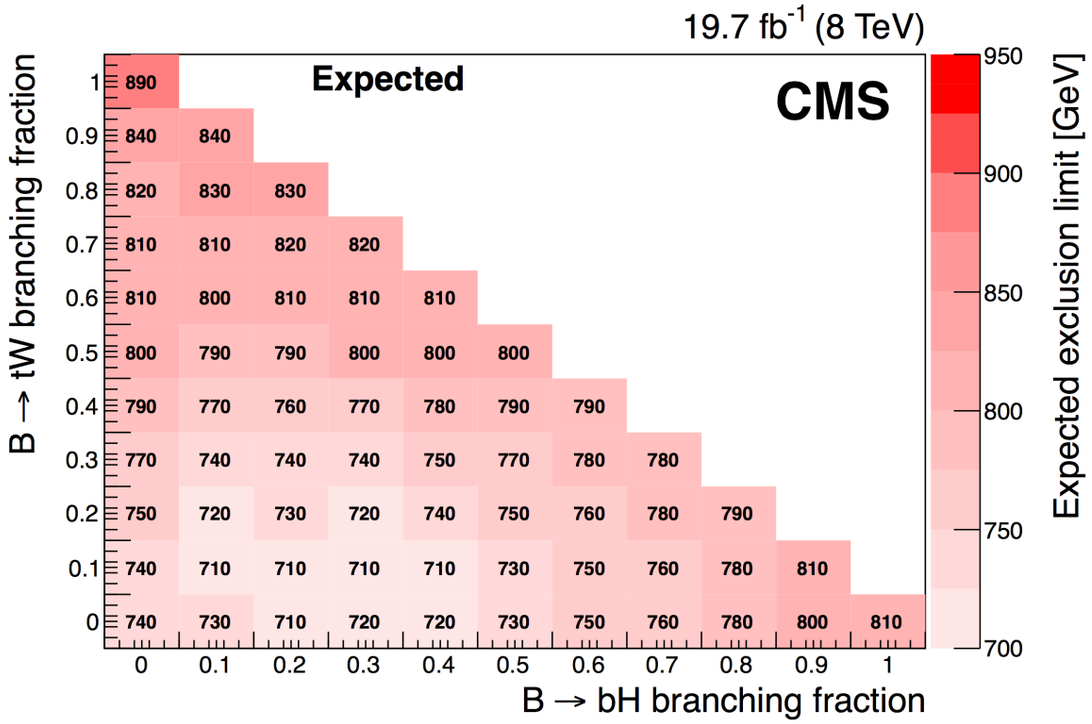
BB legacy combination results

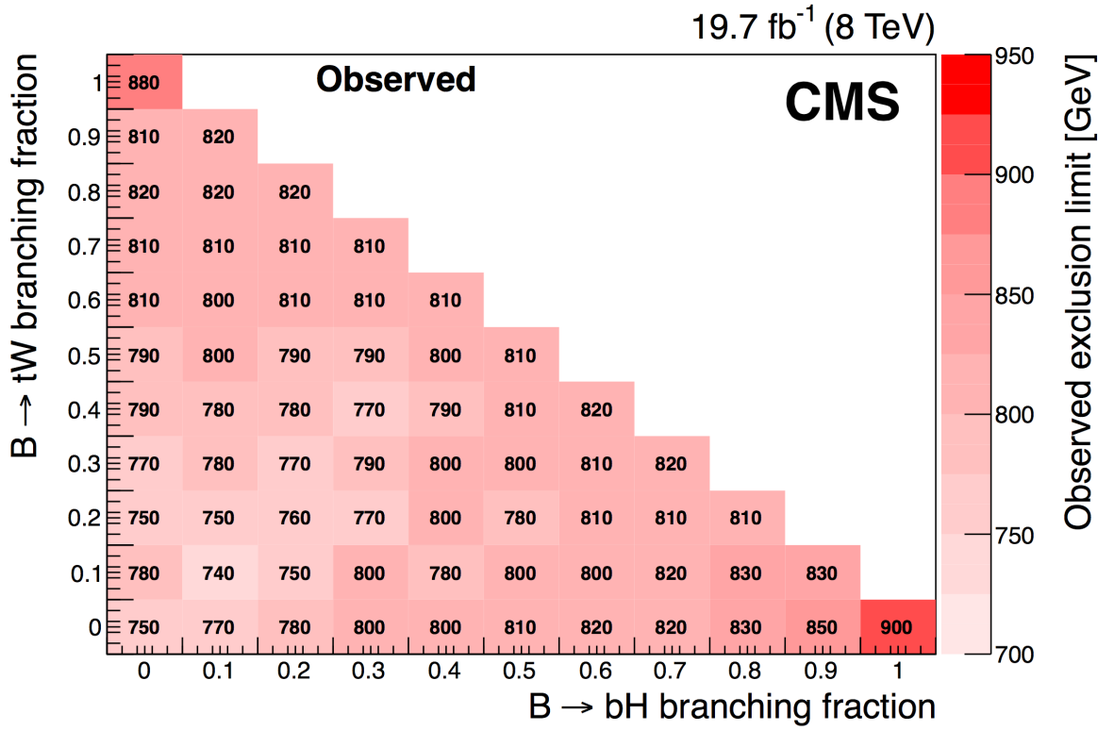
No significant excess of events found

B quark is excluded at 95% CL below 740-900 GeV (depending on the branching ratio)

Limits assuming 100% BR to the following channels

	95% CL $M(\mathrm{B})$ exclusion limit [GeV]	
	Expected	Observed
$\mathrm{B} \to \mathrm{tW}$	890	880
$\mathrm{B} \to \mathrm{bH}$	810	900
$\mathrm{B} \to \mathrm{bZ}$	740	750

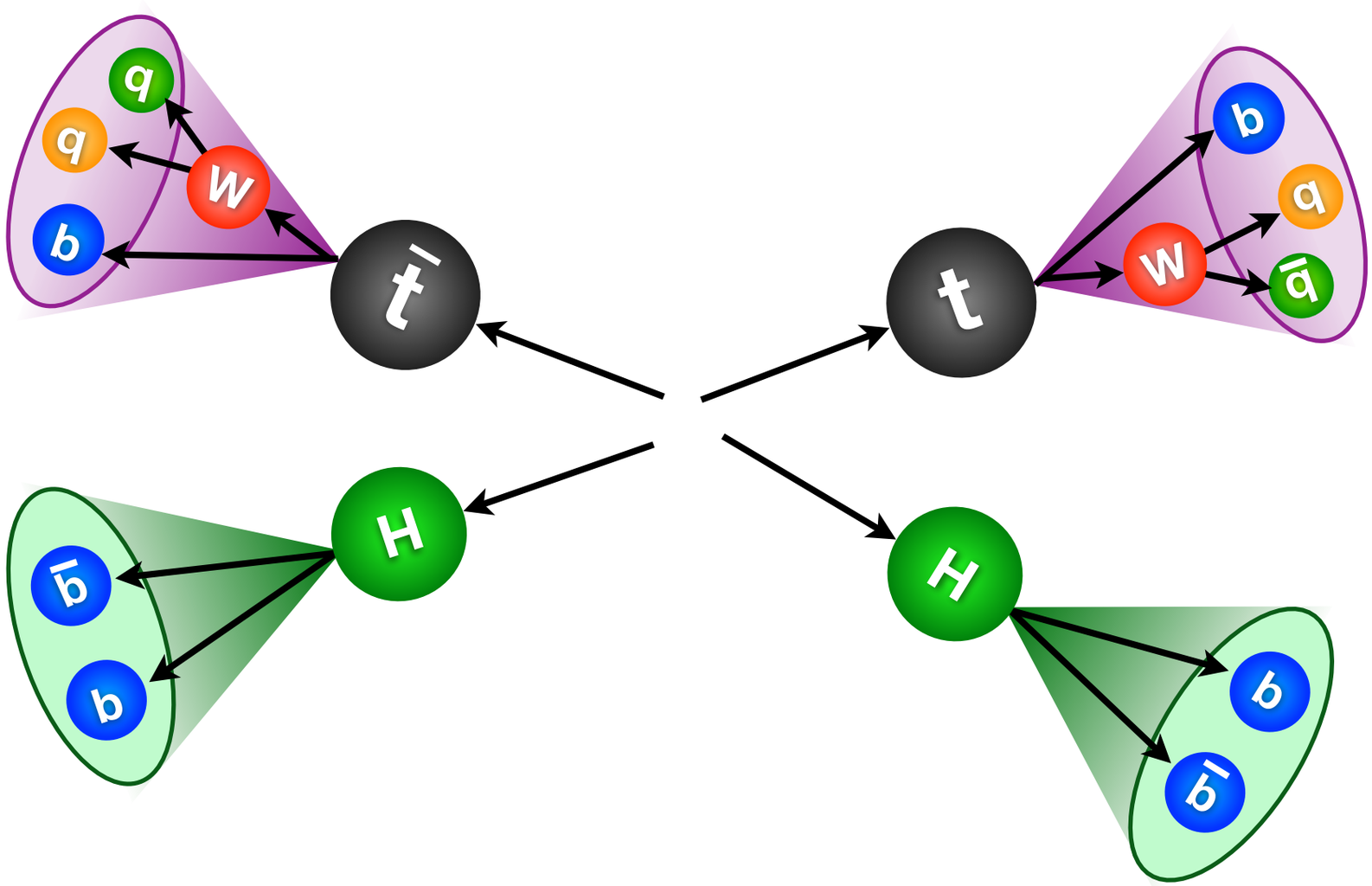




$T_{2/3}\,\bar{T}_{2/3} \rightarrow tH\bar{t}H$ all-hadronic

CMS B2G-14-002

- Search for pair produced $T_{2/3}$
- Optimized for the tH decay channel
- Consider hadronic decays of both t and H
- $T_{2/3}$ is heavy ⇒ t and H will be boosted ⇒ utilize t-tagging and H-tagging



$T\,T \rightarrow tHtH$ analysis strategy

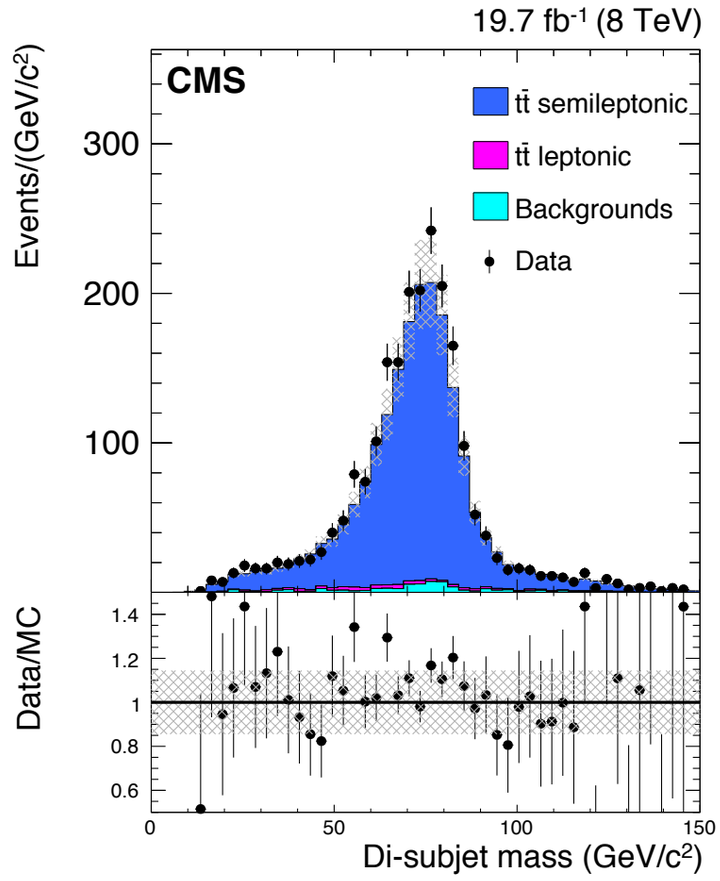
CMS B2G-14-002

- Cluster with large R jets (Cambridge Aachen R=1.5)
- Apply jet filtering (R=0.3, N=3)
- Basic selection
  - HT > 720 GeV (HT = sum p_T of all subjets contained within CA15 p_T>150 jets)
  - 1 t-tagged jet with p_T >200
  - 1 H-tagged jet with p_T >150

t-tag = CA15 jet tagged with HEP Top Tagger (HTT) and one filtered subjet b-tag

H-tag = CA15 jet with 2 filtered subjet b-tags and pairwise b-tagged subjet mass > 60 GeV

- Split the events passing the basic selection into two categories:
  1. Events with 1 H-tag
  2. Events with ≥ 2 H-tags
- Search in HT and m_{bb} (combined into a single discriminant with a likelihood ratio)

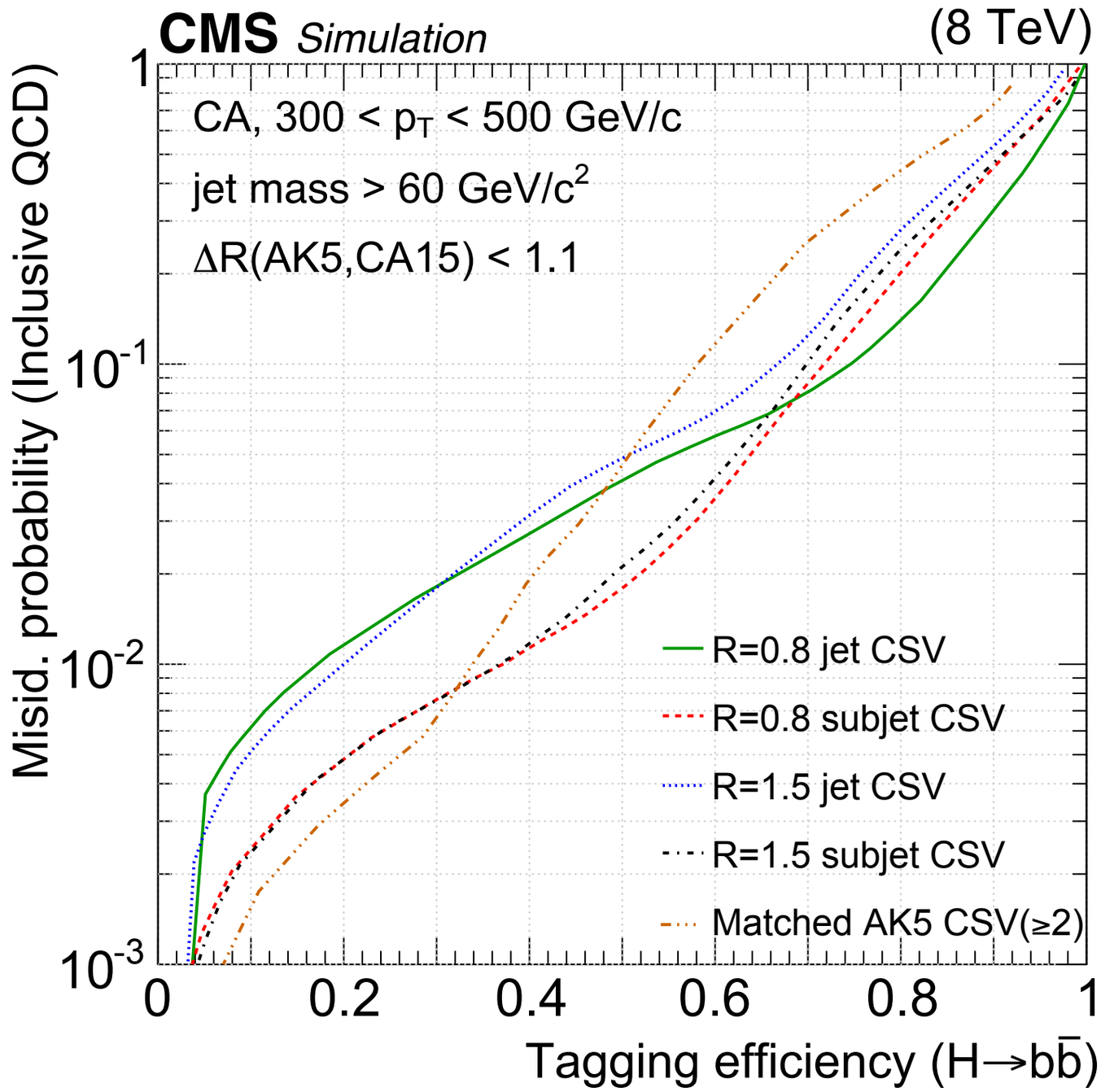


Higgs tagging with b-tagged subjets

CMS B2G-14-002

see also

CMS BTV-13-001



For 50% Higgs tagging efficiency:
Double subjet b-tag > 2 matched AK5 b-tagged jets > 1 b-tagged fat jet

$T\,T \rightarrow tHtH$ background estimation

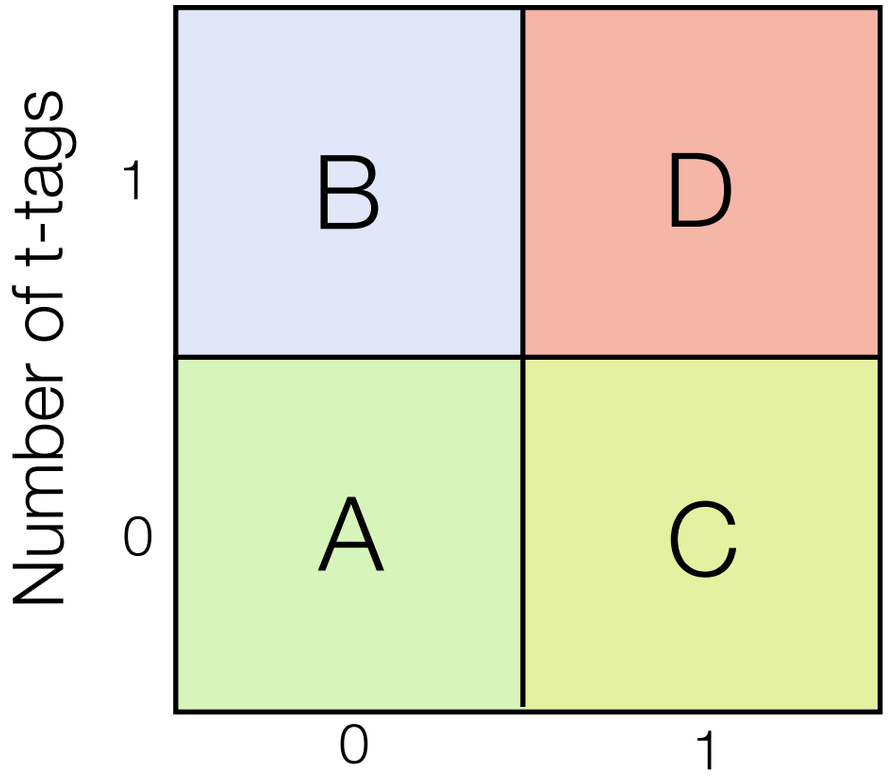
CMS B2G-14-002

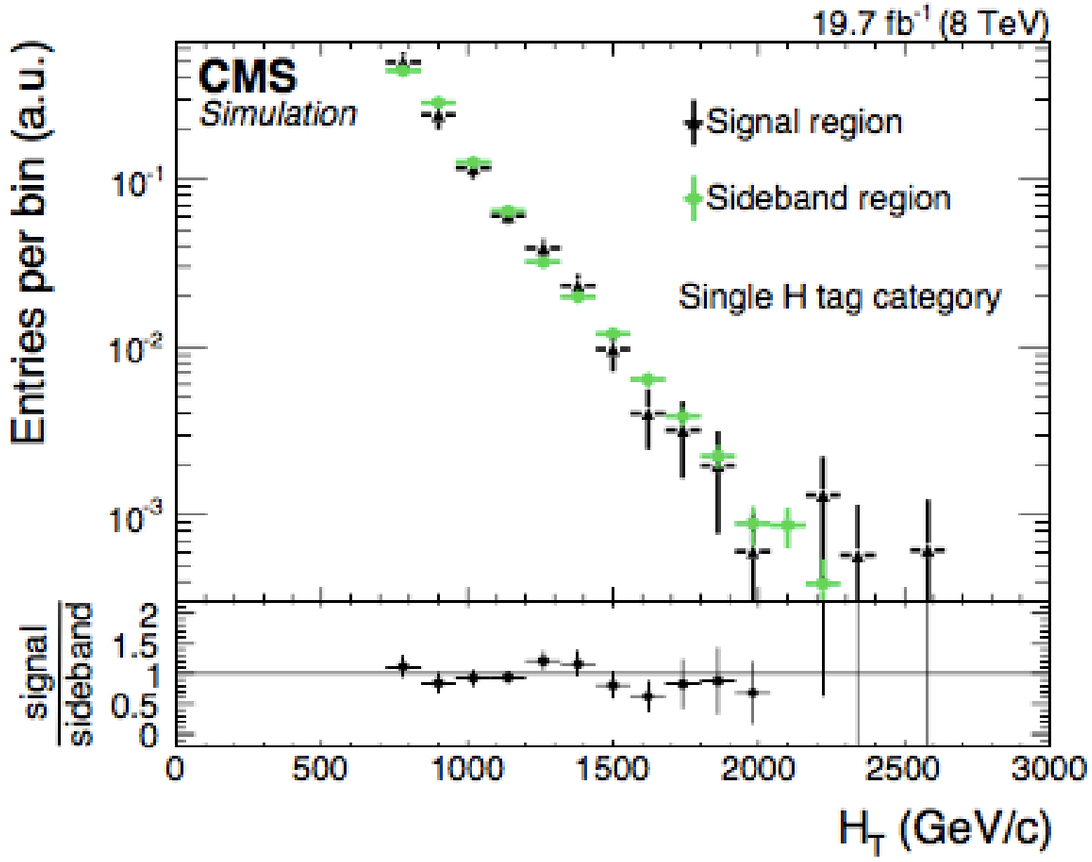
D = signal

C - Invert T-tag (HTT top mass window and W mass window)
Require 1 H-tag

B - Invert H tag mass requirement (keep double b-tag)
Require 1 t-tag

A - Invert H tag and t tag

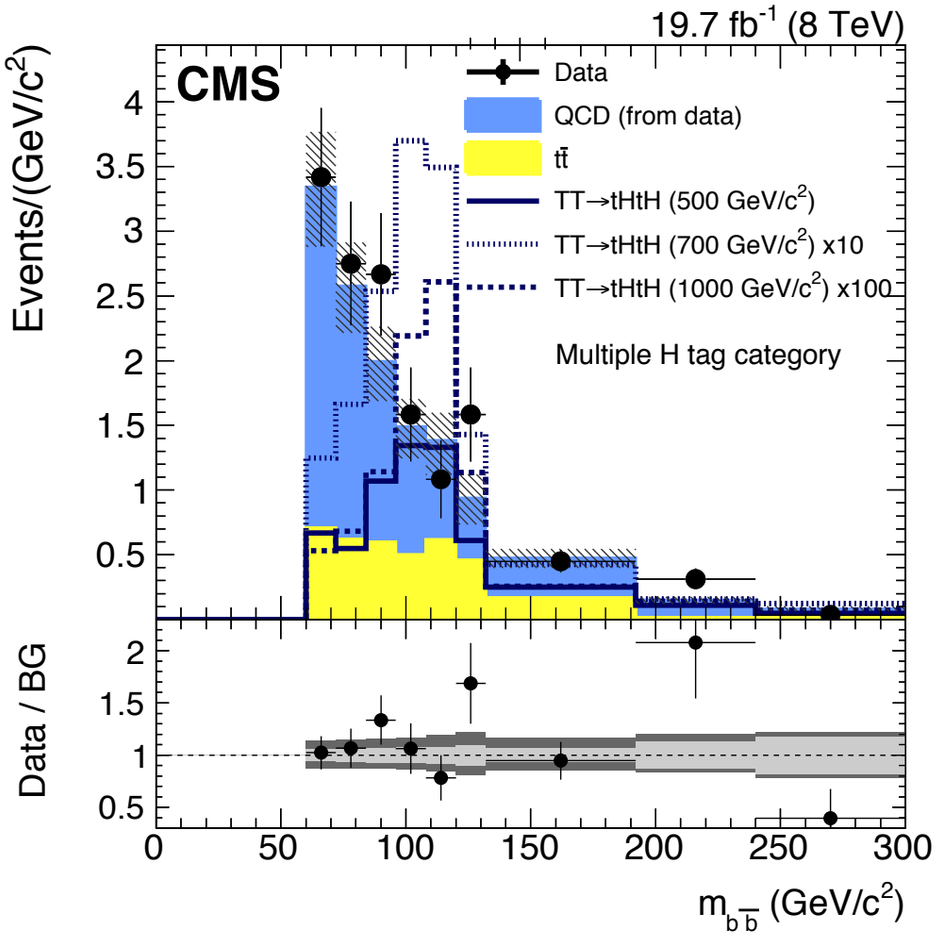


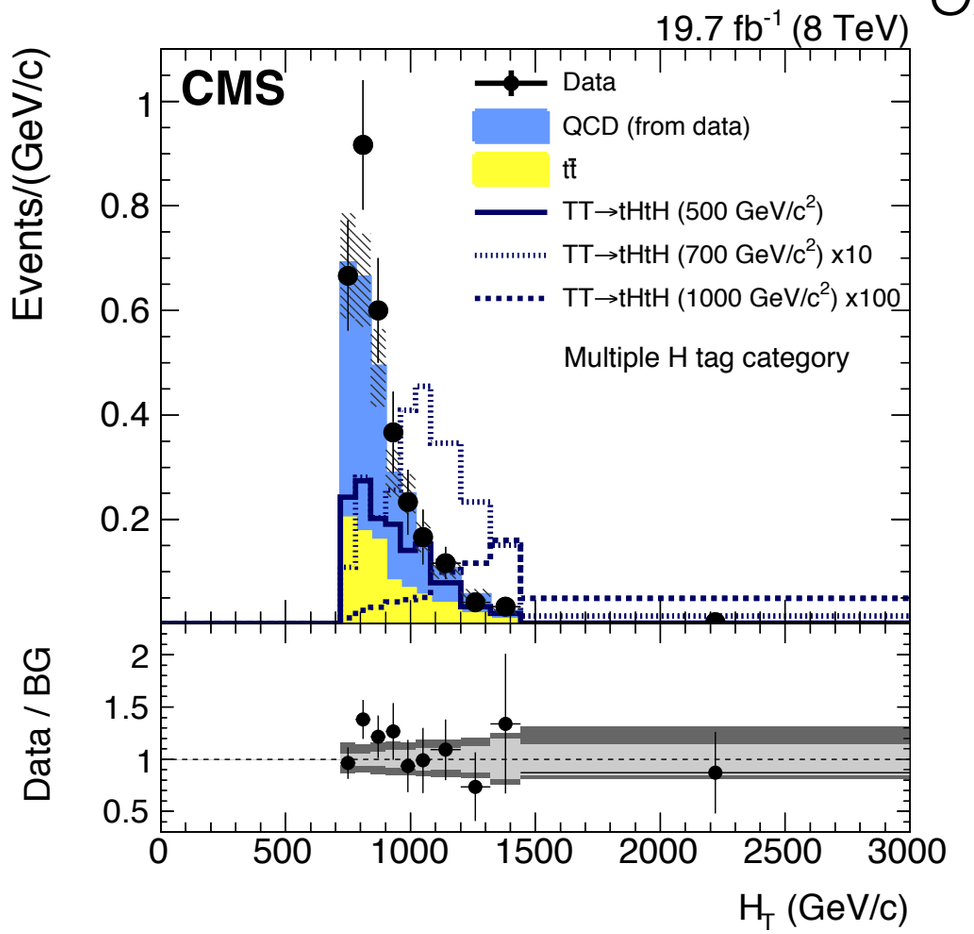


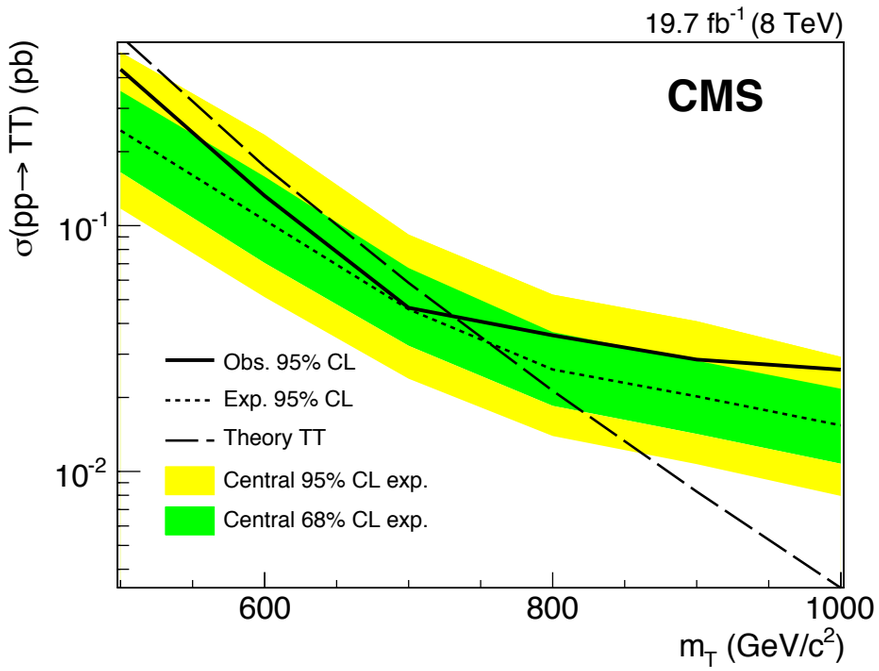
$$R_D = R_B \frac{R_C}{R_A}$$

$TT \rightarrow tHtH$ results

CMS B2G-14-002







For BR(tH)=100%

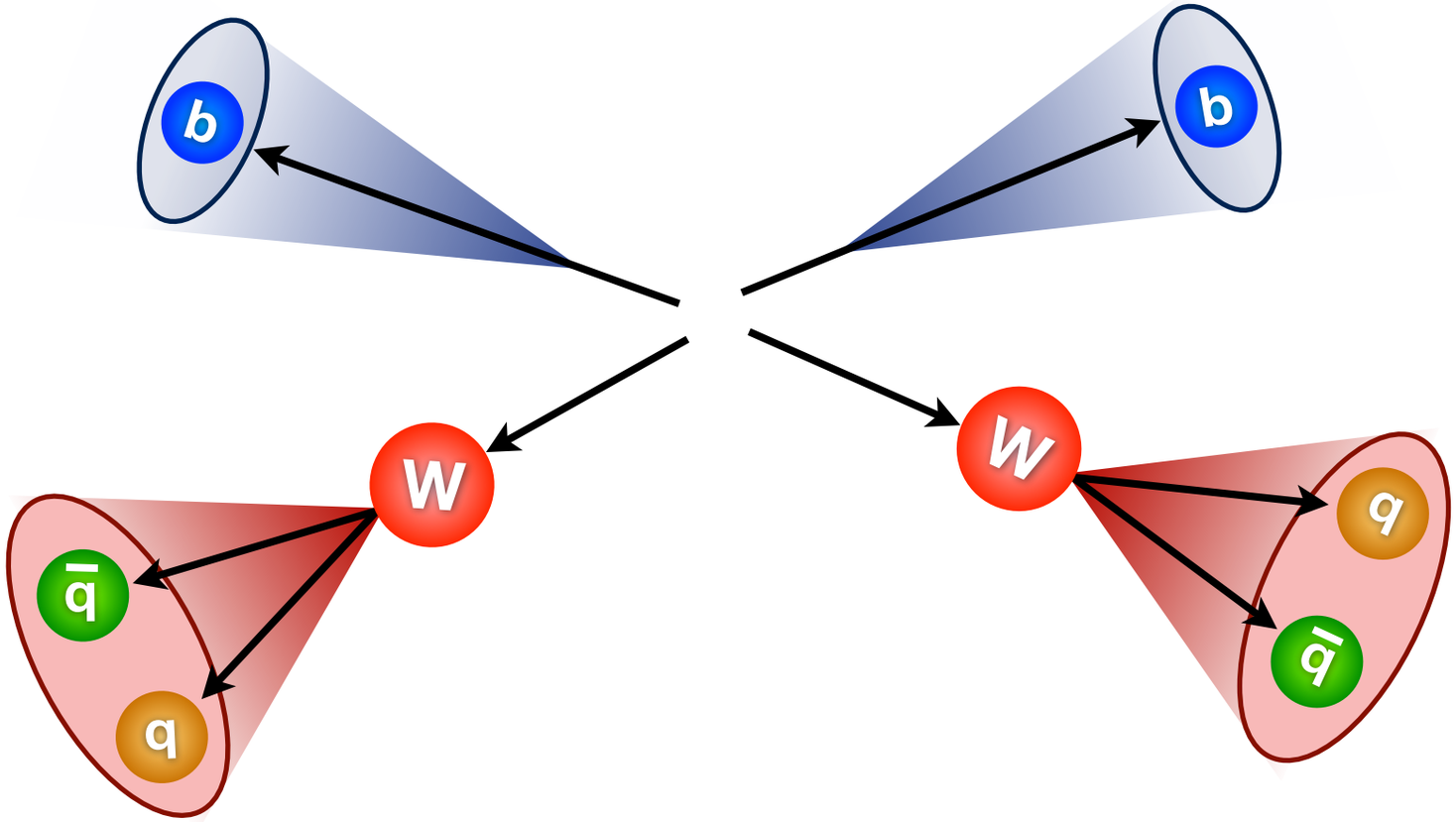
Exclude below 745 GeV at 95% confidence level

Expected limit 773 GeV

$T_{2/3}\,\bar{T}_{2/3} \rightarrow bW\bar{b}W$ all-hadronic

CMS B2G-12-013

- Search for pair produced $T_{2/3}$
- Optimized for the bW decay channel
- Consider hadronic decays of both b and W
- $T_{2/3}$ is heavy ⇒ W will be boosted ⇒ utilize W-tagging

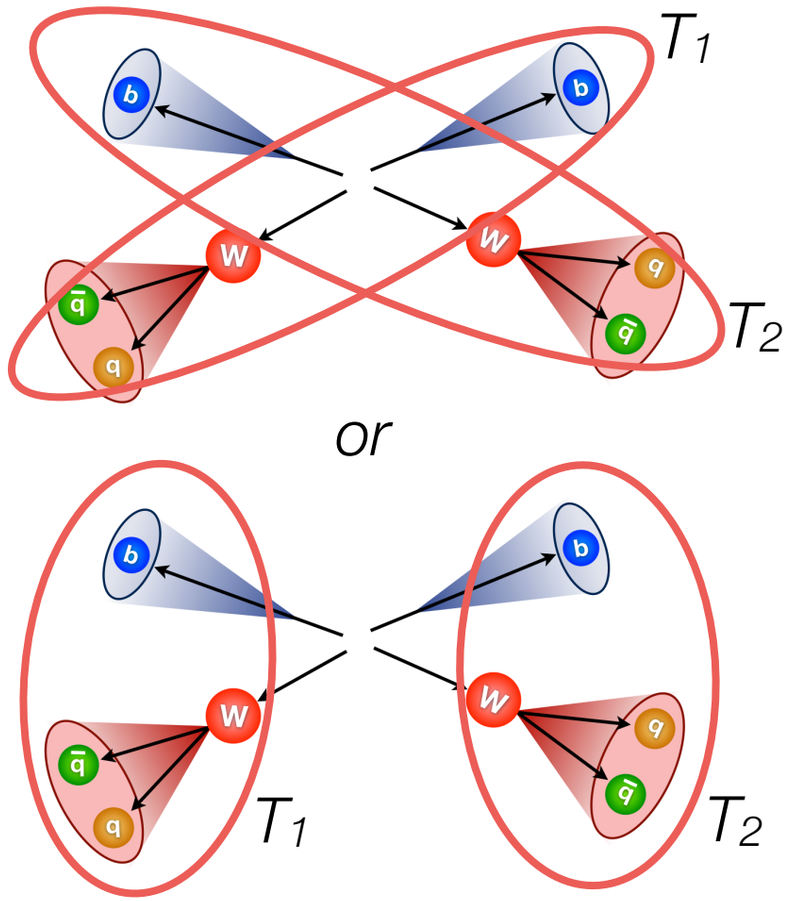


$T\,T \rightarrow bWbW$ analysis strategy

CMS B2G-12-013

- Trigger HT > 750 GeV
- Cluster with CA R=0.8 and AK R=0.5 algorithms
- Basic selection
  - 2 W-tagged CA8 jets (pT>150)
  - 2 AK5 jets (pT>50) with ΔR(CA8,AK5) > 0.8
  - Define 2 T quark candidates by minimizing the mass difference between all combinations of 1 CA8 jet and 1 AK5 jet
  - Require T quark candidate mass > 200 GeV
  - Require azimuthal separation for T quark candidates $\Delta\phi(T_1, T_2) > 5\pi/6$
  - Both T candidates should be close in mass
    - Require fractional mass difference $a_f < 0.1$
    - $a_f \equiv |(m_{T1} - m_{T2})|/(m_{T1} + m_{T2})$
  - ST > 1000 GeV
- Define 2 categories $N_{btag} = 1$ and $N_{btag} \geq 2$

W-tag =
CA8 jet (p_T>150)
$60 < m_{prune} < 100$
subjet mass drop < 0.4



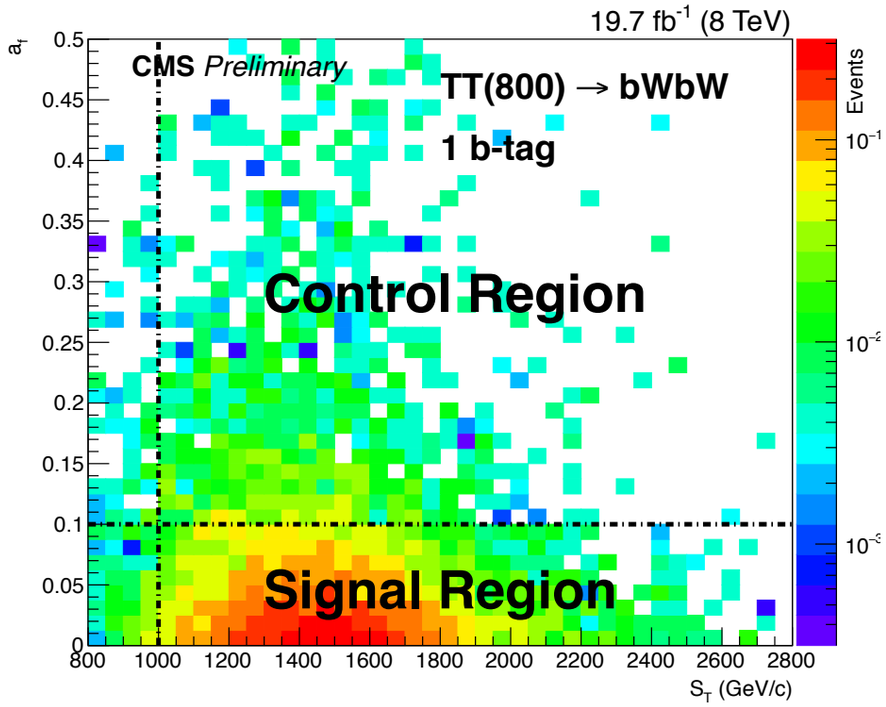
$T\,T \rightarrow bWbW$ QCD multijet background estimation

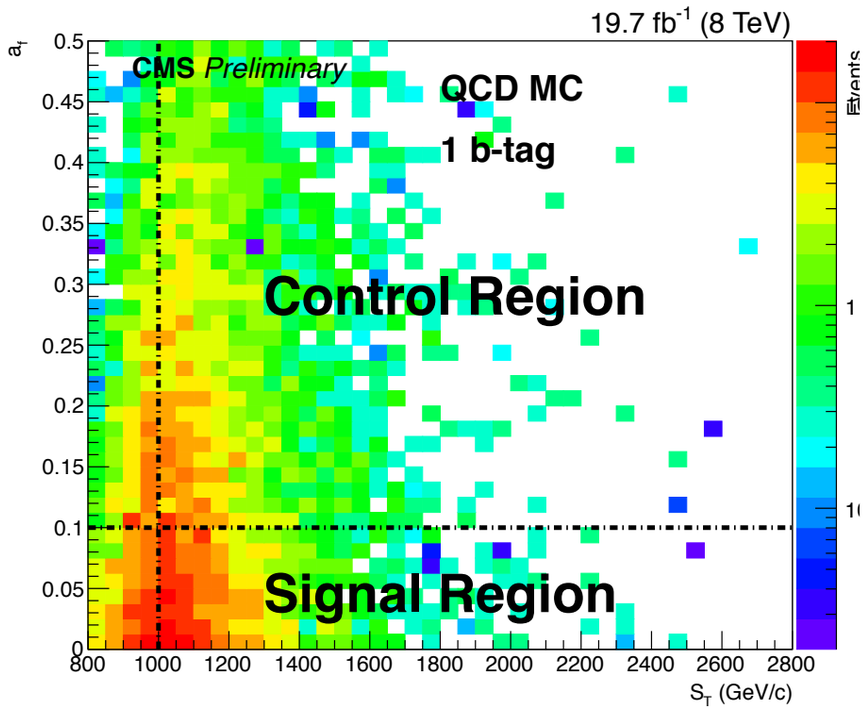
CMS B2G-12-013

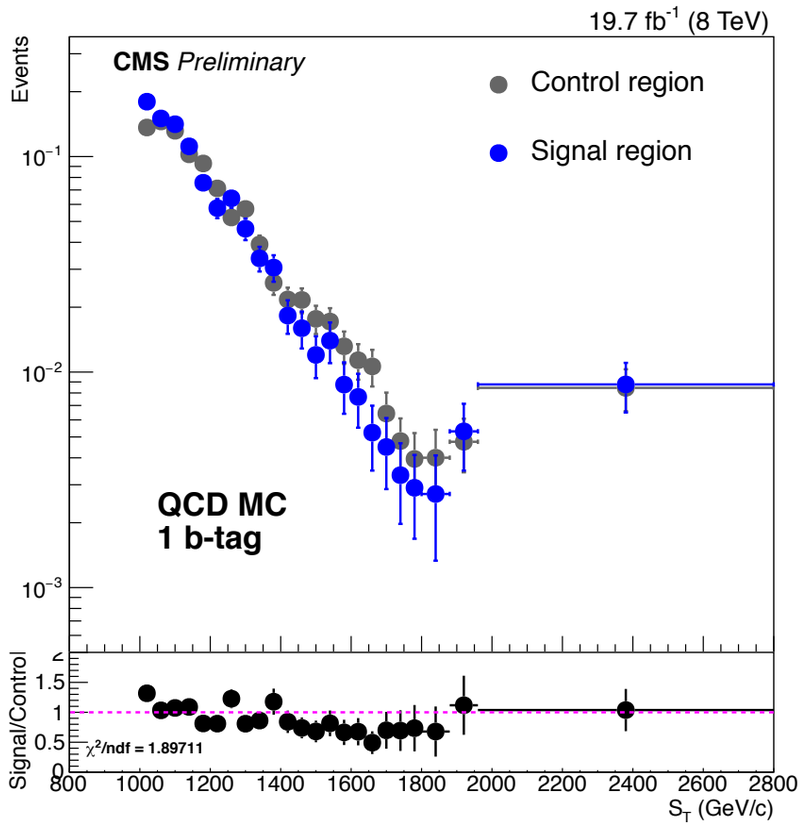
- Define a control region by inverting the fractional mass difference requirement
  - Signal: $a_f<0.1$
  - Control: $a_f>0.1$

$$a_f \equiv |(m_{T1} - m_{T2})|/(m_{T1} + m_{T2})$$

- Use control region ST distribution to estimate the QCD background shape. Allow normalization to float during the limit setting.
  - Use the shape difference between the CR and SR in QCD MC as a systematic uncertainty

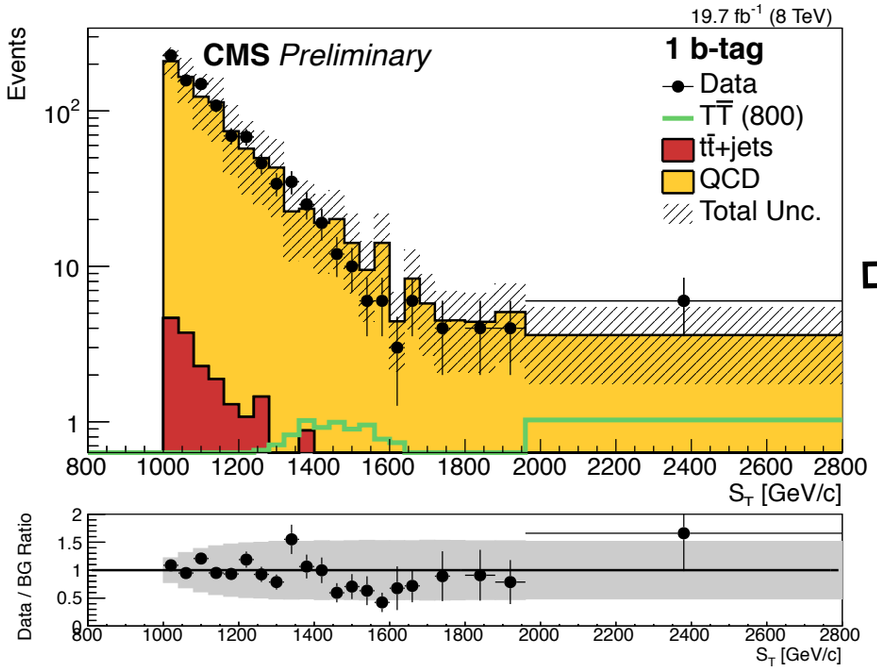


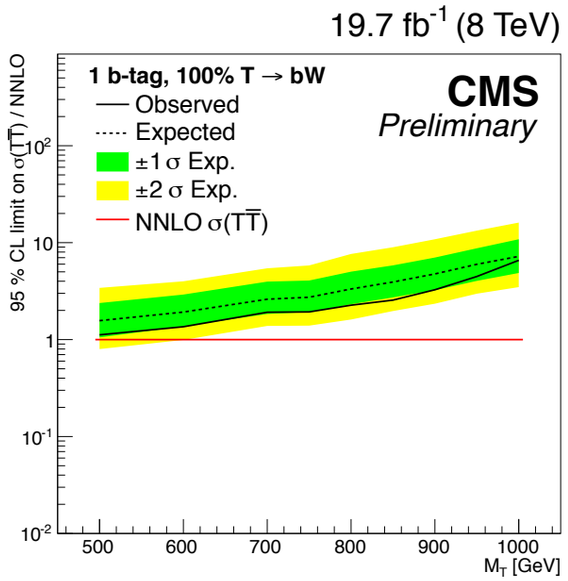


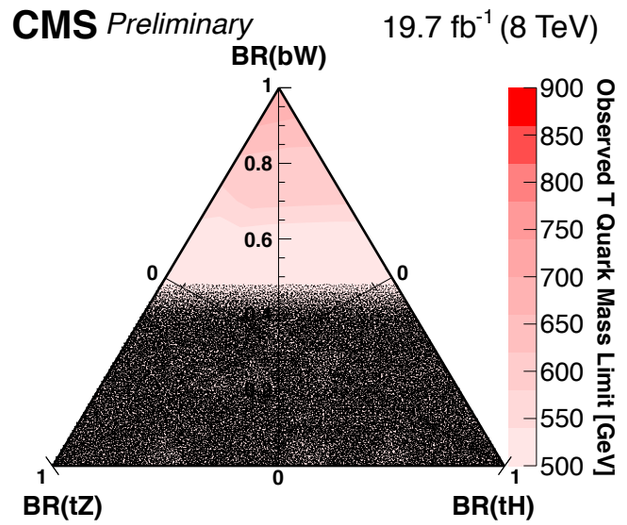


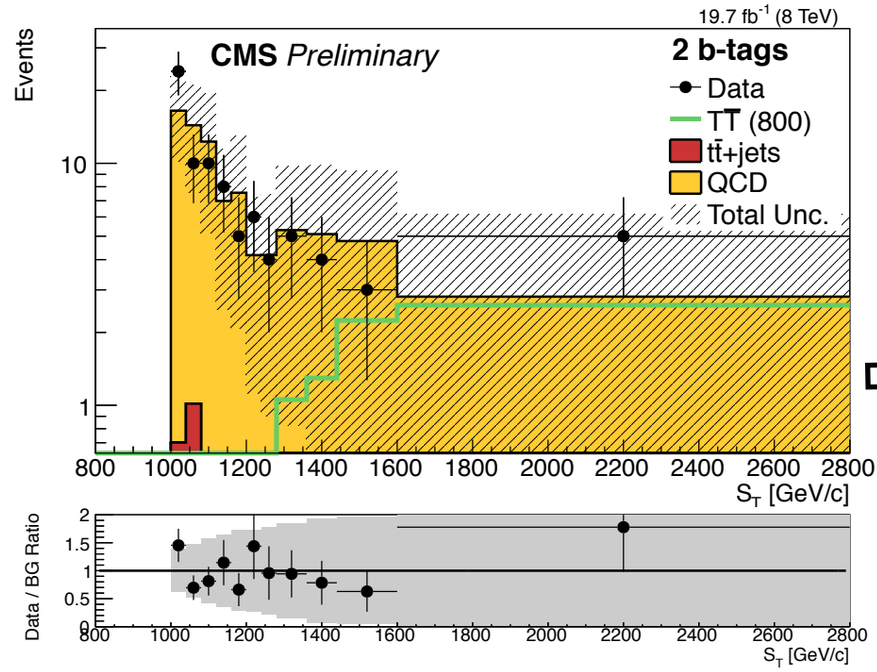
$T\,\bar{T} \rightarrow bWbW$ results

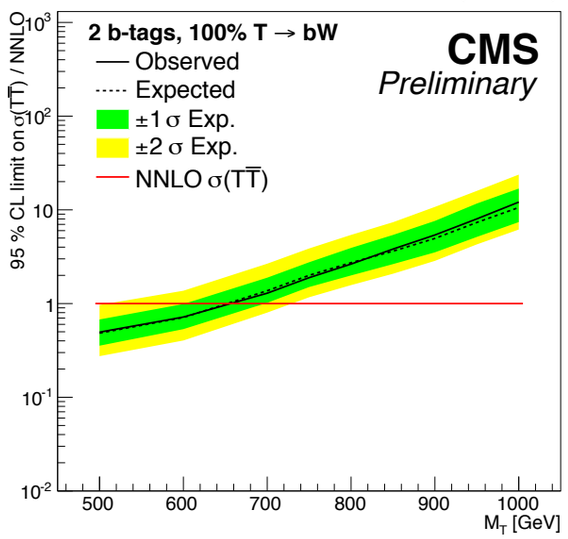
CMS B2G-12-013









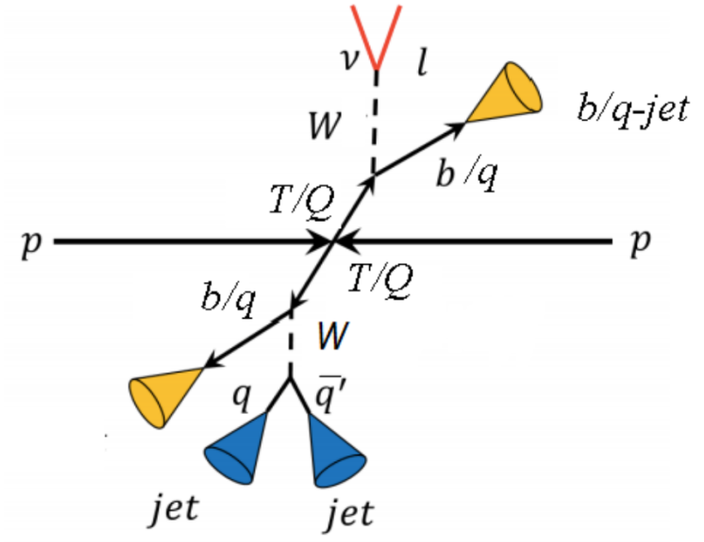


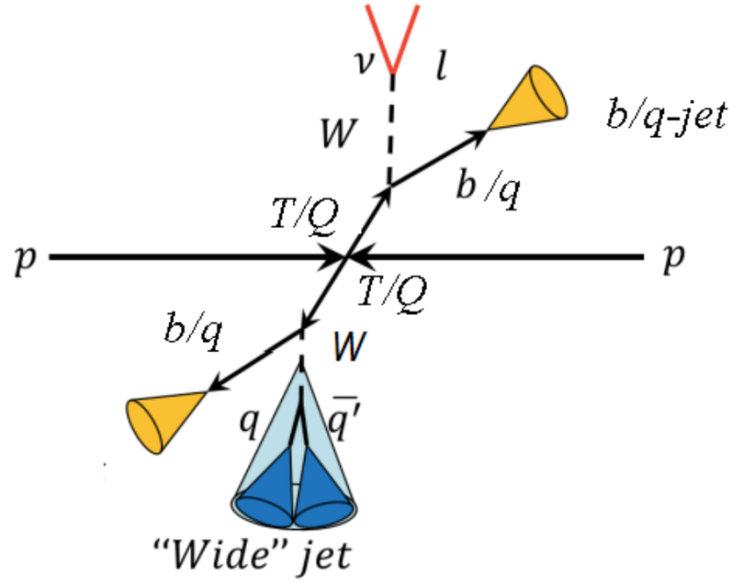
For BR(bW) = 100%
T quarks with masses below
705 GeV/c^2 are excluded at
the 95% confidence level

$T_{2/3}\,\bar{T}_{2/3} \rightarrow bW\bar{b}W$ lepton + jets

CMS B2G-12-017

- Search for pair produced $T_{2/3}$ or $Q_{2/3}$
- Optimized for the bW decay channel
- Lepton + jets final state
- $T_{2/3}$ is heavy ⇒ W will be boosted ⇒ utilize W-tagging
  - Novel hybrid resolved+boosted approach (kinematic fitter with subjets)





Two decay hypotheses:

(1) $T\bar{T} \rightarrow bW^{+}\bar{b}W^{-} \rightarrow b\ell\nu\bar{b}q\bar{q}'$

(2) $Q\bar{Q} \rightarrow qW^{+}\bar{q}W^{-} \rightarrow q\ell\nu\bar{q}q\bar{q}'$

→ b-tag - main background = tt

→ anti b-tagged - main background = W+jets

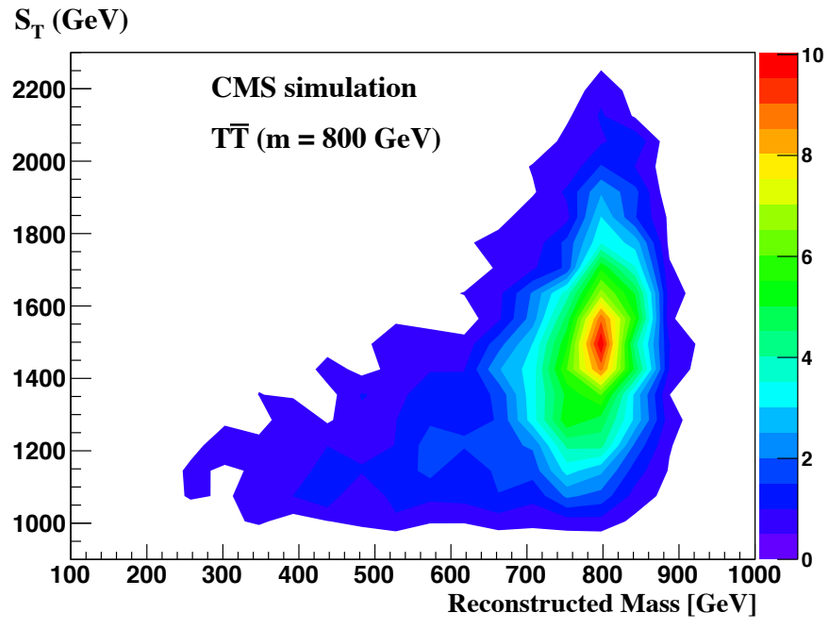
$T\,T \rightarrow bWbW$ lepton + jets analysis strategy

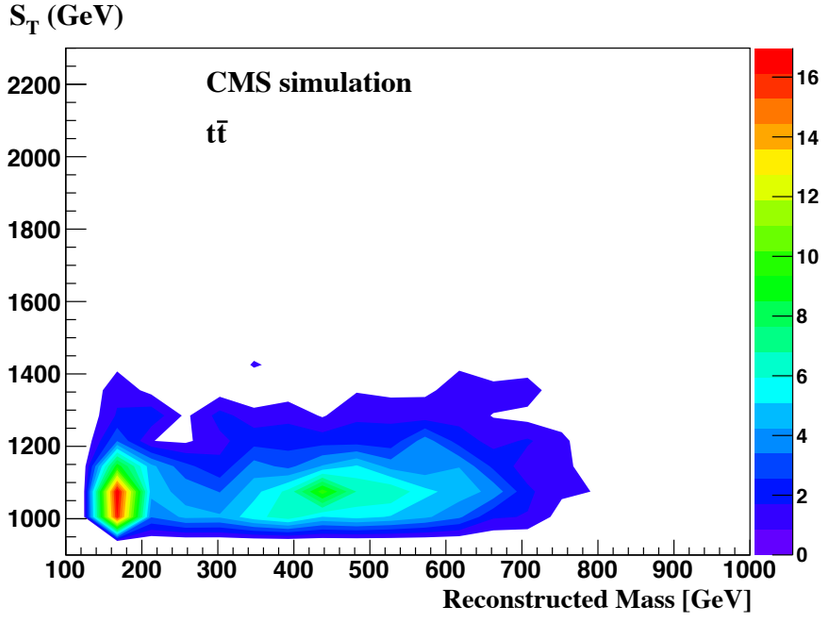
CMS B2G-12-017

- Event selection
  - 1 lepton + 4 jets + MET
    - Either 4 AK5 jets or 3 AK5 jets + 1 CA8 jet
  - ST > 1000 GeV
- If there is overlap with a CA8 W-tagged jet ($60<m_{prune}<100$, $p_T>200$), replace AK5 jets with pruned CA8 subjets
  - After substitution of subjets, the highest pT jets/ subjets must satisfy $p_T>120, 90, 50, 30$ GeV
- Constrained kinematic fit used to group the objects and determine the T/Q mass (M_{fit})
- Use the M_{fit} and S_T to search for signal

$$S_T = p_T^{\ell} + E_T^{miss} + p_T^{J_1} + p_T^{J_2} + p_T^{J_3} + p_T^{J_4}$$

$$m(\ell\nu b) = m(q\bar{q}'b) = M_{fit}$$
$$m(\ell\nu q) = m(q\bar{q}'q) = M_{fit}$$





$T\,T \rightarrow bWbW$ lepton + jets mass reconstruction

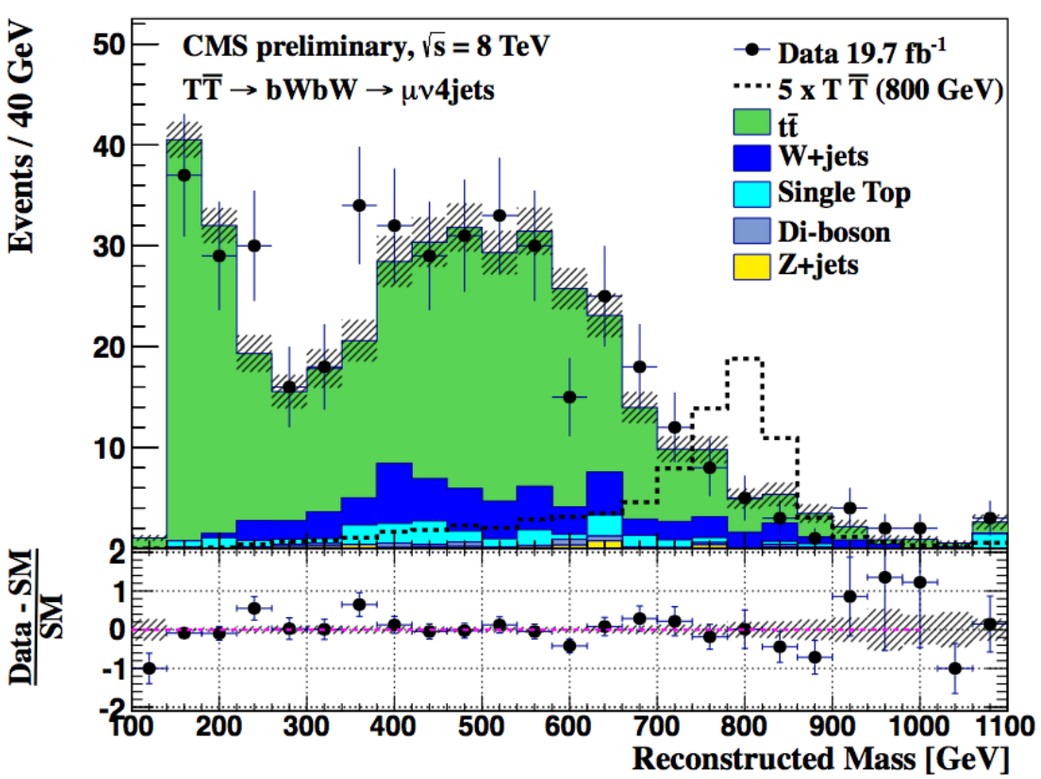
CMS B2G-12-017

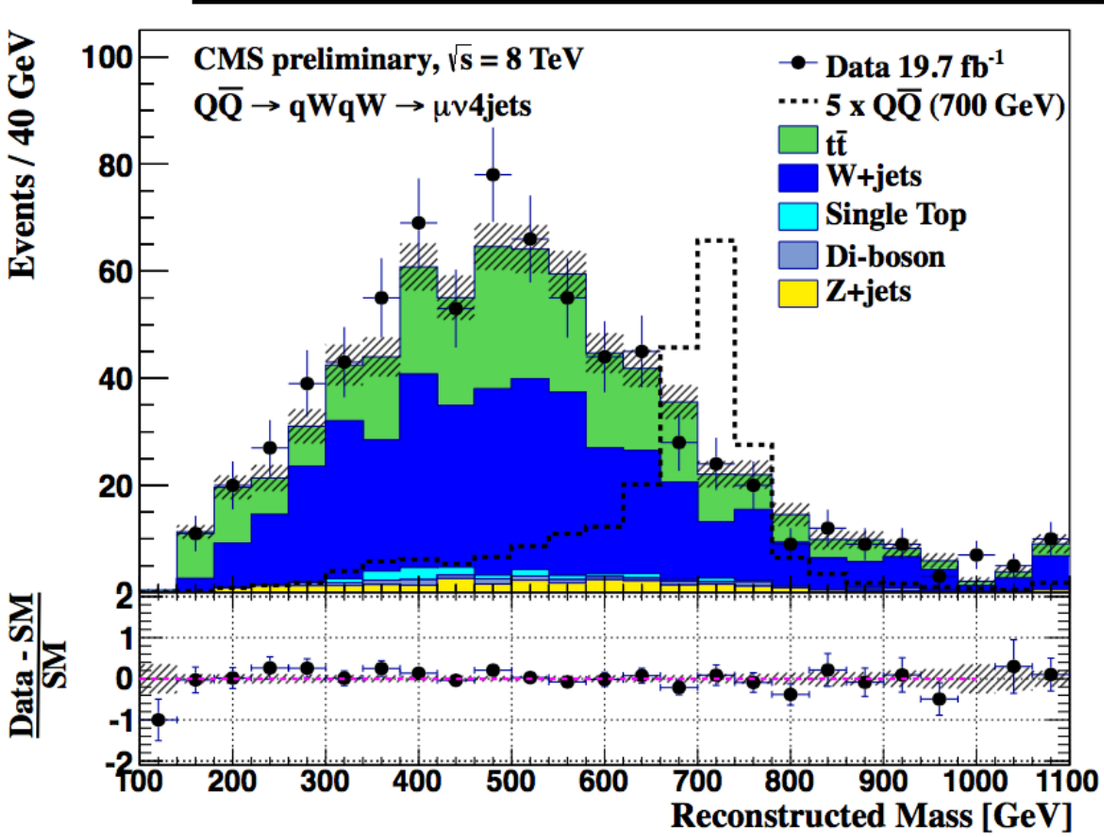
- Kinematic fit
  - If N_{jets} >4, use only 5 highest p_T jets. Check all combinations of 4 jets
  - Subjets are used to decrease the combinatorics (assigned to be W decay quarks)
  - b-tagging used for TT hypothesis
  - quark/gluon discrimination used for QQ hypothesis

$$
\begin{aligned}
m(\ell\nu) &= M_{\mathrm{W}},\\
m(\mathrm{q}\bar{\mathrm{q}}') &= M_{\mathrm{W}},\\
m(\ell\nu\mathrm{b}) = m(\mathrm{q}\bar{\mathrm{q}}'\mathrm{b}) &= M_{\mathrm{fit}}\\
(\text{or } m(\ell\nu\mathrm{q}) = m(\mathrm{q}\bar{\mathrm{q}}'\mathrm{q}) &= M_{\mathrm{fit}}),
\end{aligned}
$$

Two decay hypotheses:

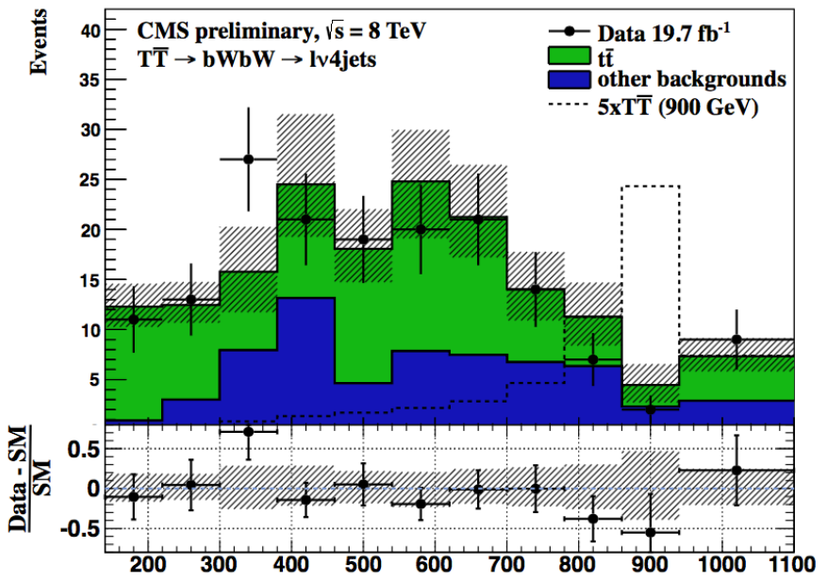
$$
\begin{aligned}
&(1)\quad \mathrm{T}\bar{\mathrm{T}} \rightarrow \mathrm{b}\mathrm{W}^{+}\bar{\mathrm{b}}\mathrm{W}^{-} \rightarrow \mathrm{b}\ell\nu\bar{\mathrm{b}}\mathrm{q}\bar{\mathrm{q}}'\\
&(2)\quad \mathrm{Q}\bar{\mathrm{Q}} \rightarrow \mathrm{q}\mathrm{W}^{+}\bar{\mathrm{q}}\mathrm{W}^{-} \rightarrow \mathrm{q}\ell\nu\bar{\mathrm{q}}\mathrm{q}\bar{\mathrm{q}}'
\end{aligned}
$$

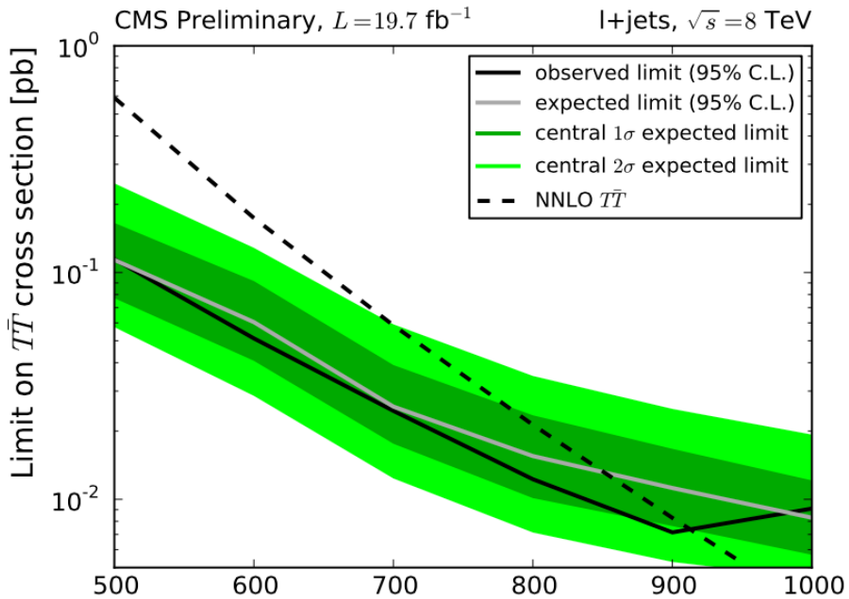




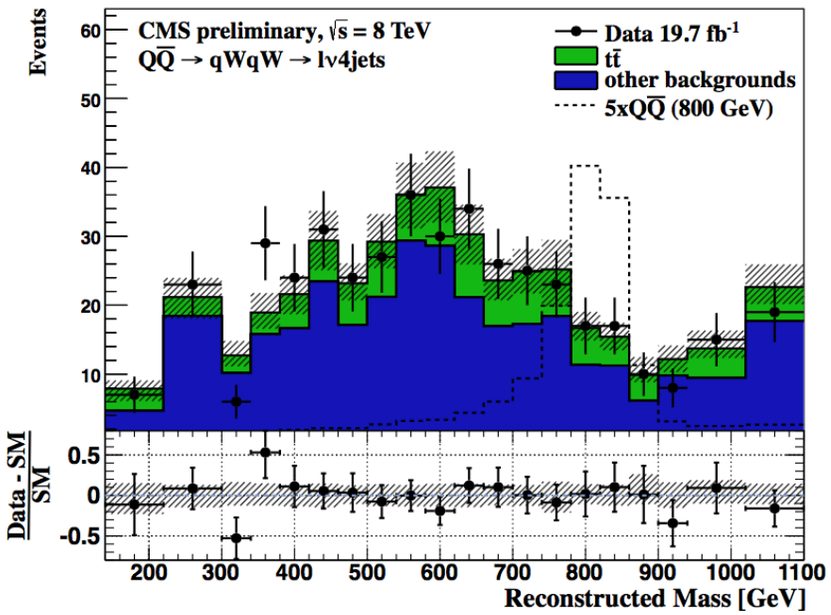
$T\,T \rightarrow bWbW$ lepton + jets mass results

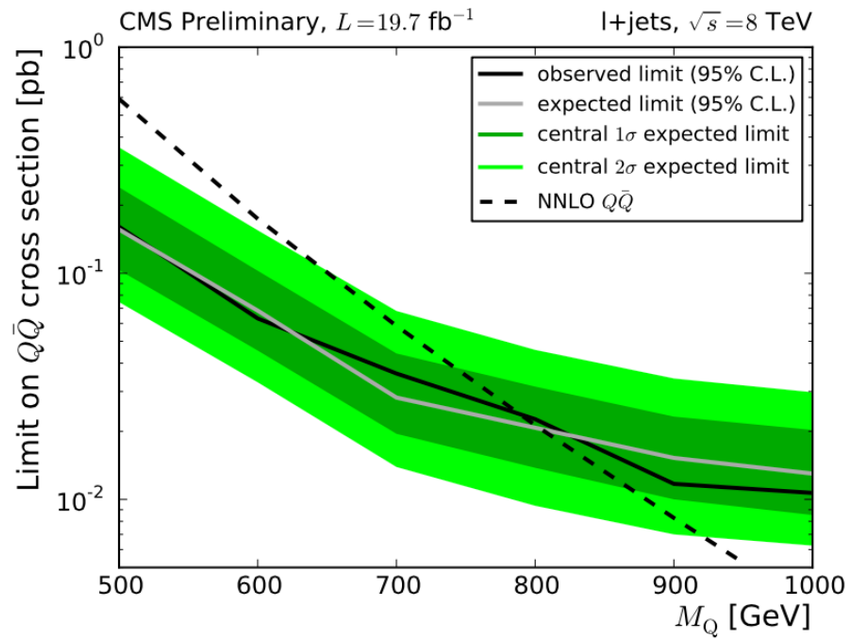
CMS B2G-12-017





Assume BR(T→bW) = 100%, lower limit on T quark mass at 95% C.L. = 912 GeV





Assume BR(Q→bW) = 100%, lower limit on Q quark mass at 95% C.L. = 788 GeV

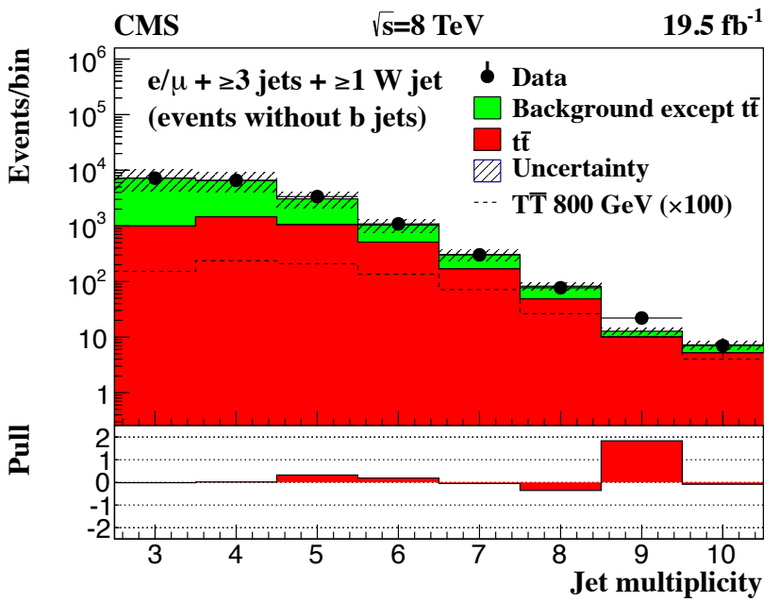
$T_{2/3}T_{2/3}$ inclusive

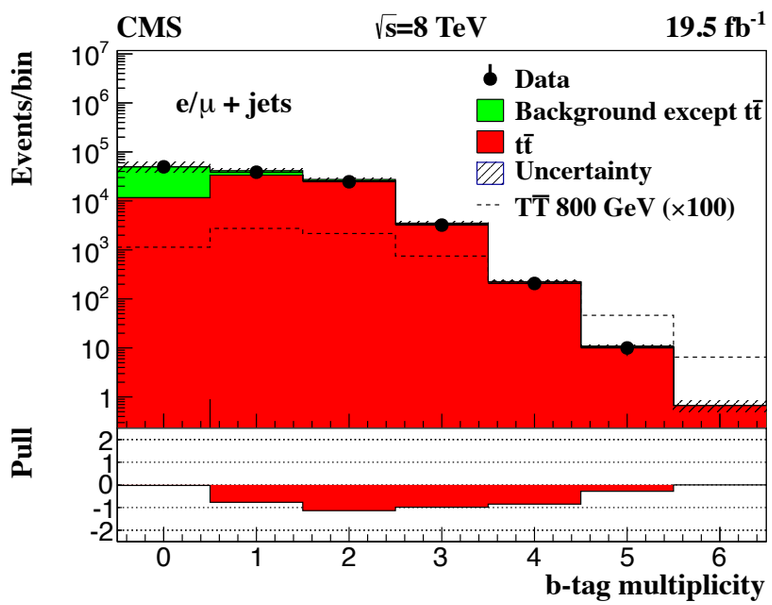
CMS B2G-12-015

- Search for pair produced $T_{2/3}$ with ≥ 1 lepton + jets
  - TT → bWbW, bWtH, bWtZ, tZtZ, tZtH, tHtH
- Single lepton event selection
  - Isolated muon or electron (p_T>32)
  - At least 3 jets (p_T>120, 90, 50 GeV)
  - At least one W jet or a 4th jet with pT>35
  - MET>20 GeV

W-tag =
CA8 jet (p_T>200)
60<m_{fat}<130

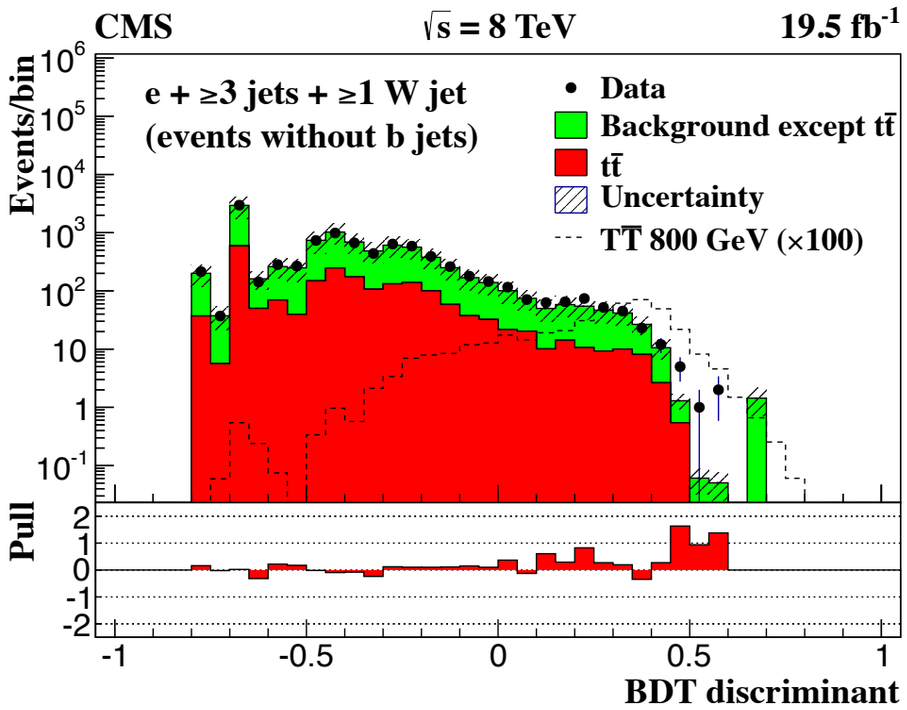
- Multilepton event selection
  - Doesn't use V-tagging …. so I'll skip it

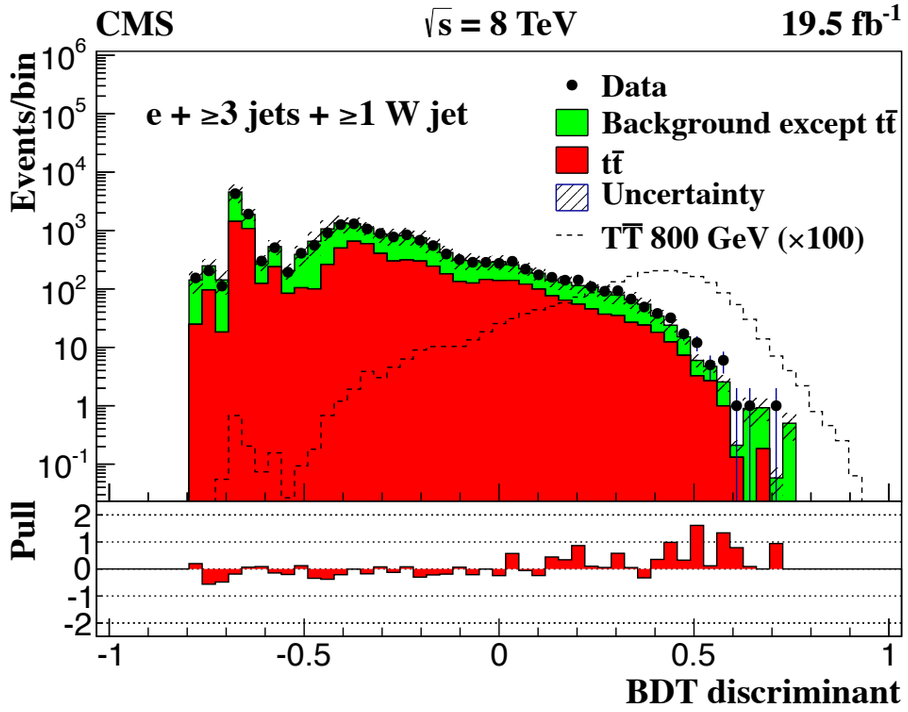


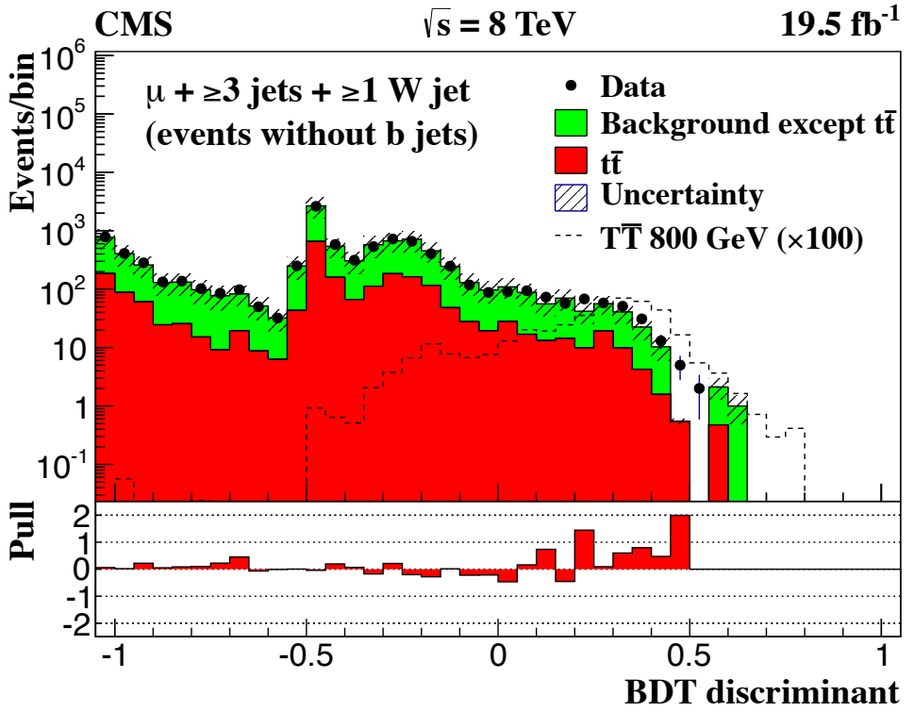


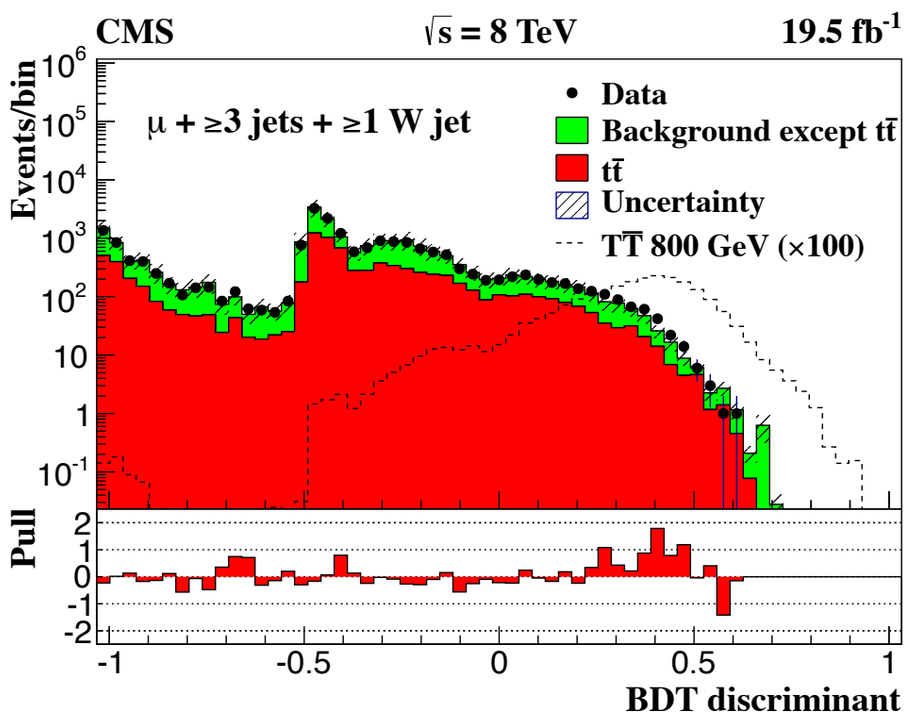
TT lepton + jets results

CMS B2G-12-015



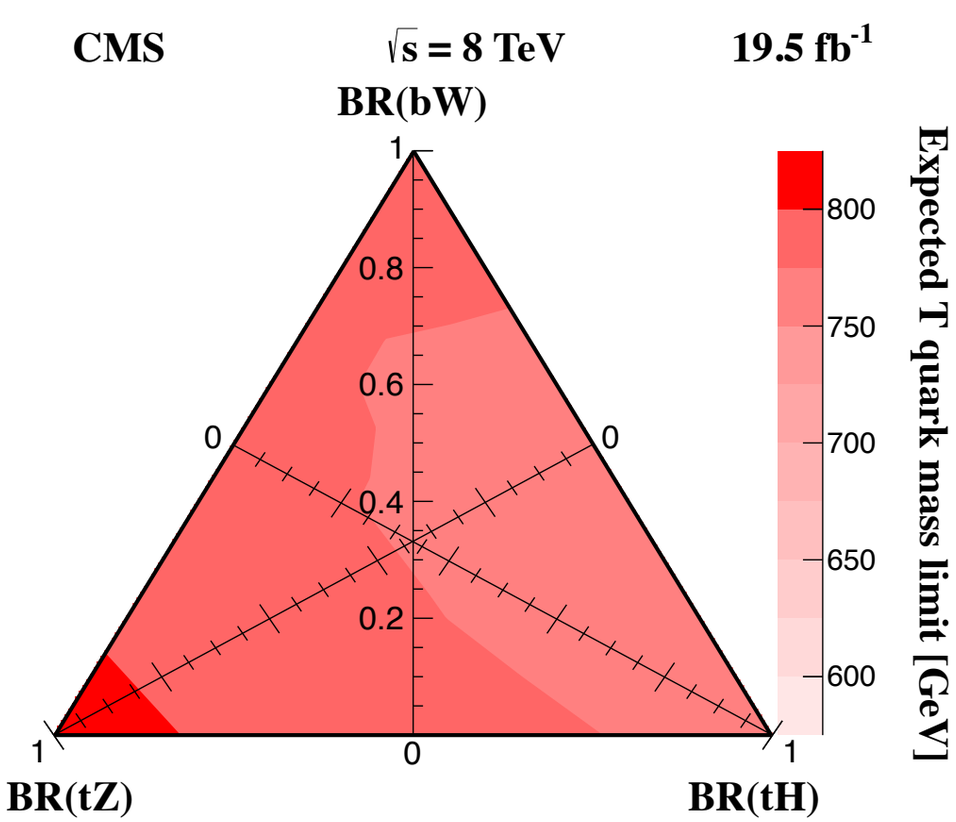


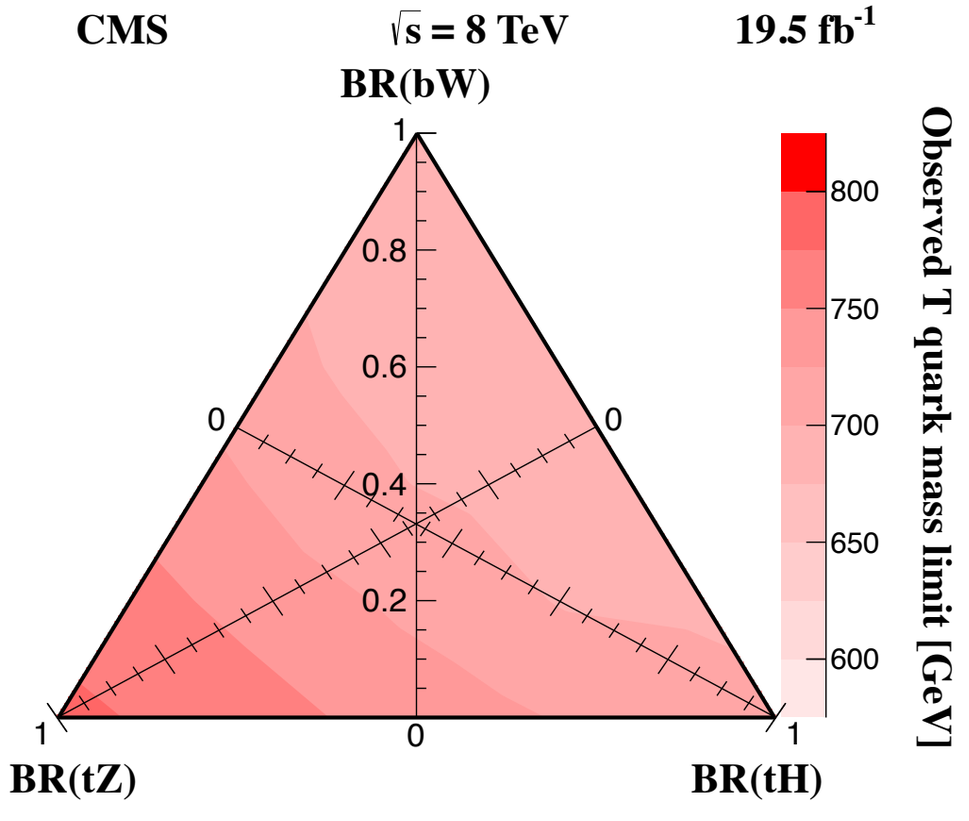




TT lepton + jets limits

CMS B2G-12-015



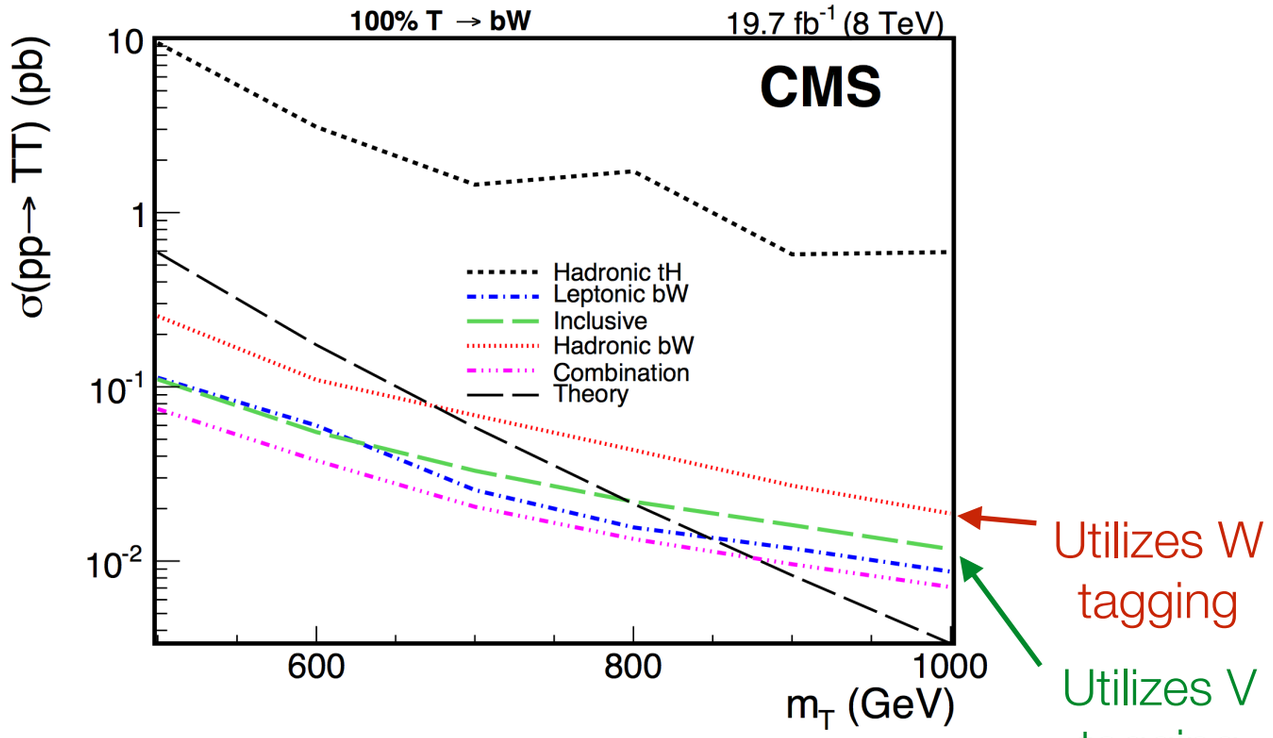


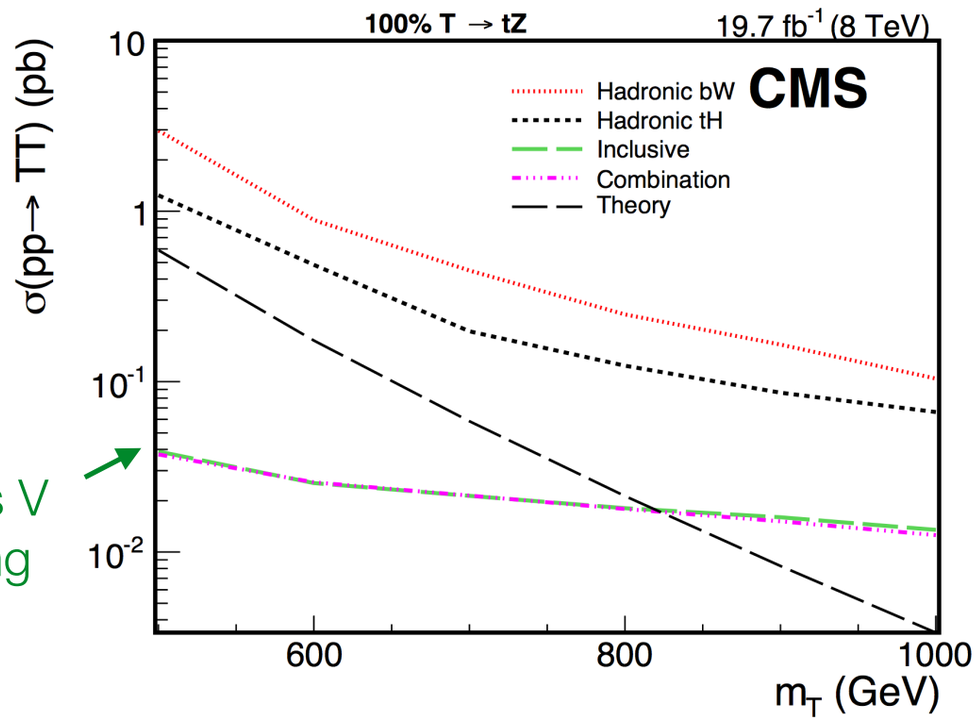
T quarks with masses below 687 - 782 GeV/c^2 (depending on the BR) are excluded at the 95% confidence level

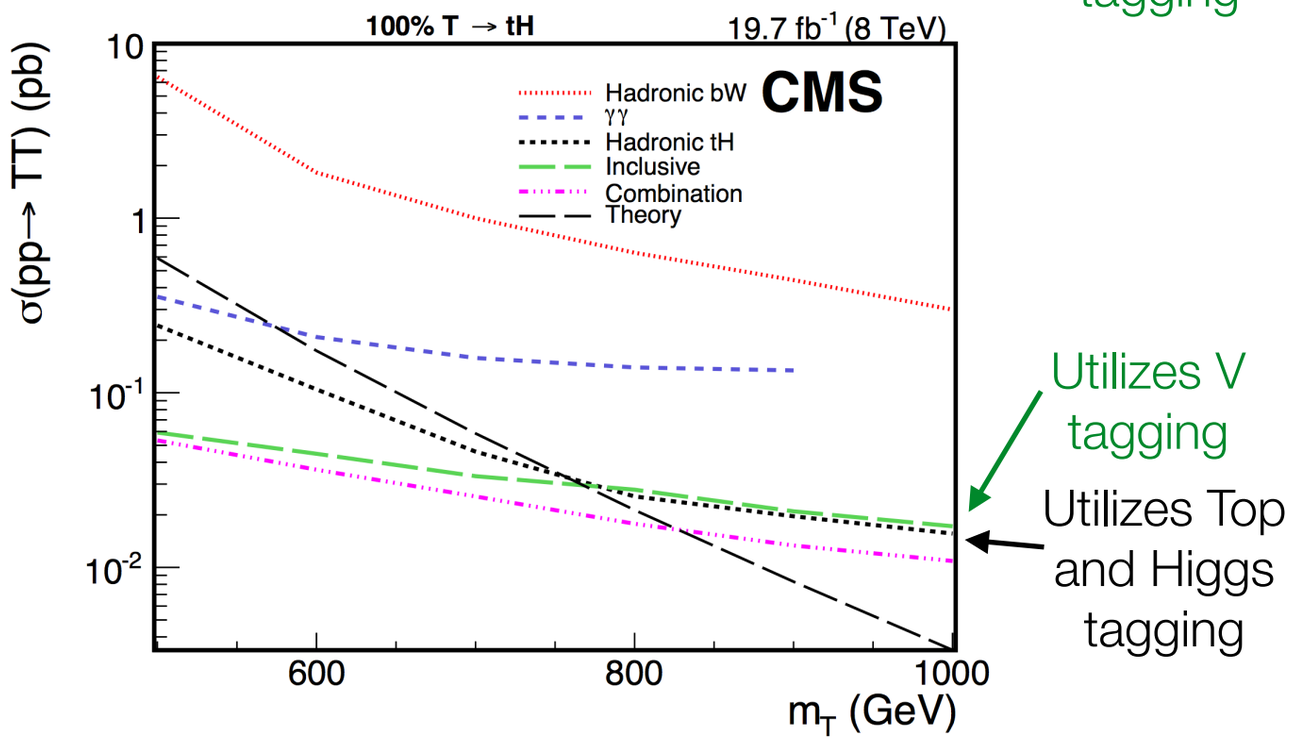
$T_{2/3}\,\bar{T}_{2/3}$ legacy combination

CMS B2G-13-005

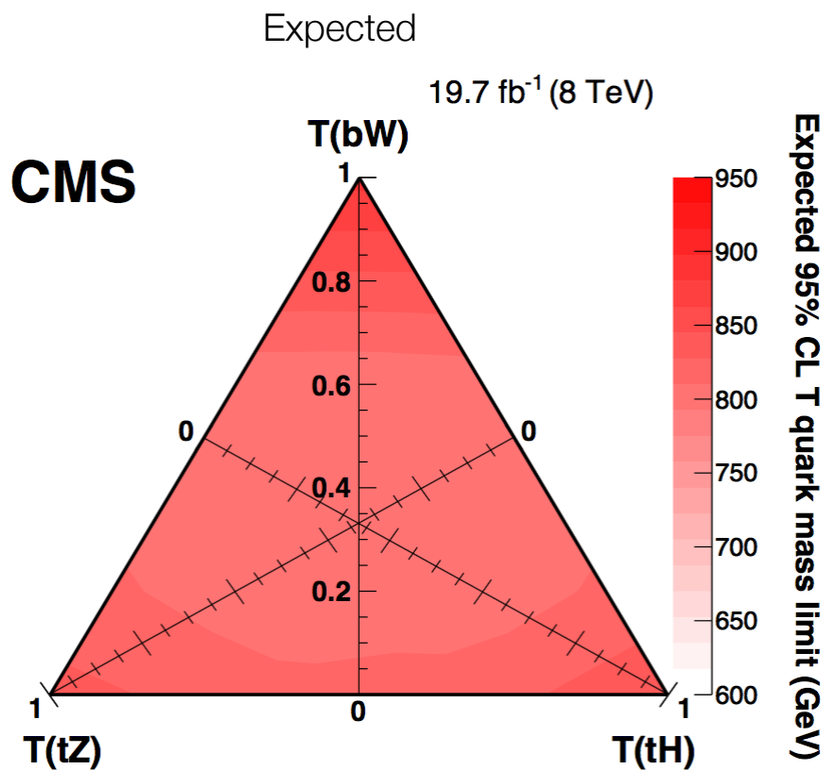
- Search for pair produced $T_{2/3}$ decaying to bW tZ or tH
- Combination of 5 analyses:
  - all-hadronic bW
  - all-hadronic tH
  - single-lepton
  - multi-lepton
  - tH, H → γγ

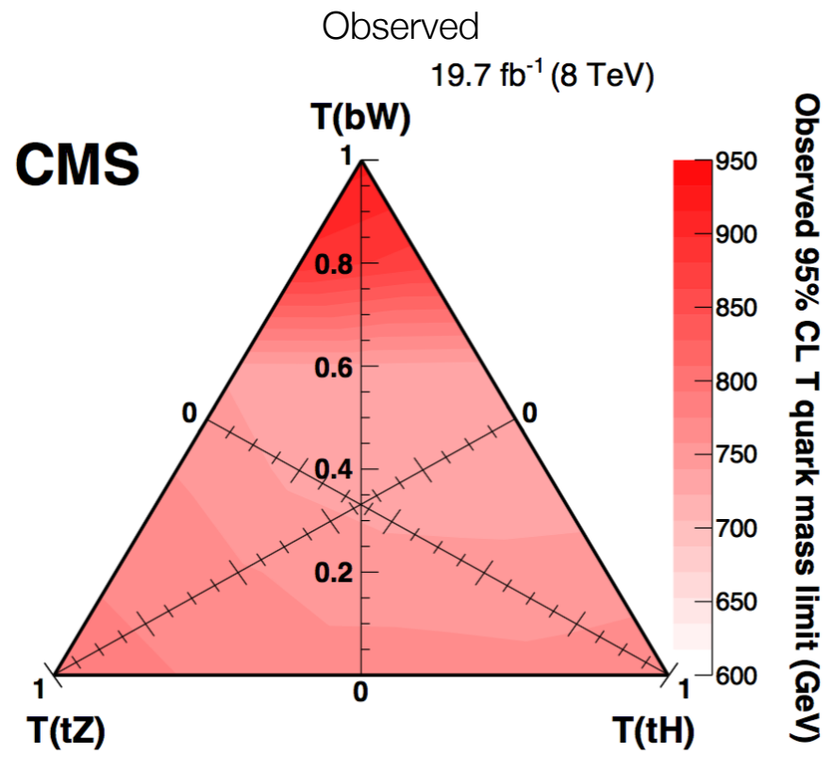


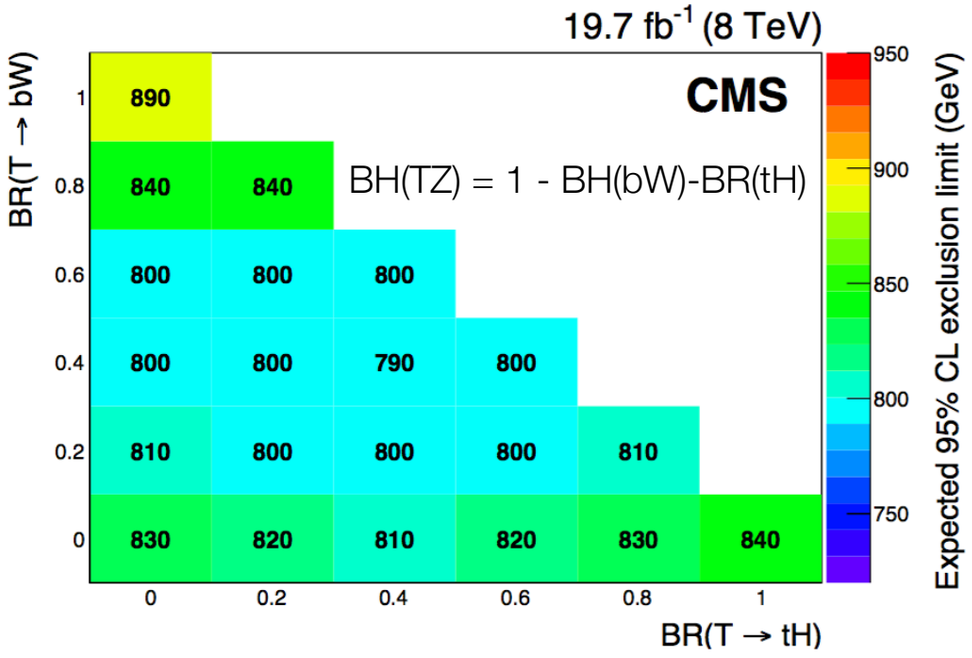




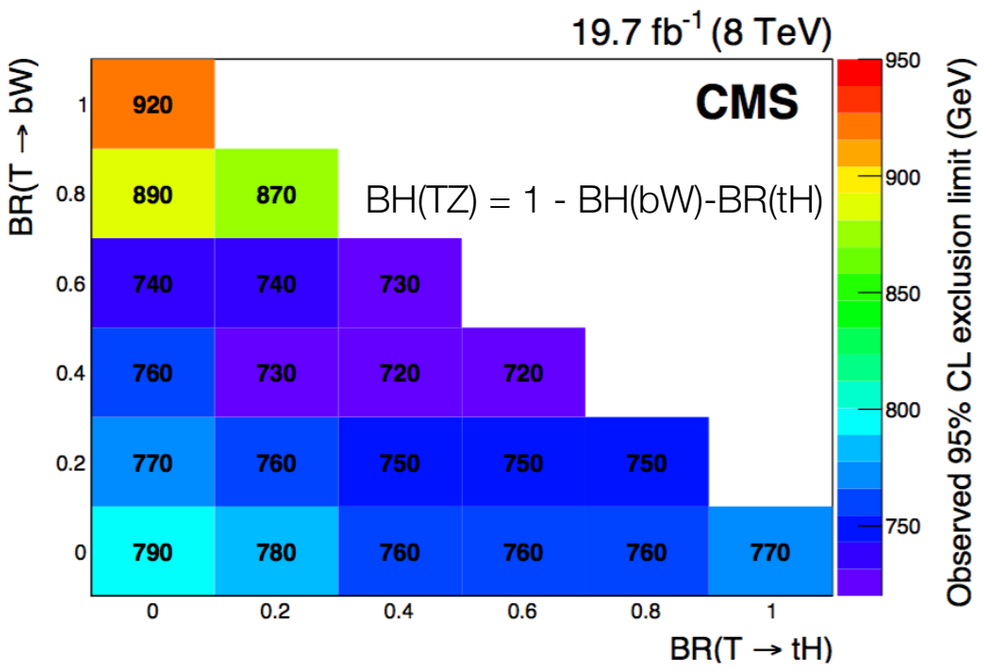
T combination limits







Expected lower limits on T mass 790-890 GeV

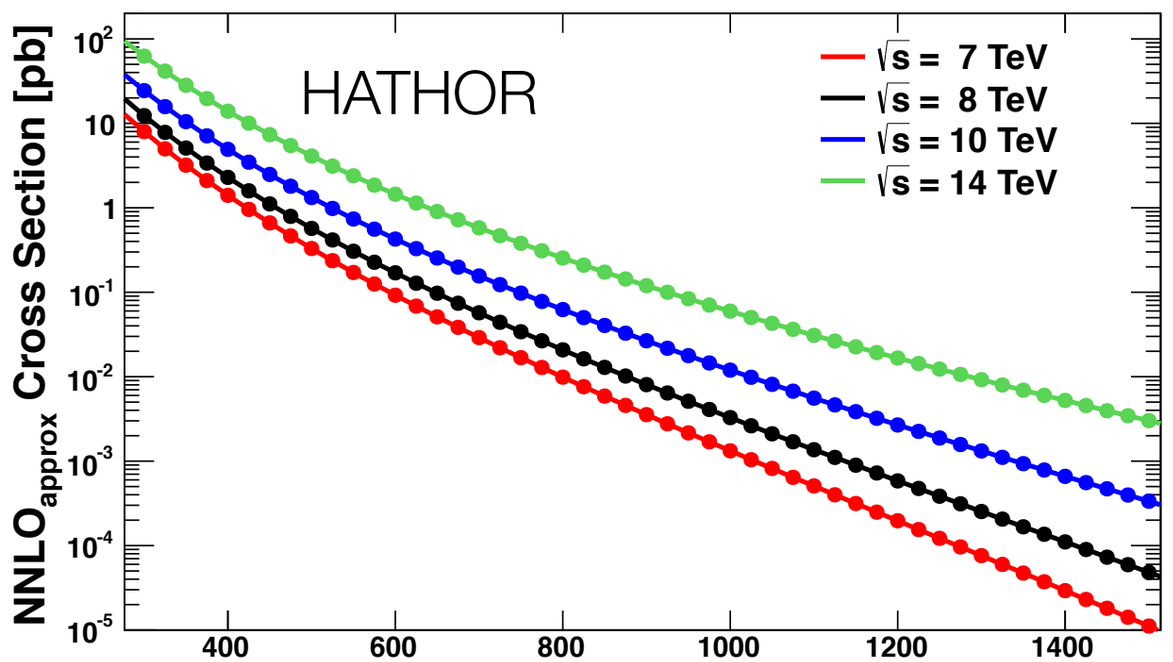


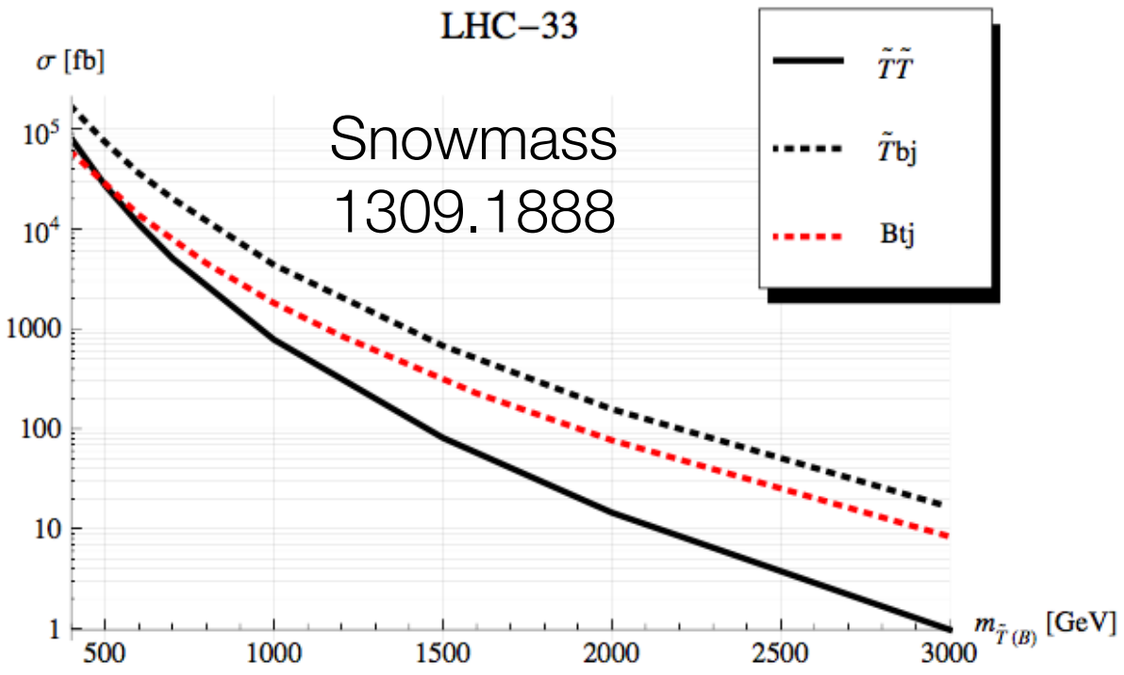
Observed limits on T mass 720-920 GeV

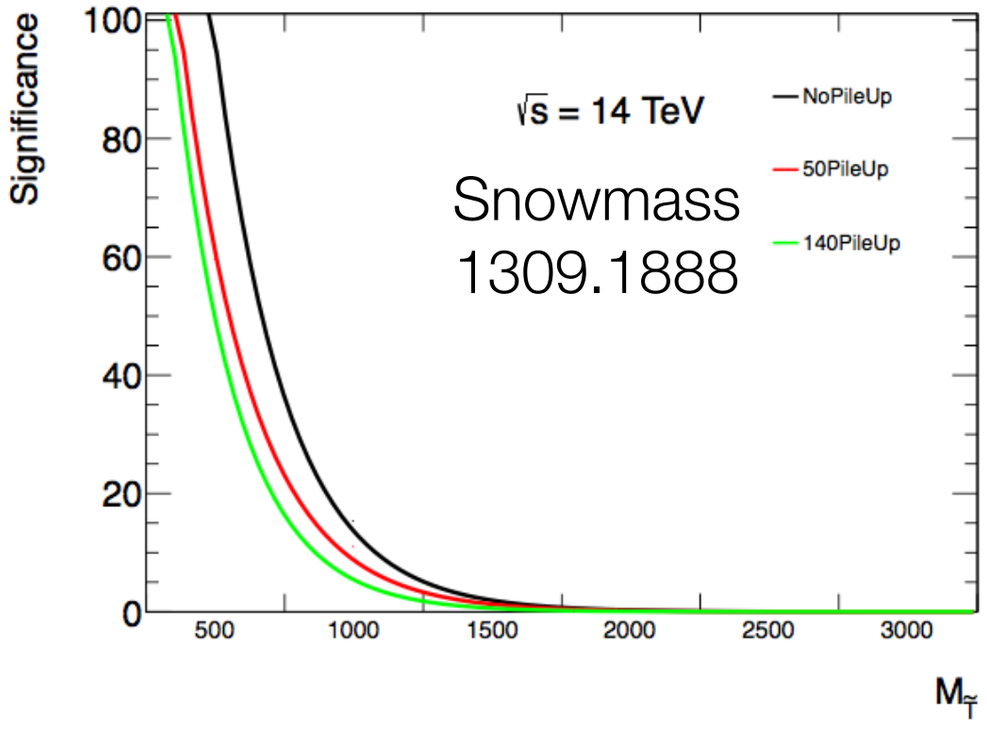
Run 2 prospects

- Large increase in cross section
- Run 2 analyses
  - Expand the number of considered channels (single production etc.)
  - Tools to reduce pileup and tag boosted objects become necessary

CMS FTR-13-026







Conclusions

- VLQs provide an exciting array of final states
- Impressive search program at CMS
- Legacy combinations of run 1 analyses provide strong limits for all possible branching fraction of VLQs
- Boosted tools increasingly necessary

Backup

Vector like quark production

VLQs can have CC and NC decays: the branching ratios are constrained by the relation:

BR(Wb)+BR(tZ)+BR(tH)=1