



# Search for Vector-like quarks at CMS

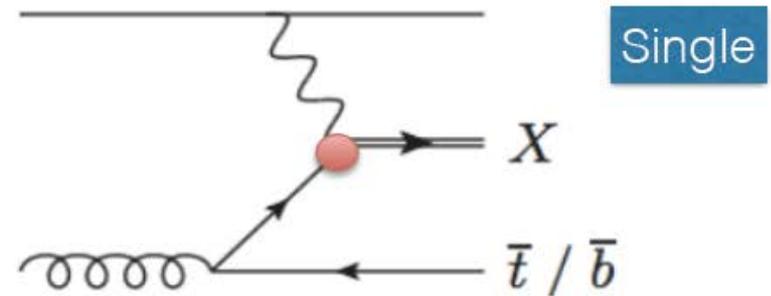
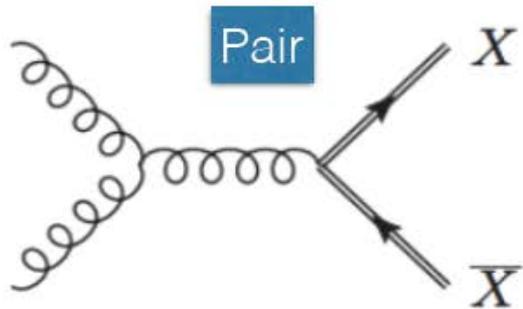
Alice Bean – University of Kansas  
For the CMS Collaboration



# Vector Like Quarks

Have non-chiral couplings (left handed or right handed)  
 Found in Models for Little Higgs, extra-dimensions,  
 Composite Higgs, etc.

- Production:



## Decays and allowed combinations

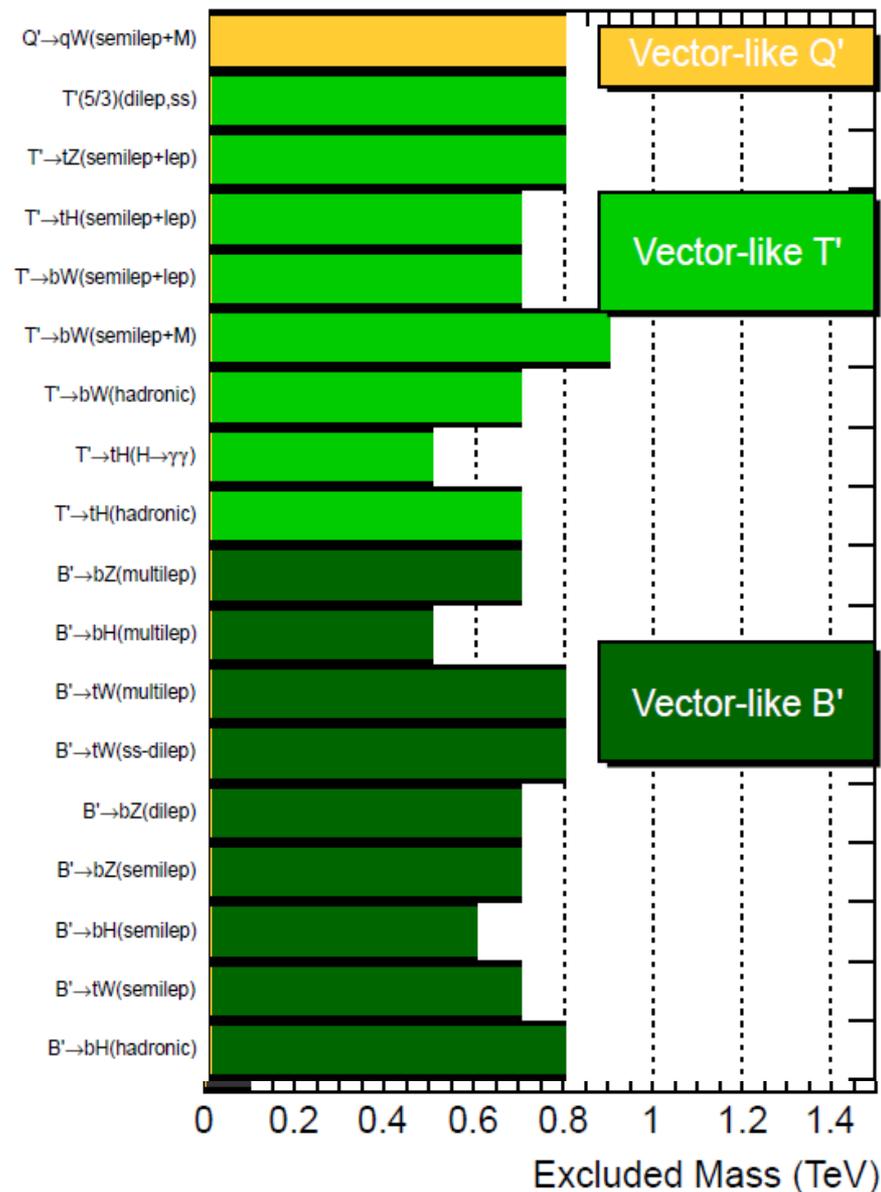
	Q <sub>Ele.Charge</sub>	Decays
<b>T</b>	$\frac{2}{3}$	$bW^+, tH, tZ$
<b>B</b>	$-\frac{1}{3}$	$tW^-, bH, bZ$
<b>X</b>	$\frac{5}{3}$	$tW^+$
<b>Y</b>	$-\frac{4}{3}$	$bW^-$



# CMS analyses



- Results from running at 8 TeV
  - 19.7 fb<sup>-1</sup>
  - Mainly from pair production
  - 95% C.L. limits excluding masses
    - B < 800 GeV
    - T < 900 GeV
    - Q < 800 GeV
  - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
  - Won't talk about these today





# 13 TeV newer Results

## Coupling to 3<sup>rd</sup> generation quarks



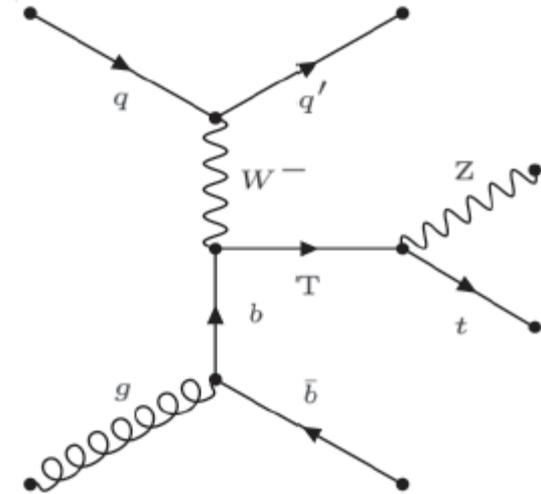
• Singly produced	lum. used (fb <sup>-1</sup> )	CMS-PAS-B2G-
– $T \rightarrow t Z, t \rightarrow \text{had}, Z \rightarrow ee/\mu\mu$	35.9	17-007
– $T \rightarrow t H, H \rightarrow bb$	2.3	15-008
• $t \rightarrow \ell + \text{jets}, t \rightarrow \text{had}$		16-005
– $T/Y \rightarrow W b, W \rightarrow e/\mu + \text{MET}$	2.3	16-006
• Pair produced		
– $X \rightarrow t W, \text{ same sign di-leptons}$	35.9	16-019
– $T \rightarrow bW/tZ/tH \ell + \text{jets}$	2.3	16-024



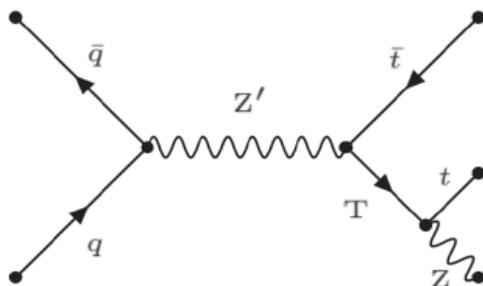
# $T \rightarrow tZ$



- Search for singly produced charged  $2e/3$   $T$  as a singlet or doublet
- 13 TeV analysis ( $35.9\text{fb}^{-1}$ ) follow on from arXiv:1701.07409
- Associated quark in the production tends to be forward
- Search for narrow widths, as well as 10%, 20%, 30% width/mass
- Search also for  $Z' \rightarrow Tt$ ,  $T \rightarrow tZ$



Mass [TeV]	$\sigma(pp \rightarrow Tbq)$ [pb]	$\sigma(pp \rightarrow Ttq)$ [pb]
0.7	1.455	0.125
0.8	0.965	0.091
0.9	0.680	0.068
1.0	0.488	0.051
1.1	0.338	0.038
1.2	0.246	0.029
1.3	0.179	0.022
1.4	0.135	0.017
1.5	0.102	0.014
1.6	0.076	0.011
1.7	0.058	0.008



Theoretical cross sections with couplings set to 0.5 in narrow width approximation



# Single $T \rightarrow tZ$

$t \rightarrow$  hadrons,  $Z \rightarrow \mu\mu$  or  $ee$

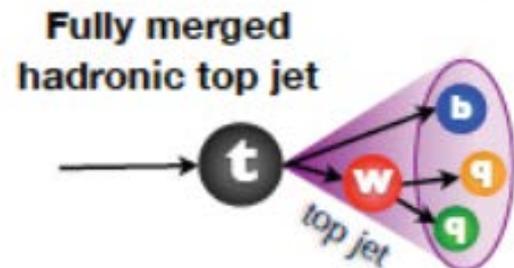
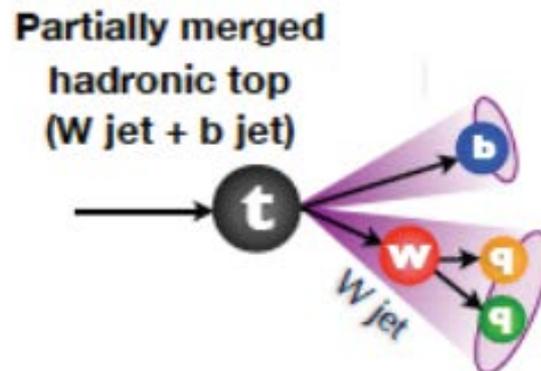
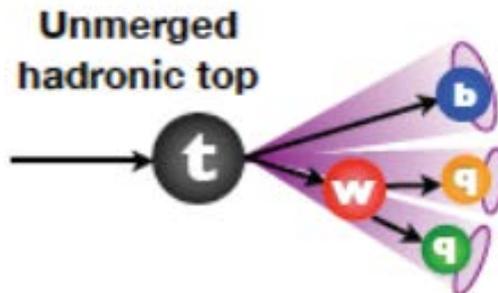


Use  $e$  or  $\mu$  trigger

Many (10) different categories explored

With heavy resonance **BOOSTED JETS**

- $t$  resolved topology,  $Z \rightarrow \mu\mu/ee$ 
  - No forward jets/  $\geq 1$  forward jet
- $t$  partially merged,  $Z \rightarrow \mu\mu/ee$ 
  - No forward jets/  $\geq 1$  forward jet
- $t$  fully merged,  $Z \rightarrow \mu\mu/ee$





# T → tZ Analysis

- Cuts

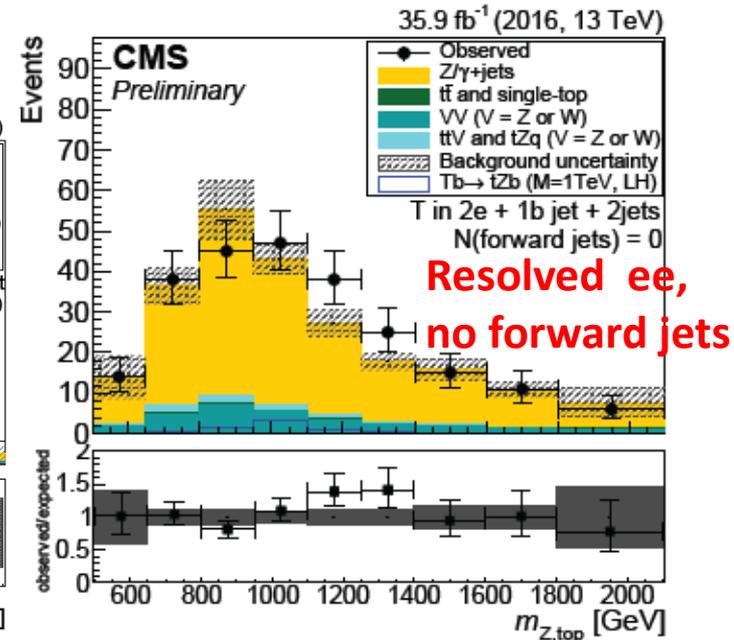
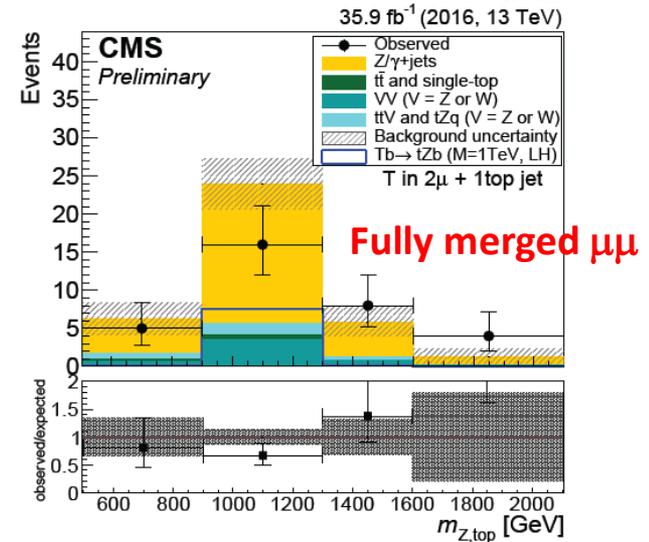
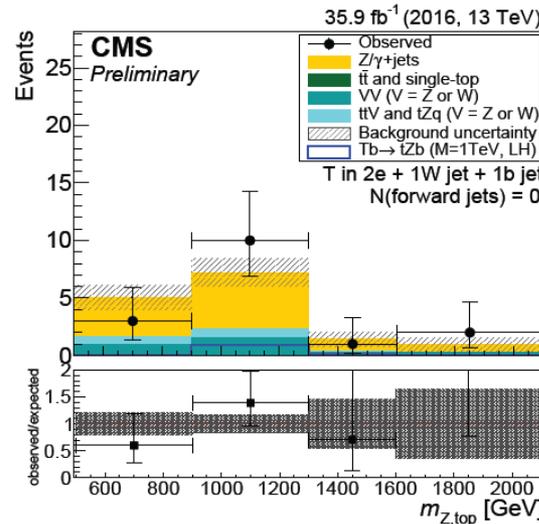
- Jet cuts, Number of b tagged jets
- 2 well IDed leptons with leading lepton  $p_T$
- $\Delta R$  between leptons and between Z and top
- Mass cuts on top and Z and  $p_T$  of top and Z

- Data control region to estimate background

$$N_{bkg}(M_{top,Z}) = N_{cr}(M_{top,Z}) \cdot \frac{N_{sr}^{mc}(M_{top,Z})}{N_{cr}^{mc}(M_{top,Z})}$$

- Examine  $M_{top,Z}$  for limits

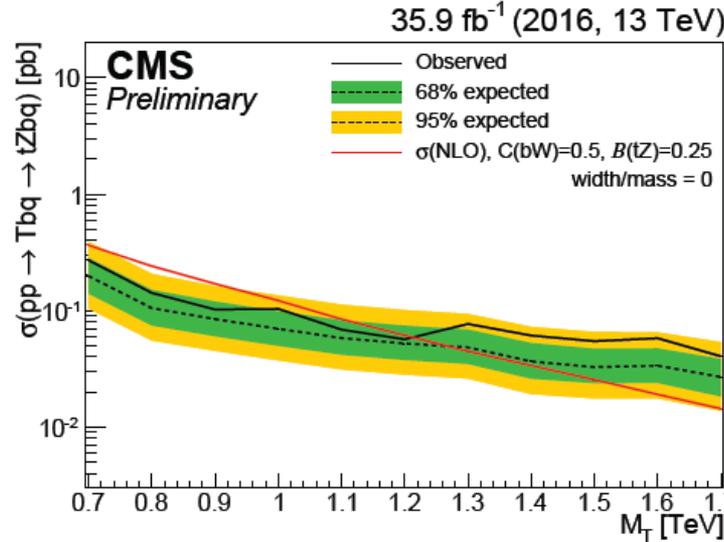
Partially merged ee



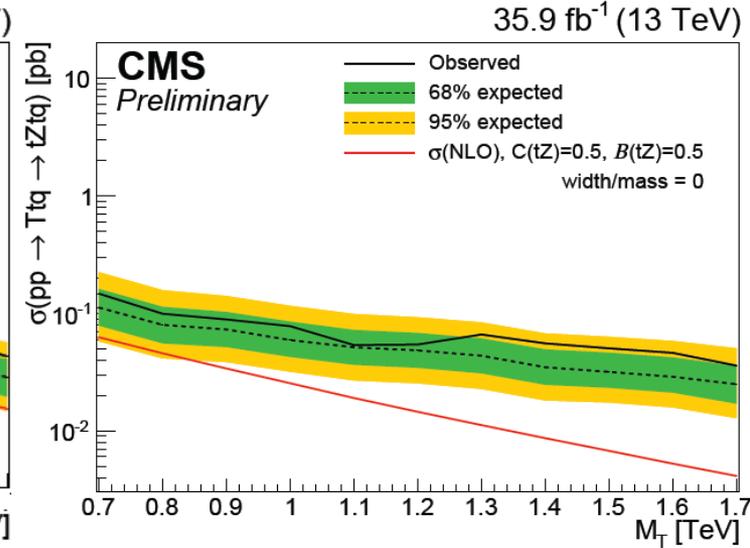


# T $\rightarrow$ tZ Cross Section Limits

Narrow width

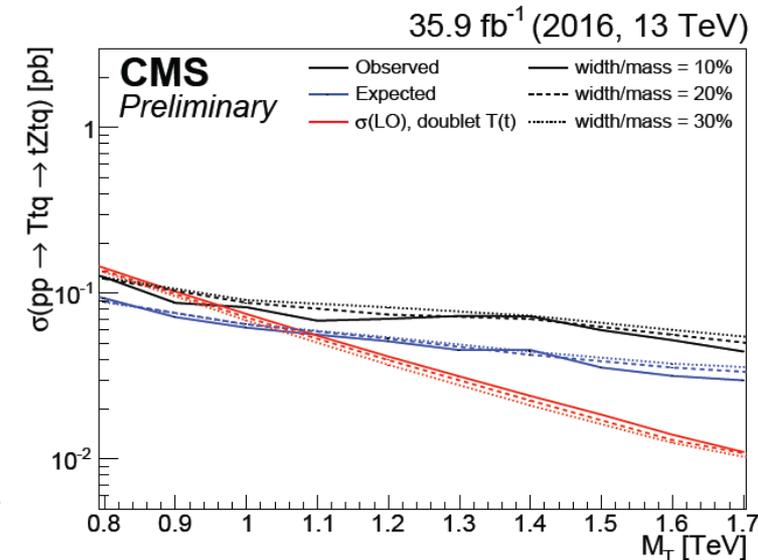
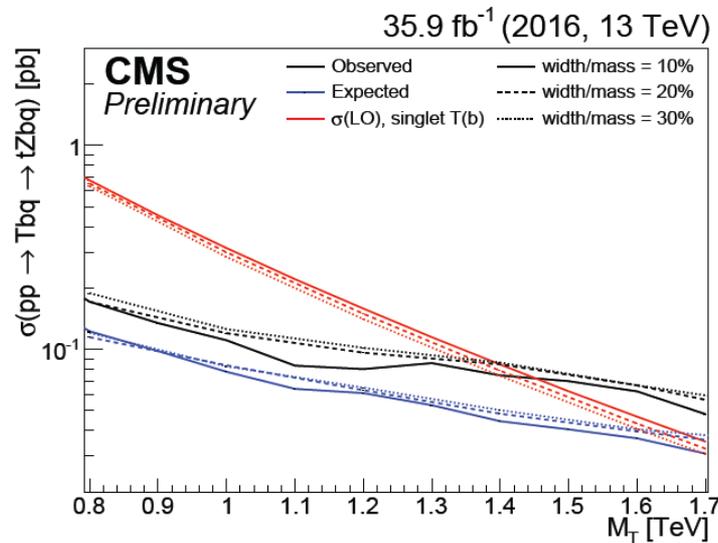


Tb signal

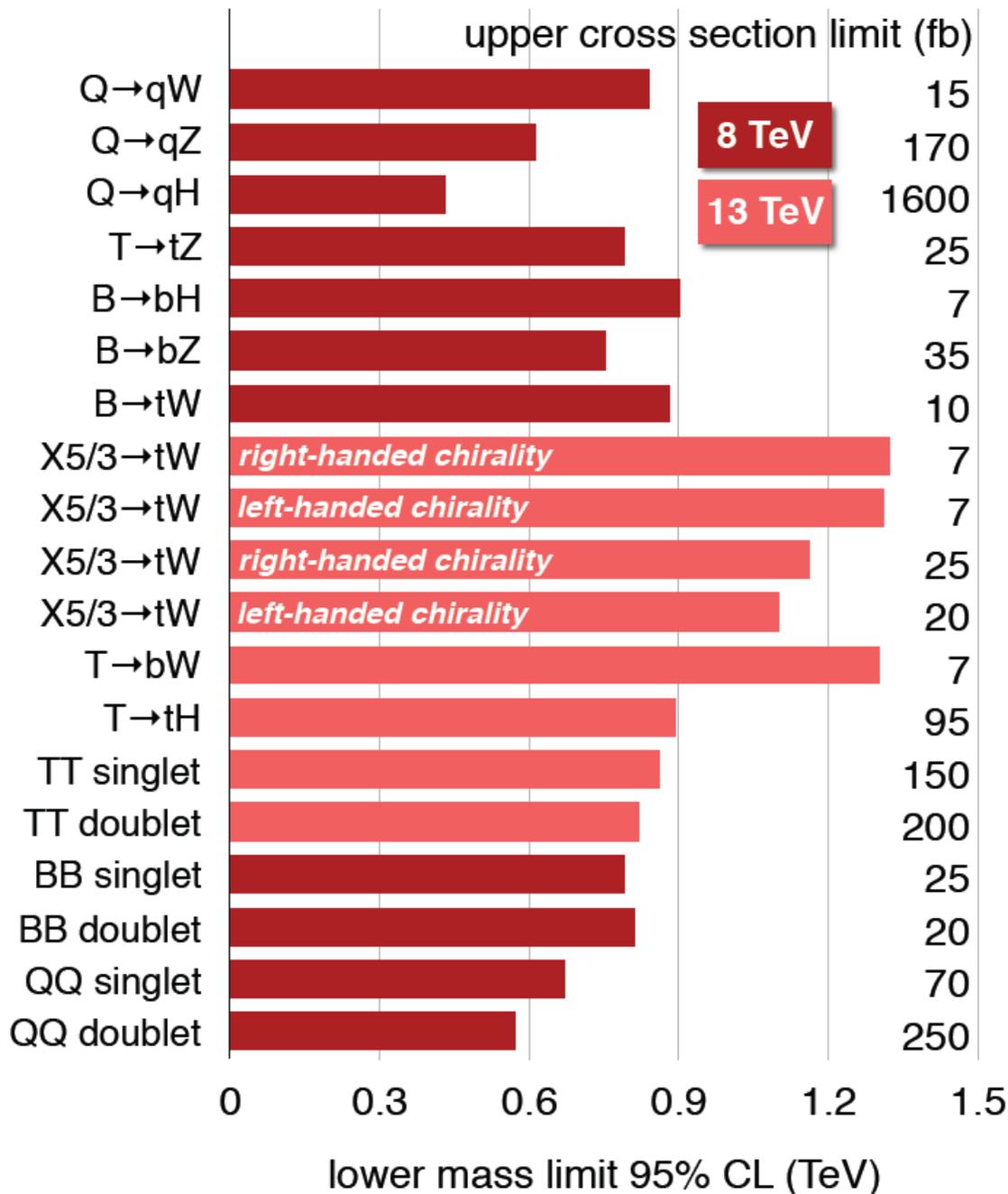


Tt signal

10%, 20%, 30%  
width/mass



# Vector-like quark pair production



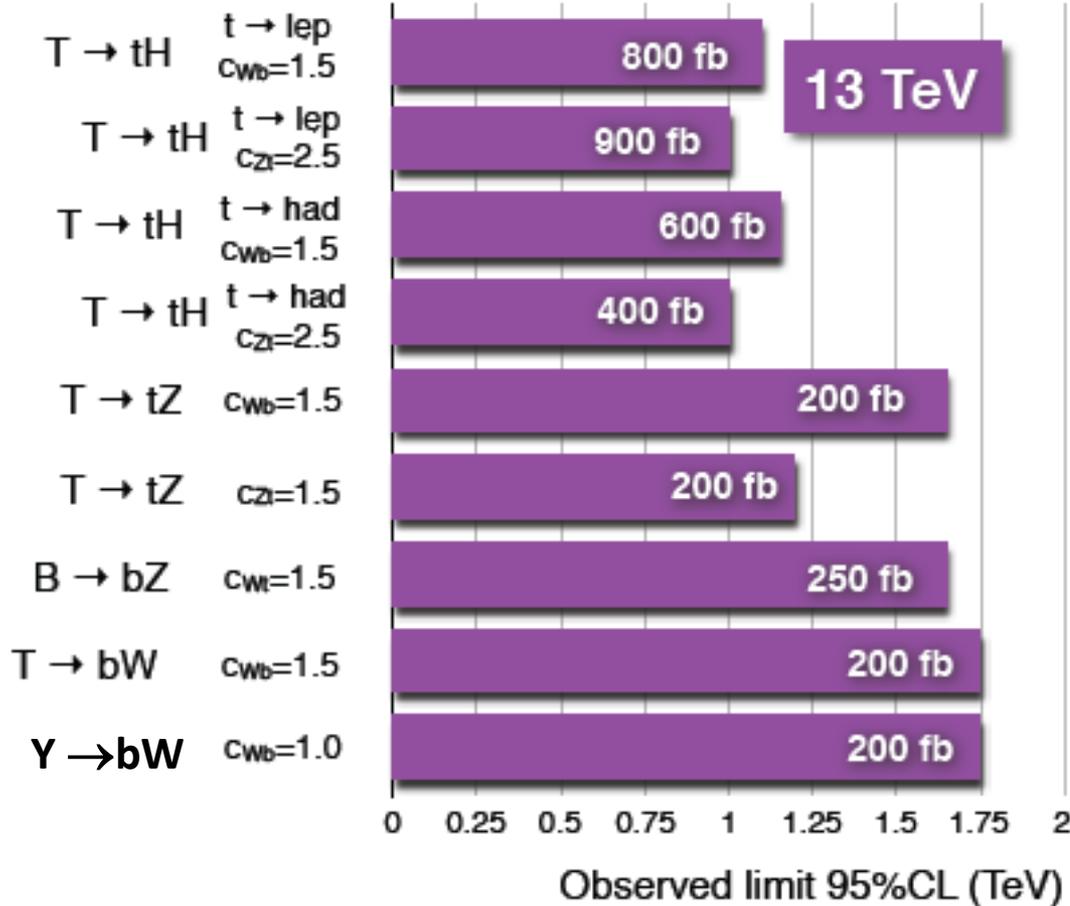
Limits on expected particles and decay modes

- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>



# VLQ single production summary

## Vector-like quark single production



Limits as function of VLQ mass rule out various cross sections/couplings

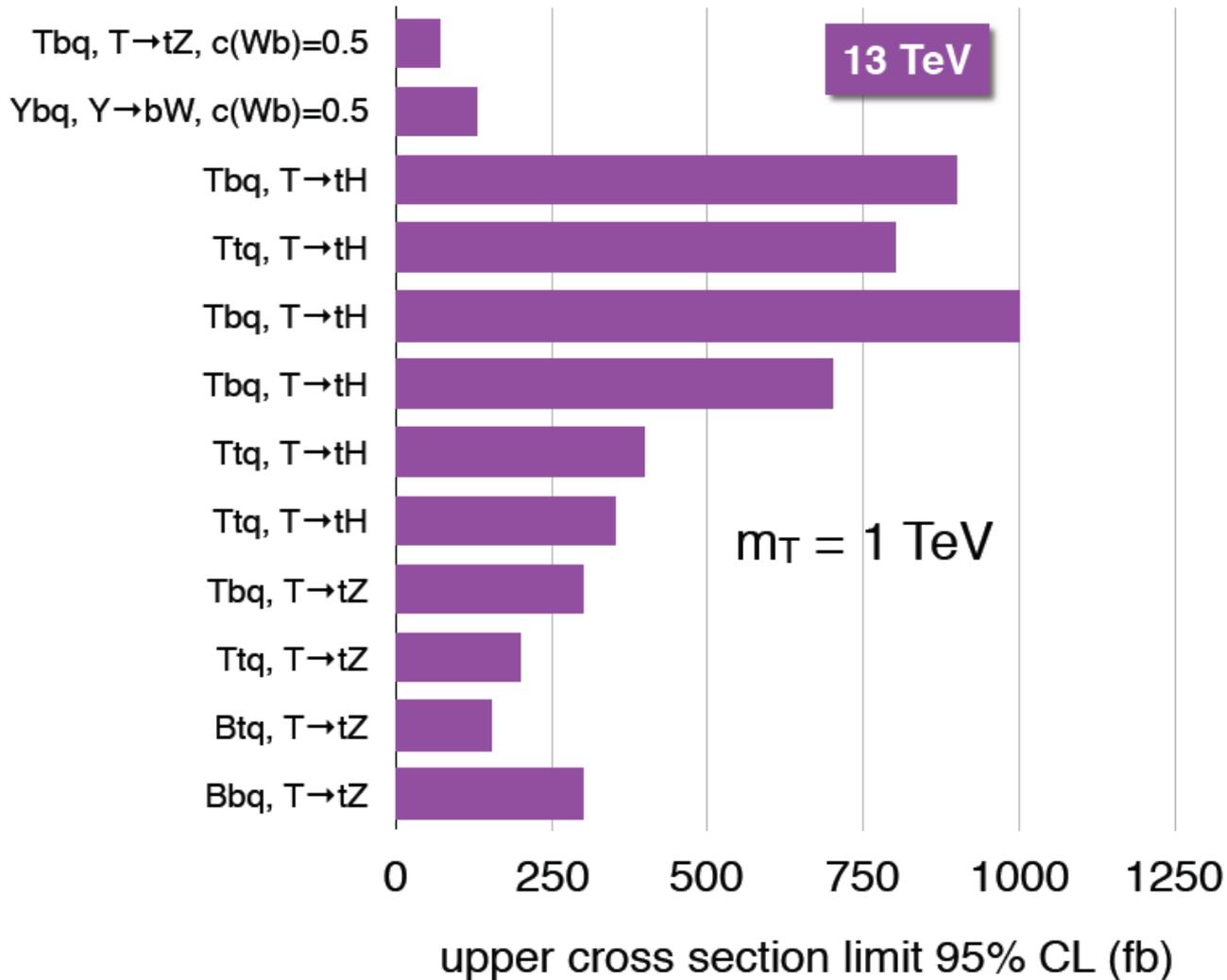
Single production becomes more important with higher mass VLQs

- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>



# VLQ single production summary

## Vector-like quark single production



- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>



# Extra slides

# Vector-like quarks

- Pair production is insensitive to couplings
- Single production is important at high energies
- Limits depend on the branching ratios — a function of mass and multiplet

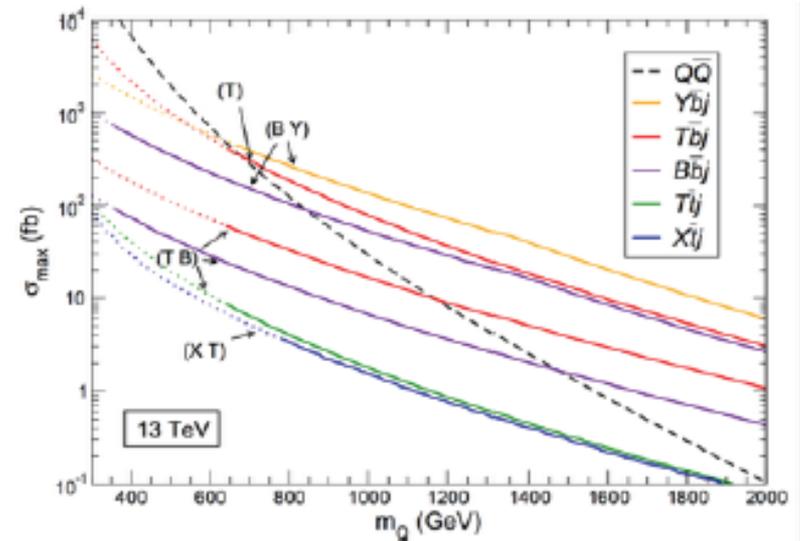
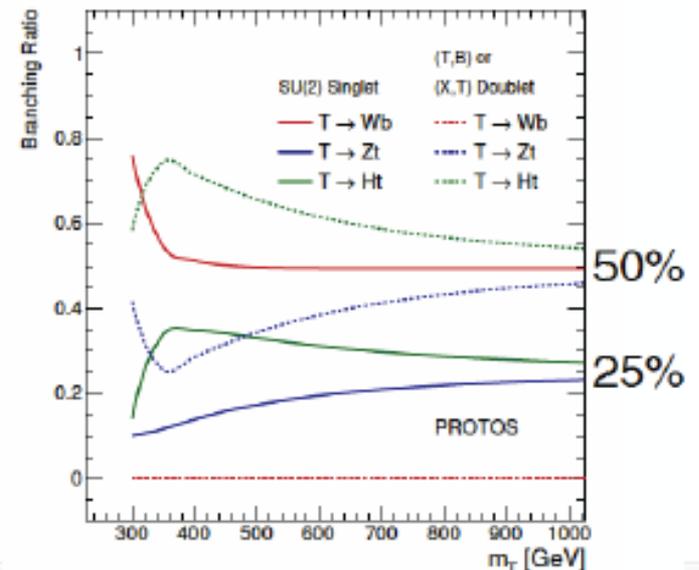


Table 1: Branching ratios, following the equivalence theorem

BR	Wt	Wb	Zt	Zb	ht	hb	Chirality
T23 singlet	0	1/2	1/4	0	1/4	0	L
T23 doublet	0	0	1/2	0	1/2	0	R
X53 doublet	1	0	0	0	0	0	L/R
B13 singlet	1/2	0	0	1/4	0	1/4	L
B13 doublet	1	0	0	0	0	0	R
Y43 triplet	0	1	0	0	0	0	L/R





# Exotic light-flavor quark partner Q

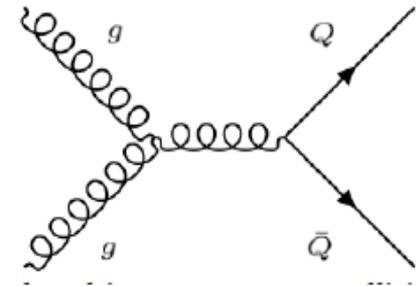
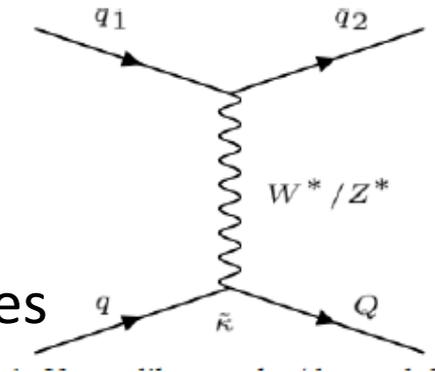
## 8 TeV analysis (CMS-PAS-B2G-12-016)



$$\mathcal{L}_{\text{interaction},D} = \frac{g}{\sqrt{2}} W_{\mu}^{+} \kappa_W \bar{u}_R \gamma^{\mu} D_R + \frac{g}{2\cos\theta_W} Z_{\mu} \kappa_Z \bar{d}_R \gamma^{\mu} D_R - \frac{m_Q}{v} H \kappa_H \bar{d}_R D_L + \text{h.c.}$$

$$D \rightarrow uW^{-} / dZ / dH$$

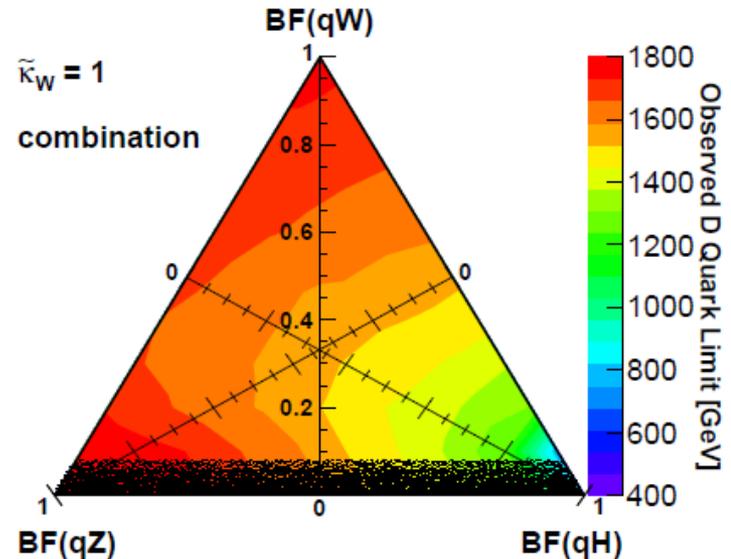
- Produced singly or in pairs
- Look for 1-4 leptons +jets
- Inclusive and Exclusive searches



CMS Preliminary

19.7 fb<sup>-1</sup> (8 TeV)

Production	Channel
Single (electroweak)	Qq → Wqq
	Qq → Zqq
Pair (strong)	QQ → WqWq
	QQ → WqZq
	QQ → WqHq
	QQ → ZqZq
	QQ → ZqHq
	QQ → HqHq





# Coupling to light quarks



B2G-12-016

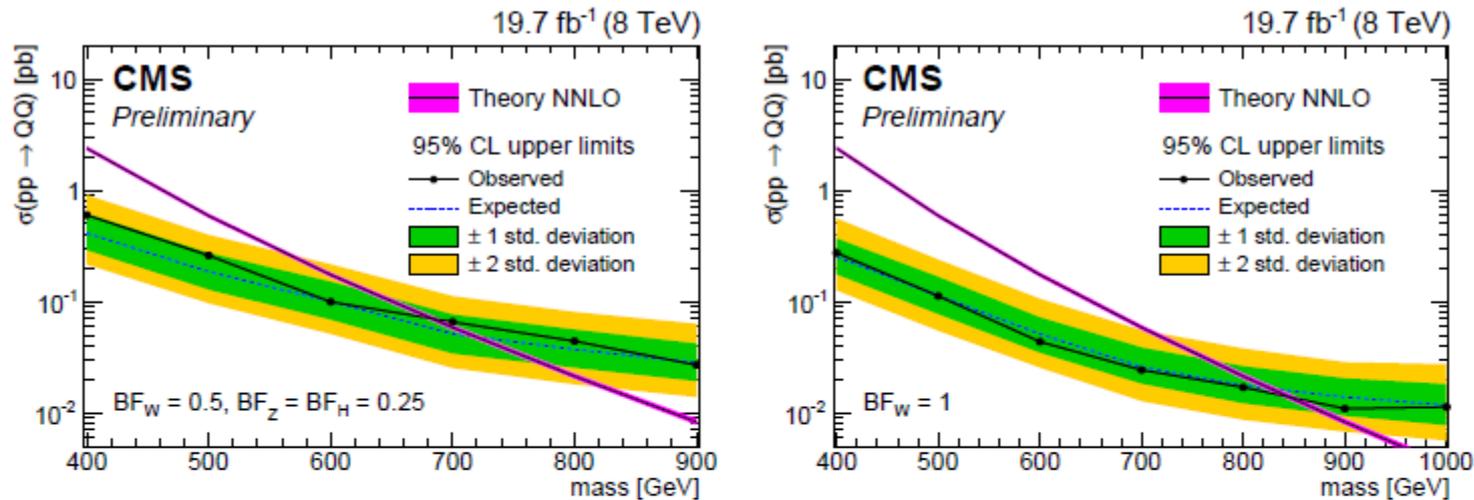


Figure 16: The 95% CL exclusion limits on the production cross section determined assuming different sets of model parameters ( $BF_W = 0.5, BF_Z = 0.25$  on the left, and  $BF_W = 1.0$  on the right) as a function of the hypothetical heavy quark mass, and for the scenario where only strong pair production of the heavy vector-like quark is considered. The median expected and observed exclusion limits are indicated with a dashed and a solid line, respectively. The  $\pm 1\sigma$  and  $\pm 2\sigma$  expected exclusion limits are represented by the inner (green) and outer (yellow) bands around the median. The cross section from a full NNLO calculation [47], including uncertainties on the PDF and the renormalization and factorization scales, is shown by the magenta band.

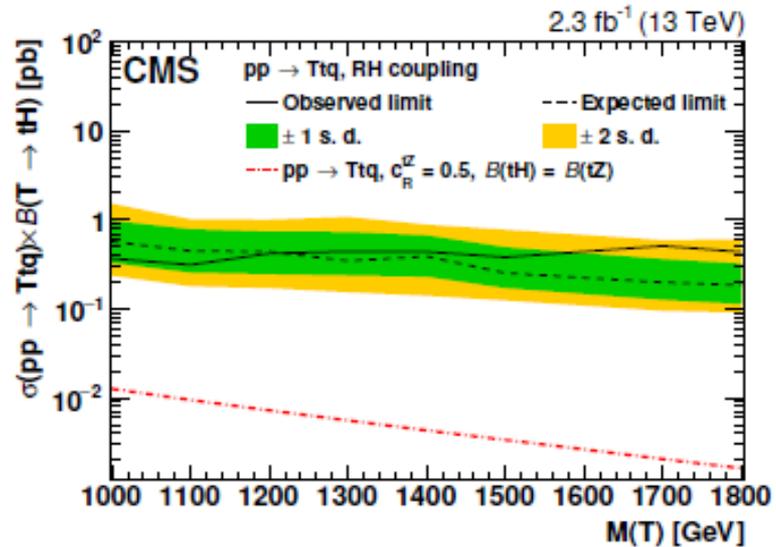
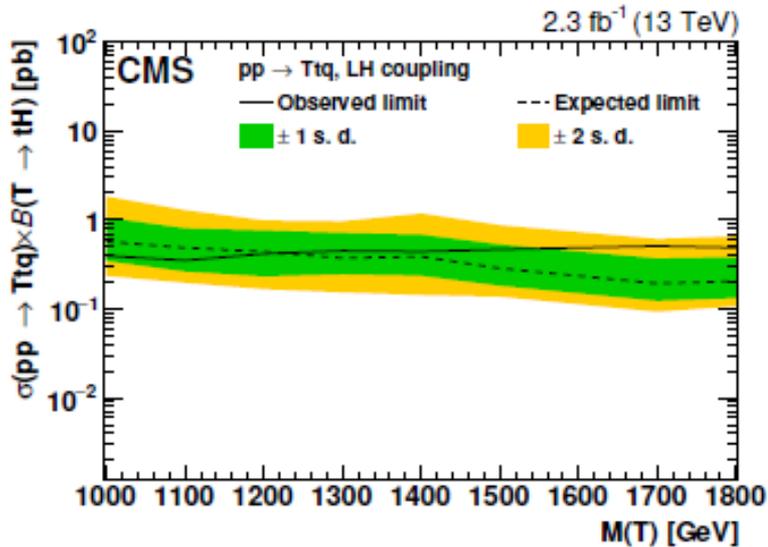
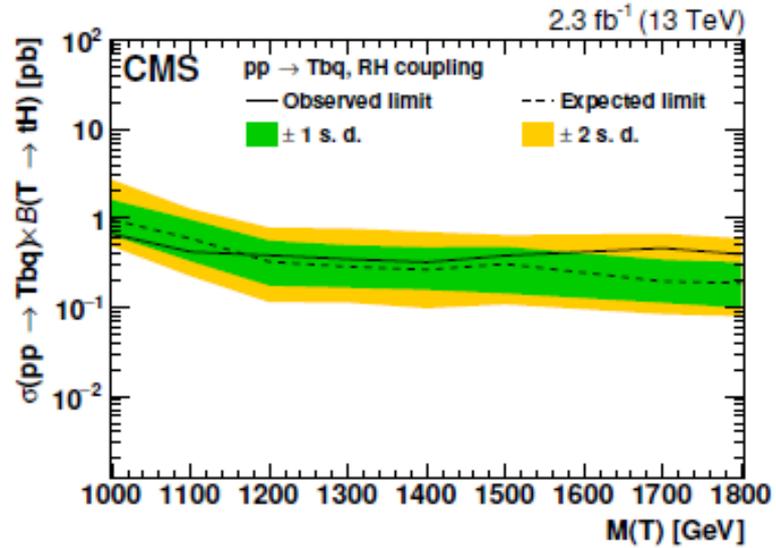
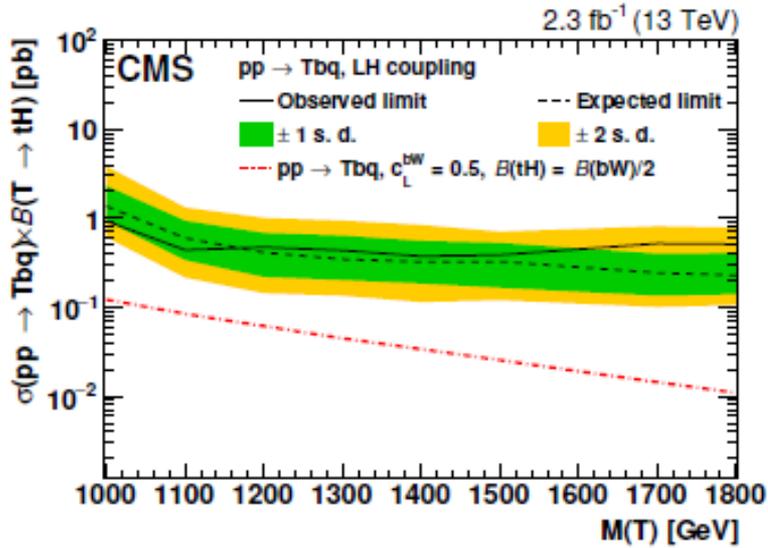
Left handed coupling

Right handed coupling



# Single $T \rightarrow tH$ , all hadronic

B2G-16-005 to be published in JHEP





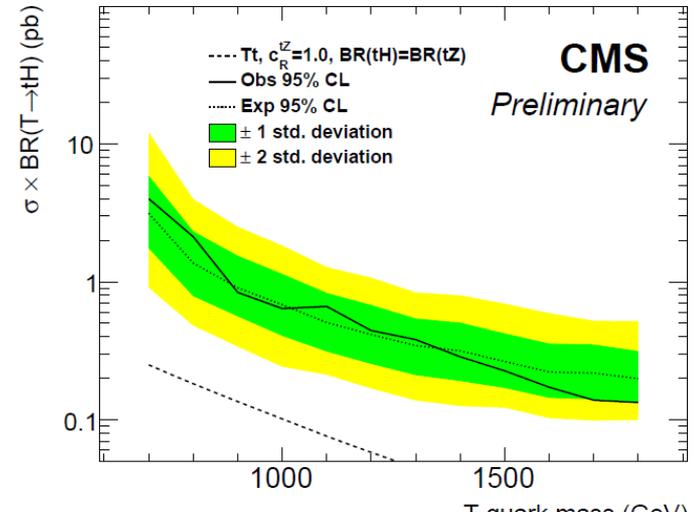
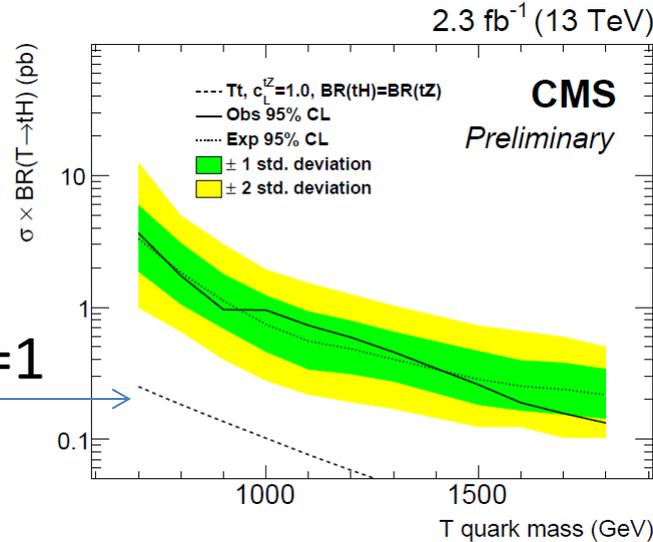
# Single $T \rightarrow tH$ , $t \rightarrow \ell + \text{jets}$



2.3 fb<sup>-1</sup> (13 TeV)

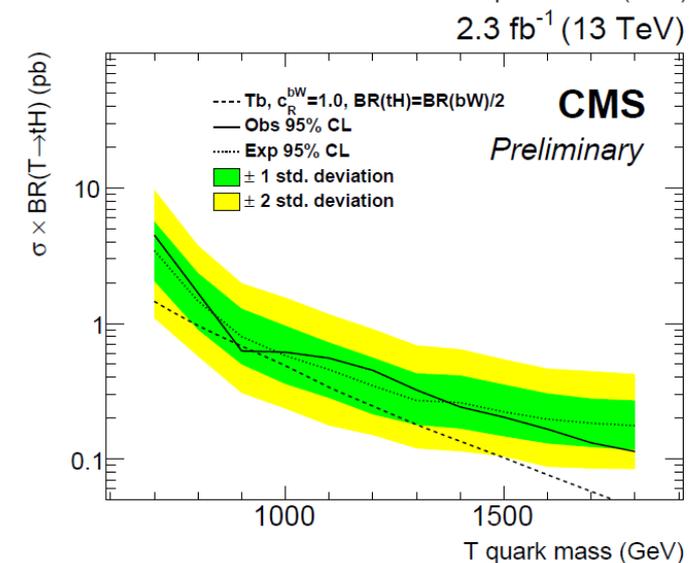
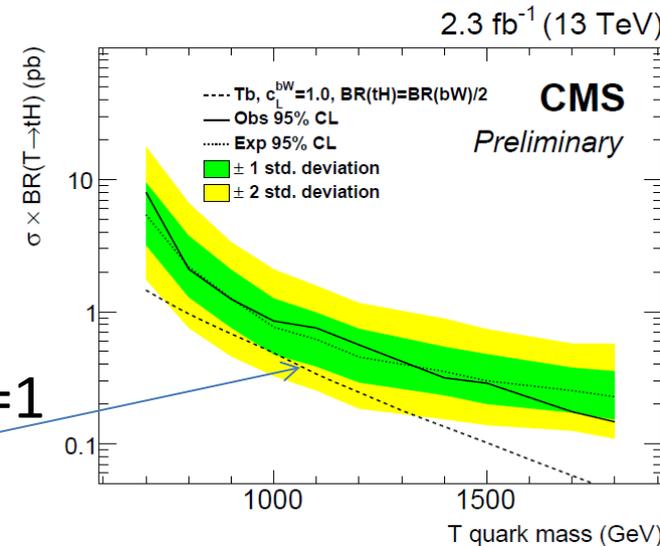
Associated T production with a t-quark

NLO Model with  $c_L=1$   
BR(tH)=BR(tZ)



Associated T production with a b-quark

NLO Model with  $c_L=1$   
BR(tH)=BR(bW)/2



Left handed coupling

Right handed coupling



# Pair produced $X^{5/3}$ same sign dileptons



13 TeV data ( $35.9 \text{ fb}^{-1}$ )

$X^{5/3} \rightarrow W^+ t$ ,  $W^+ \rightarrow \ell^+ \nu$ ,  $t \rightarrow \ell^+ + \text{jet}$ ,

Require 2 leptons, stringent e charges

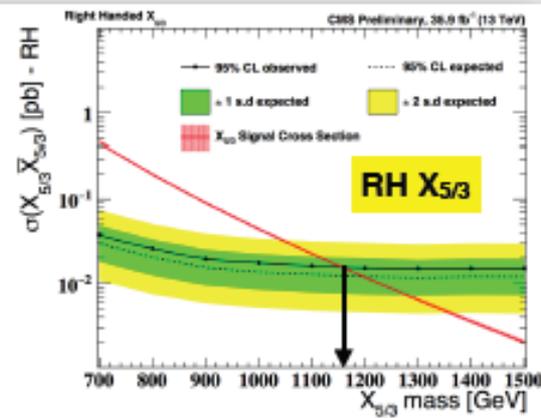
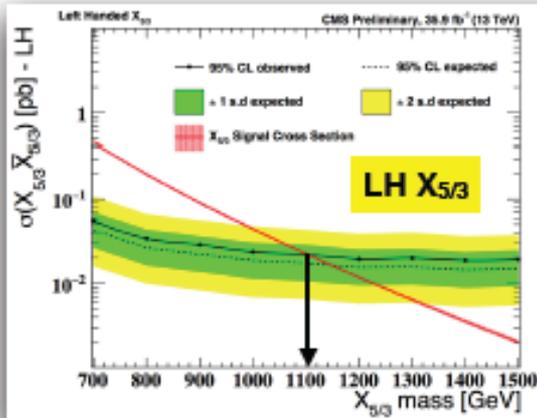
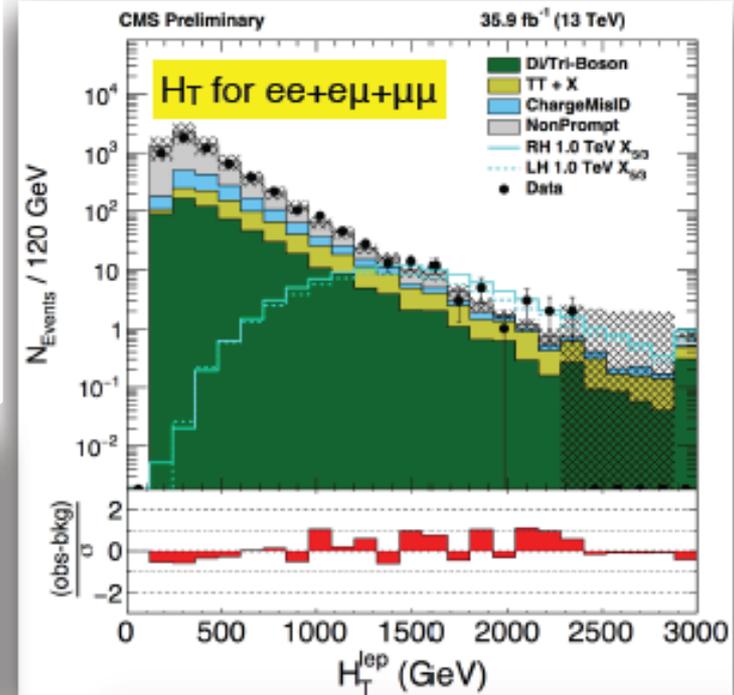
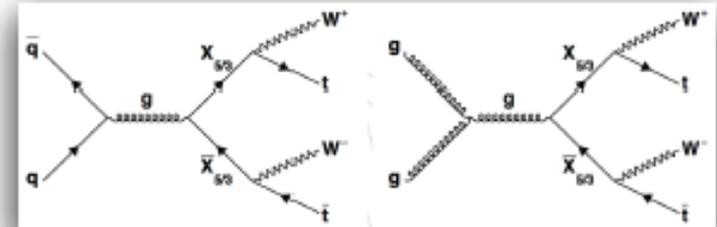
$H_T$  – scalar sum of all  $p_T$  from jets and  $\ell$ 's

Background estimation

prompt same sign from simulation

prompt opp. sign – data driven

non-prompt same sign – data driven



# Pair production TT, BB

## CMS-PAS-B2G-16-024

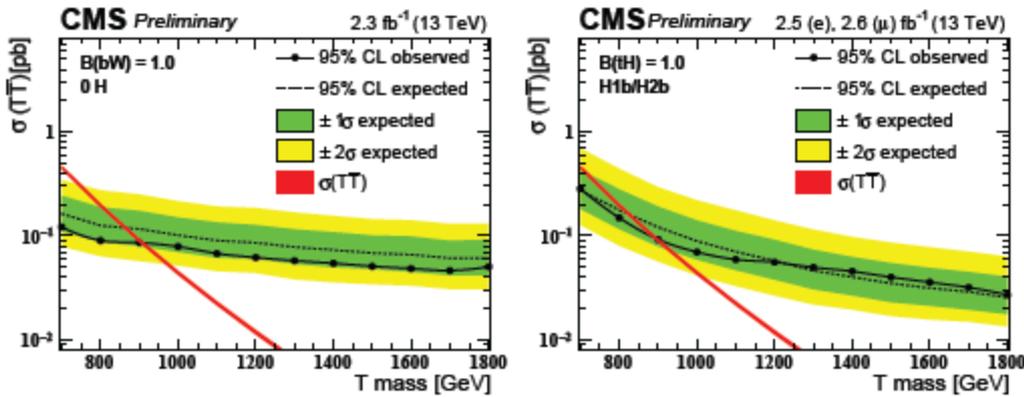


Figure 11: 95% CL expected and observed upper limits (Bayesian) on the cross section of TT production for 100%  $T \rightarrow bW$  in the boosted W channel (left), and 100%  $T \rightarrow tH$  in the boosted Higgs channel (right).

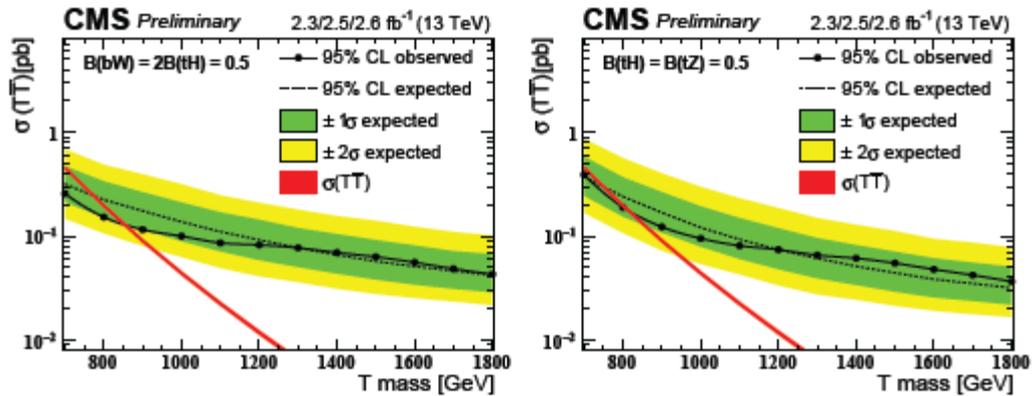
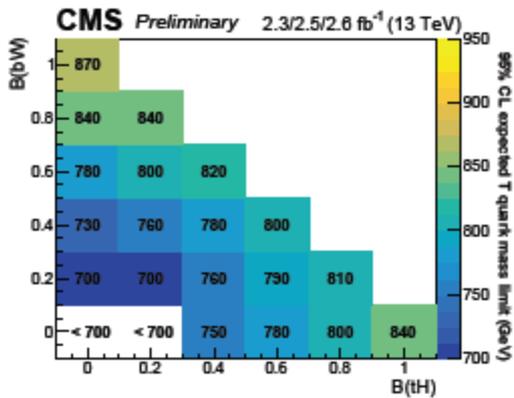


Figure 12: 95% CL expected and observed upper limits (Bayesian) on the cross section of TT production for the singlet benchmark (left) and the doublet benchmark (right).

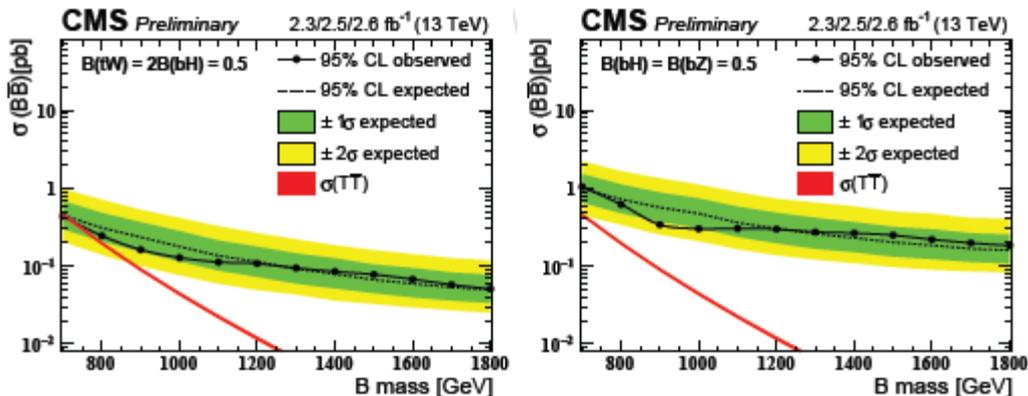


Figure 13: 95% CL expected and observed upper limits (Bayesian) on the cross section of BB production for the singlet benchmark (left) and the doublet benchmark (right).

