Searches for vector-like quarks at CMS

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On behalf of the CMS Collaboration
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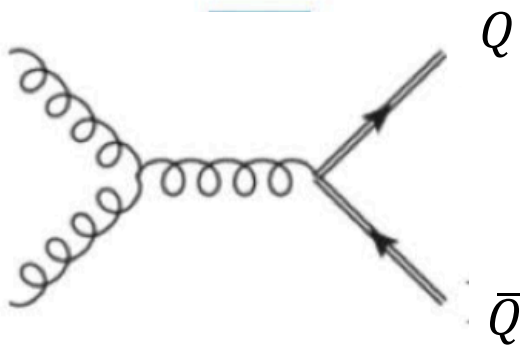
Introduction : Vector-Like Quarks

- Candidates that could solve the hierarchy problem by stabilizing quantum corrections to the Higgs mass
- $$m_h^2 = m_{bare}^2 + \delta m_h^2$$
- Appear in Many beyond the SM theories:
  - Little Higgs model, Composite Higgs models, Extra dimensions
- Properties
  - Spin ½, non chiral, colored charged particles
- Can appear as SU(2) singlets, doublets, or triplets
- Natural models tend to favor coupling to 3rd-gen SM quarks

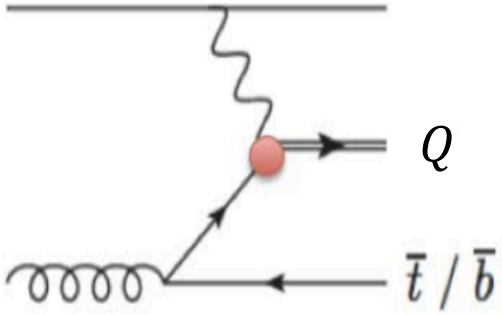
Q Ele.Charge	Decays
T $^{2/3}$	**bW^+ , tH , tZ**
B $^{-1/3}$	**tW^- , bH, bZ**
X $^{5/3}$	**tW^+**
Y $^{-4/3}$	**bW^-**

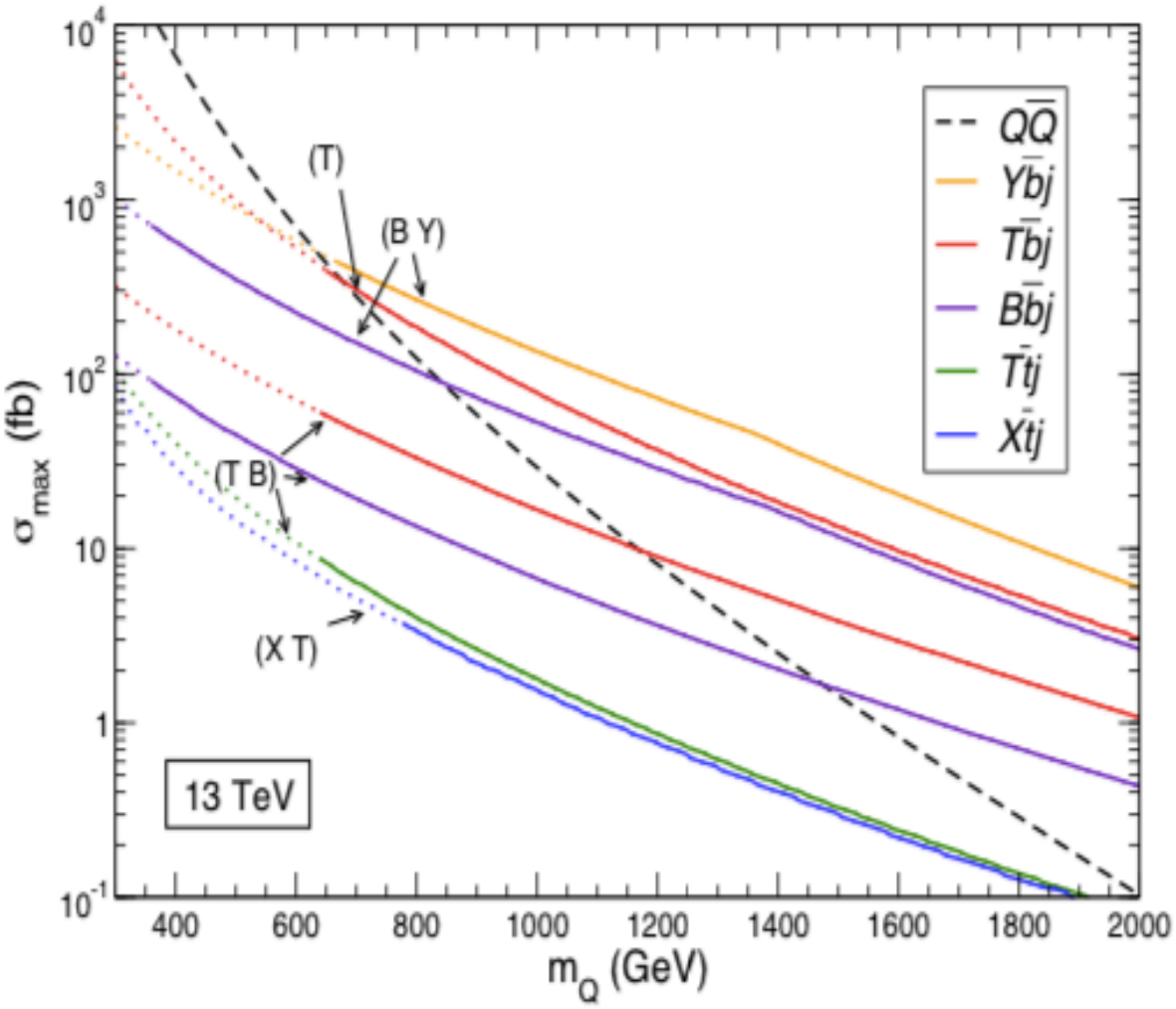
Production : Vector-Like Quarks

Pair Production:
- Dominant in lower mass range
- Produced via strong interaction
- Cross section depends only on mass



Single Production:
- Produced via electro-weak interaction
- Cross section depends on mass and EW coupling





arXiv:1306.0572

J.A. Aguilar-Saavedra, R. Benbrik, S.Heinemeyer, M. Perez-Victoria

VLQ Searches at CMS

- Searches using full 2016 data in pp collisions at center-of-mass energy of 13 TeV with the CMS detector
- In this talk,

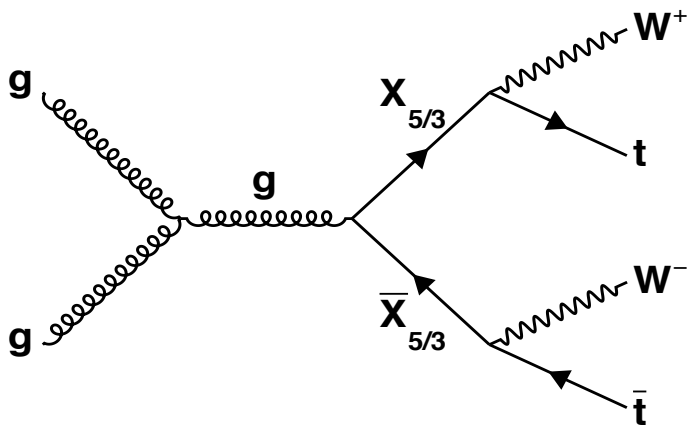
Pair Production		Paper	Int. Lumi
$X\bar{X}$ in di-lepton final state	**B2G-16-019**		**35.9**
$X\bar{X}$ in single lepton final state	**B2G-17-008**		**35.9**
$T\bar{T}$ / $Y\bar{Y}$ in single lepton final state	**B2G-17-003** arXiv:1710.01539	**Phys. Lett. B 779 (2018) 82**	**35.6-35.8**
$T\bar{T}$ / $B\bar{B}$ in single lepton, same-sign di-lepton and tri-lepton final states	**B2G-17-011**		**35.9**
Single Production		**Paper**	
$B \rightarrow bH$ in fully hadronic final state	**B2G-17-009** arXiv:1802.01486	**Submitted to JHEP**	**35.9**
$T \rightarrow tZ$ in di-lepton final state	**B2G-17-007** arXiv:1708.01062	**Submitted to PLB**	**35.9**

CMS-PAS-B2G - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html
B2GPublications - http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html

VLQ: Pair Production

Pair: $X_{5/3} \rightarrow tW$, Same Sign di-lepton

CMS-PAS-B2G-16-019

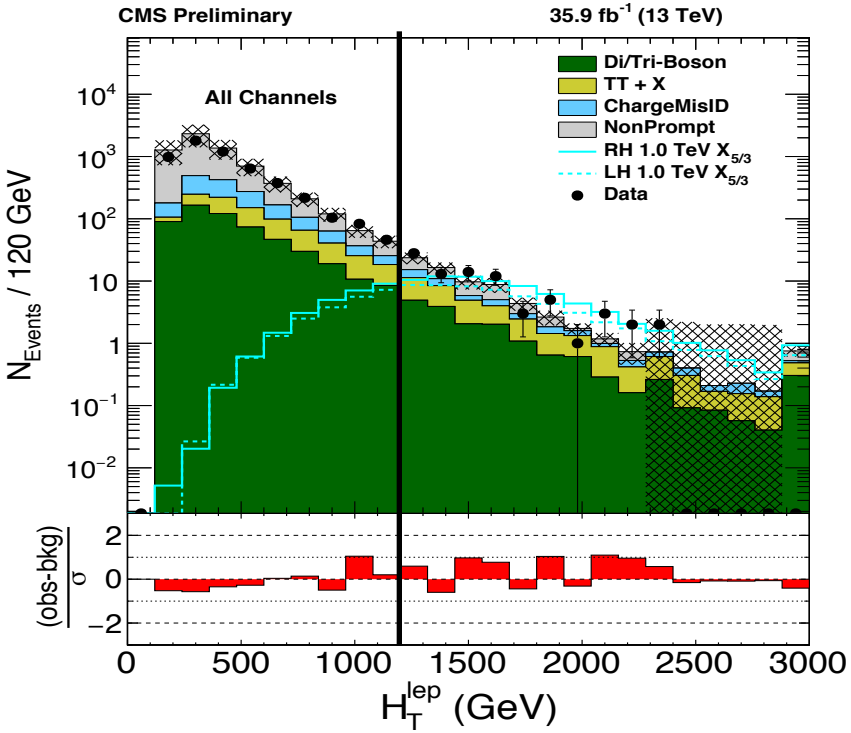


Signal:

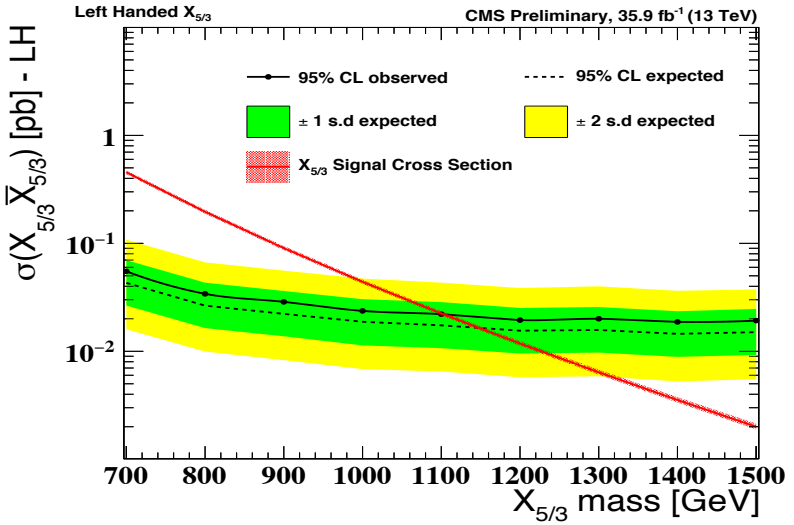
- $2\,W \rightarrow l + \nu$
- $2\,W \rightarrow q\bar{q}$
- *2 b-tagged jets*

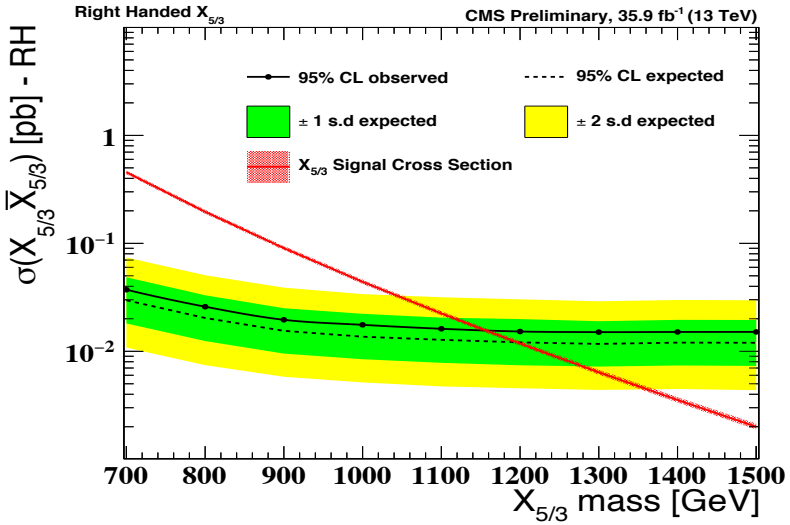
Backgrounds:

1. Same-sign prompt leptons – from simulation
2. Opposite-sign prompt leptons – data driven method
3. Same-sign non- prompt leptons – data driven method



$$H_T^{lep} \equiv \sum_{all\ jets+leptons} P_T$$



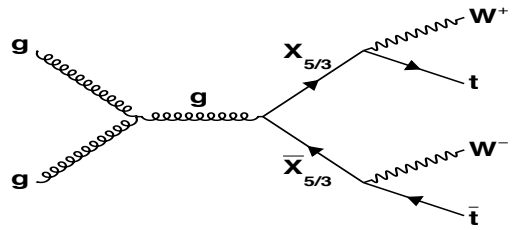


LH M_X >1.15 TeV , RH M_X >1.2 TeV @ 95 % CL

$$\mathcal{B}(X \rightarrow tW) = 100\ \%$$

Pair: $X_{5/3} \rightarrow tW$, Single lepton

CMS-PAS-B2G-17-008



Signal:
- 1 W → $l + \nu$
- 3 W → $q\bar{q}$
- 2 *b-tagged jets*

- Template likelihood fit to data: discriminating variable min**M(l, b)**
- 16 final categories based on ,

lepton flavor (e, μ)	b – tagged jets (=0 , ≥ 2)
W – tagged jets (=0 , ≥ 1)	t – tagged jets (=0 , ≥ 1)

Backgrounds:
All Backgrounds – from simulation

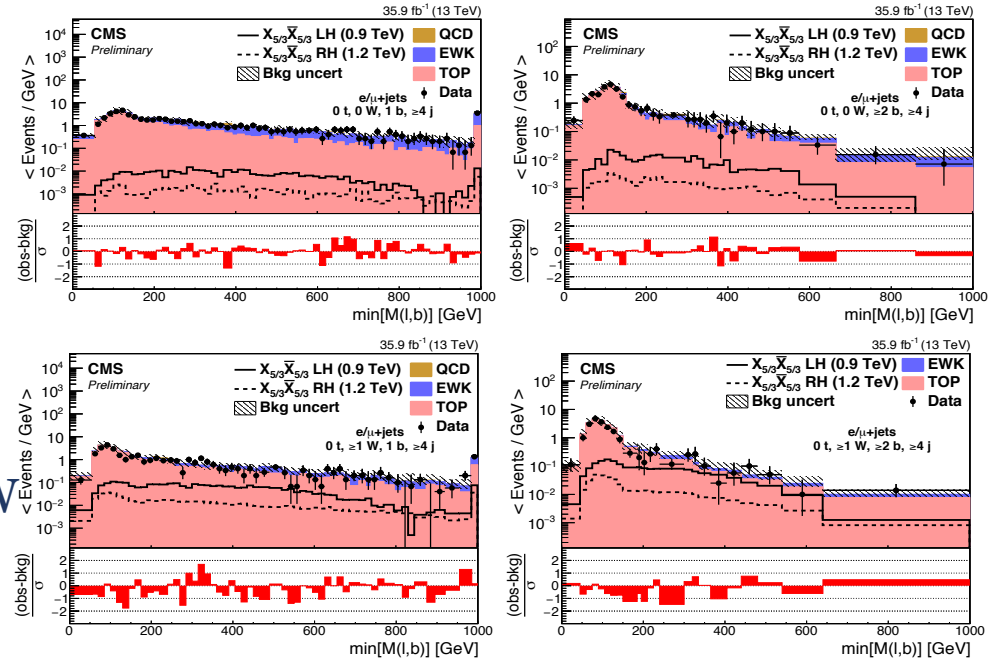
0 t - tagged

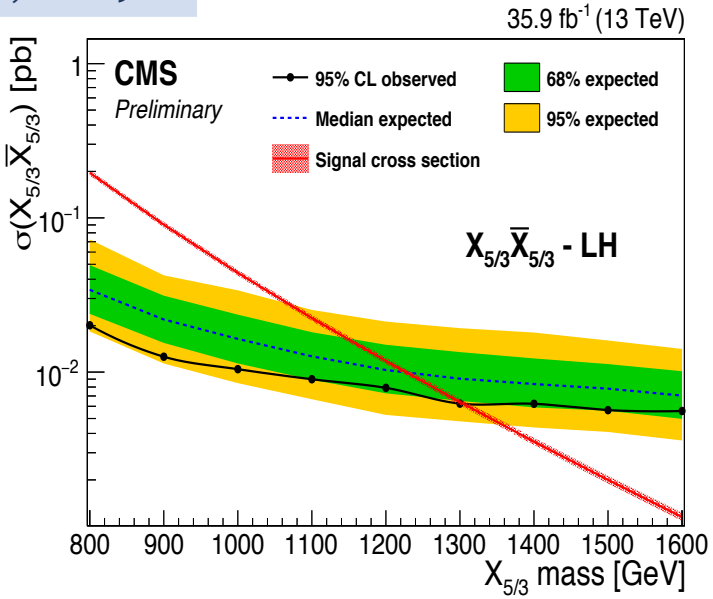
=1 b

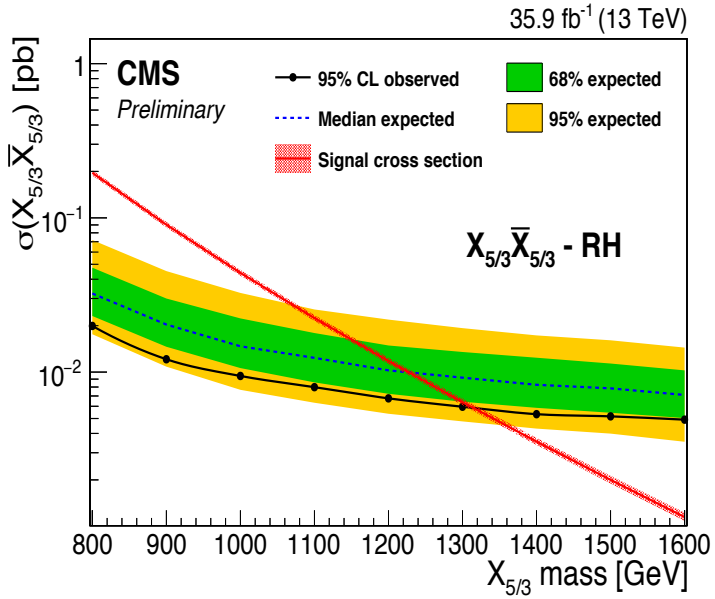
≥ 2 b

0 W

≥ 1W







LH M_x >1.30 TeV , RH M_x >1.32 TeV @ 95 % CL

$\mathcal{B}(X \rightarrow tW) = 100\ \%$

Pair: $T_{2/3}(Y_{-4/3}) \rightarrow$ bW, Single lepton + Jets

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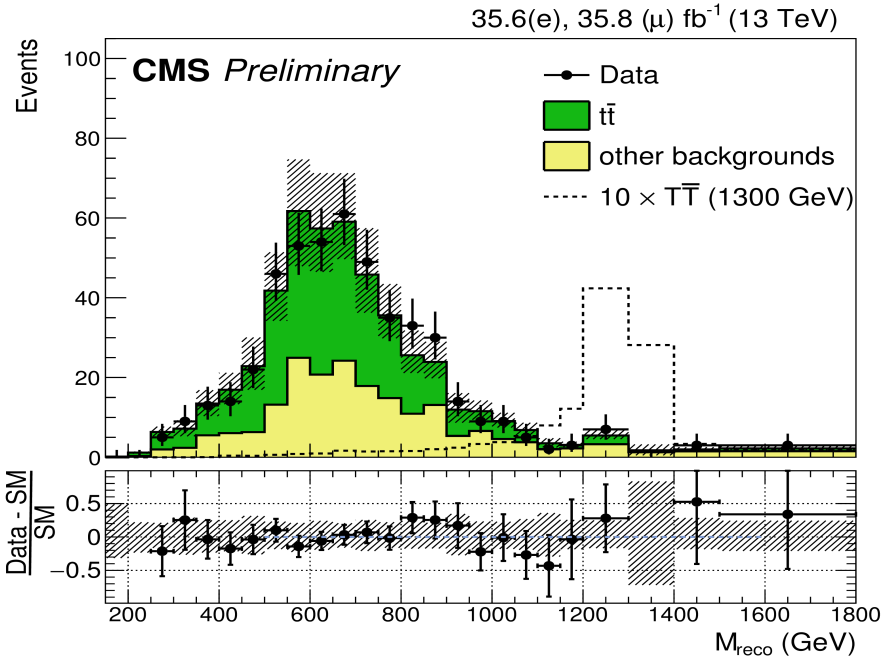
$$T\bar{T}\,(Y\bar{Y}) \rightarrow bW\bar{b}W \rightarrow bl\nu\bar{b}q\bar{q}'$$

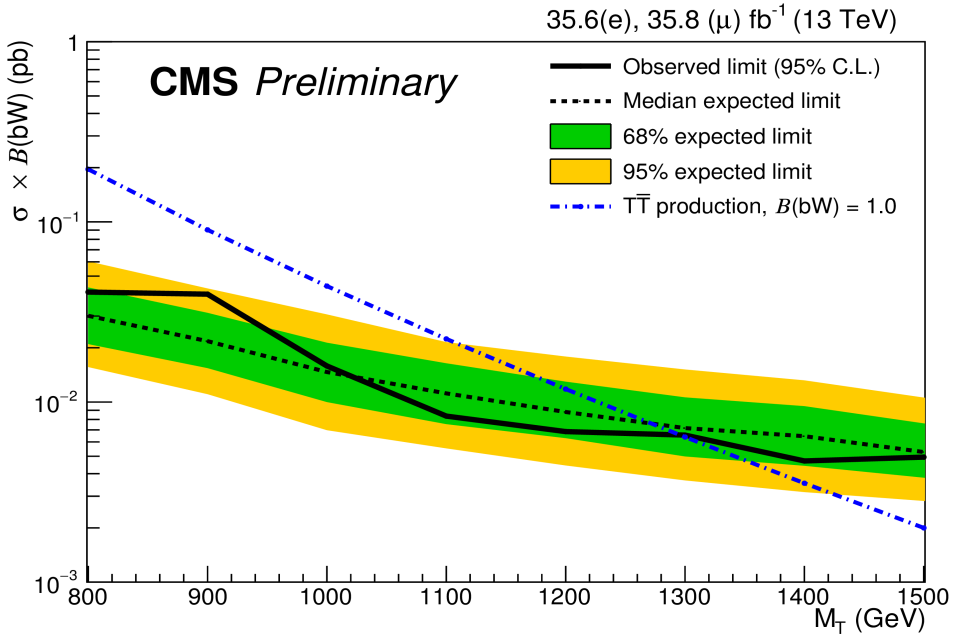
- Invariant T mass – from kinematic quantities of the final state variables (kinematic fit done similar to top quark measurement)
- Selected events are categorized according to
  - =0 W-tagged , ≥ 1W – tagged jets
- ≥ 1W – tagged jets category is sensitive to higher masses of T

Signal:
- 1 charged lepton (e or μ) + ν
- ≥ 4 AK4 jets or (≥ 3 AK4 + 1 W-Tagged Jet)

Backgrounds:
All Backgrounds – from simulation

≥ 1W – tagged jets



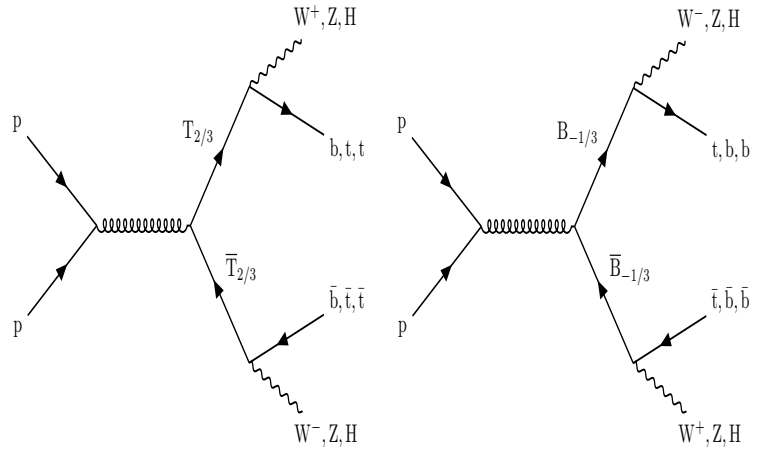


M_T >1295 GeV @ 95 % CL

$\mathcal{B}(T \rightarrow bW) = 100\,\%$

Pair: $T_{2/3}(B_{-1/3})\rightarrow$ Leptonic final states

CMS-PAS-B2G-17-011



Search Variables

Single Lepton

- 16 categories according to lepton flavor and number of H tagged, W tagged and b tagged jets
- For W categories - min**M(l, b)**
- For H Categories - $\mathbf{S_T}$

Same-sign di-leptons - H_T^{lep}

Tri-leptons

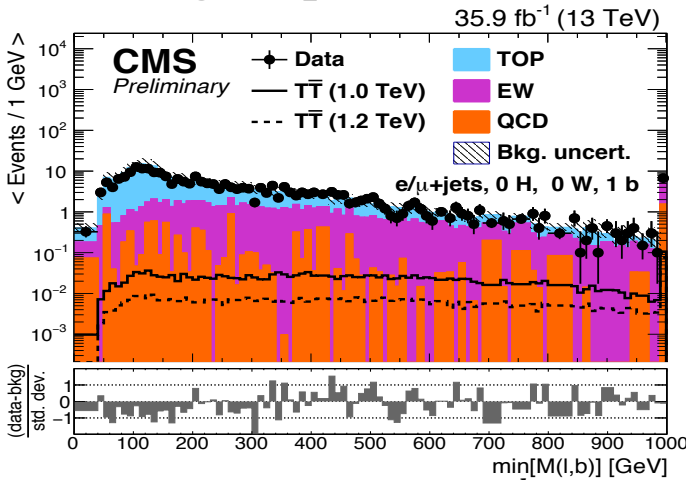
- Four categories depending on lepton flavor
  - eee, eeμ , e$\mu\mu$, $\mu\mu\mu$
- Search Variable - $\mathbf{S_T}$

$\mathbf{S_T} \equiv \sum_{all\ jets+leptons+MET} \mathbf{P_T}$

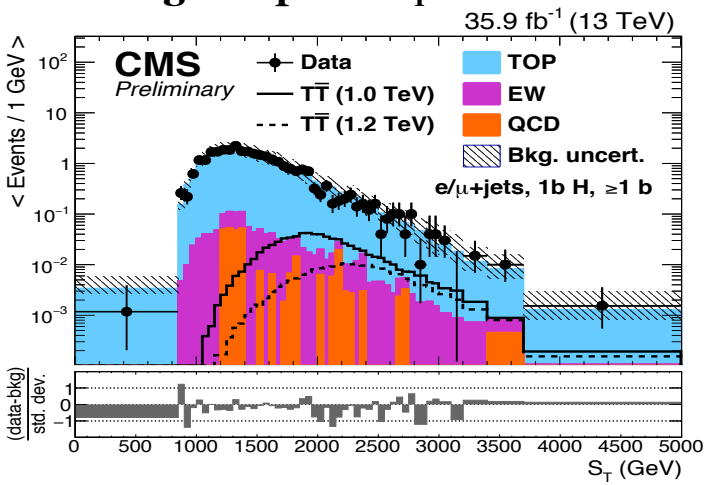
Signal:

- Single lepton - sensitive to T(B) → bW,tH (tW, bH)
- same sign di-leptons - sensitive to T(B) → tH (tW)
- Tri-leptons - sensitive to T(B) → tZ (bZ)

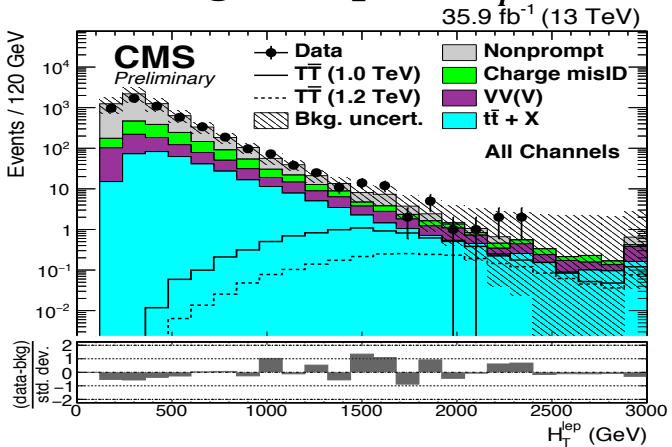
Single Lepton- minM(l, b)



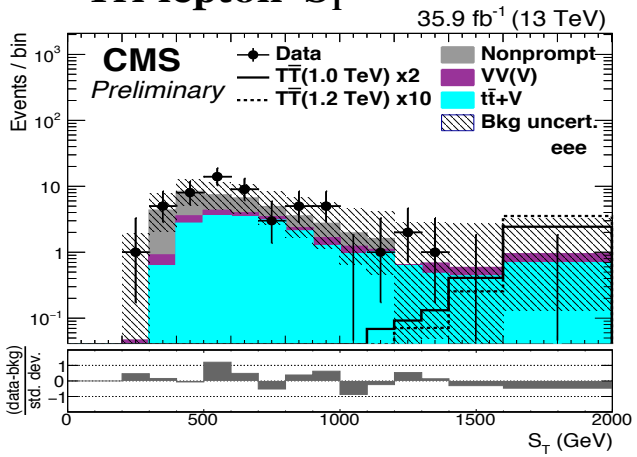
Single Lepton- S_T



Same-sign di-lepton- H_T^{lep}



Tri-lepton- S_T



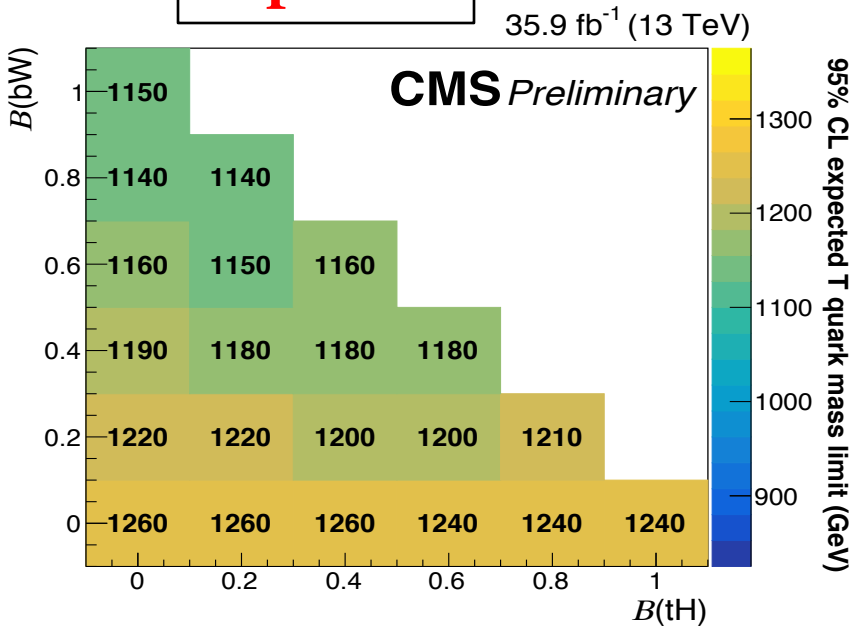
Pair: $T_{2/3}(B_{-1/3})\rightarrow$ Leptonic final states

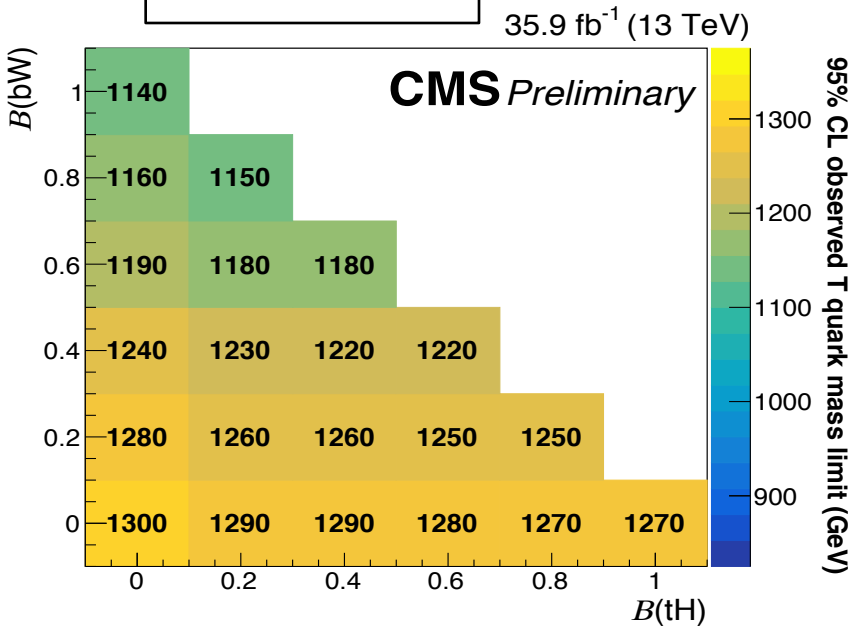
CMS-PAS-B2G-17-011

Expected

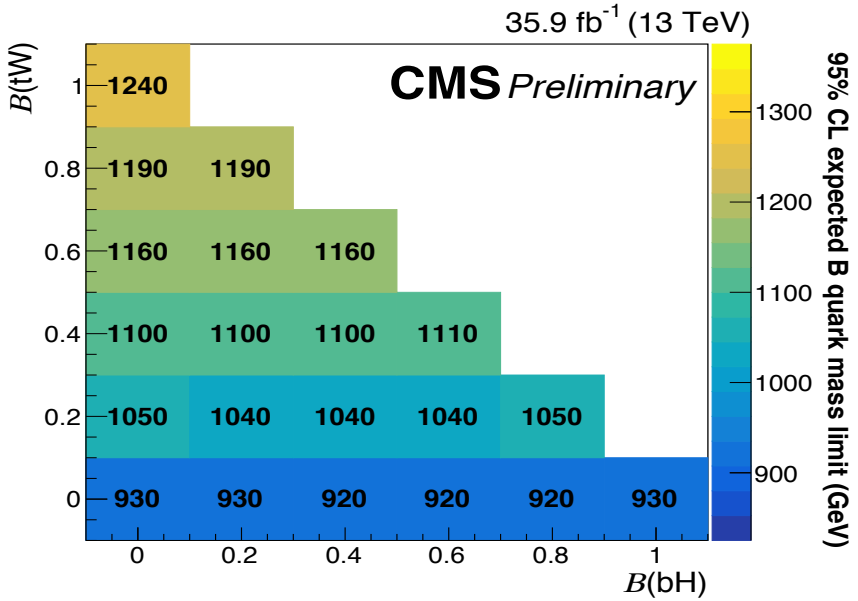
Observed

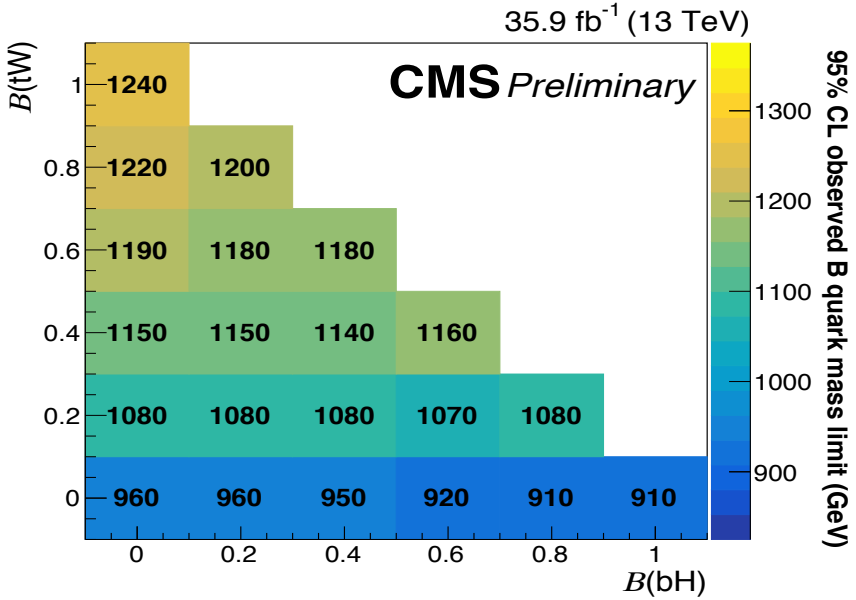
T





B

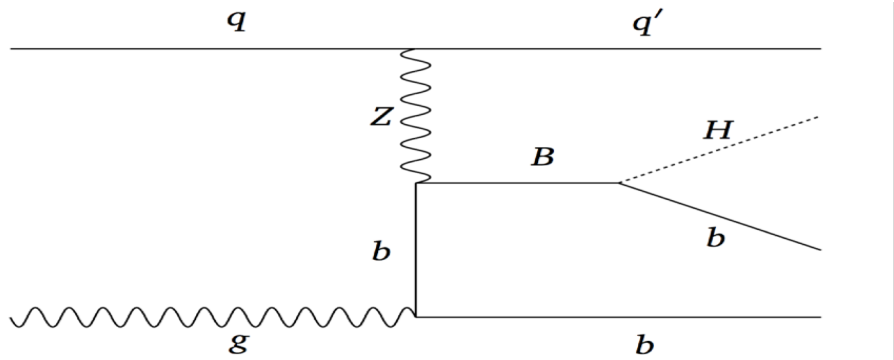




VLQ: Single Production

Single: $B_{-1/3} \rightarrow bH$, Fully Hadronic

Submitted to JHEP



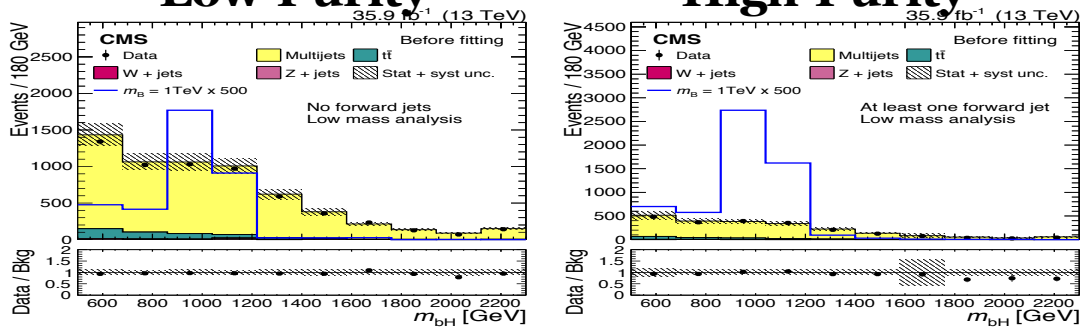
- Binned likelihood fit to reconstructed mass ($\mathbf{m_{bH}}$)
- Selected events are further divided in
  - **Low Mass** ($H_T > 950$ GeV) , **High Mass** ($H_T > 1250$ GeV)
  - **Low Purity**(=0 forward Jet) , **High Purity** (≥1 forward Jet)

Signal:
- 1 H-tagged Jet
- 1 b- tagged jet

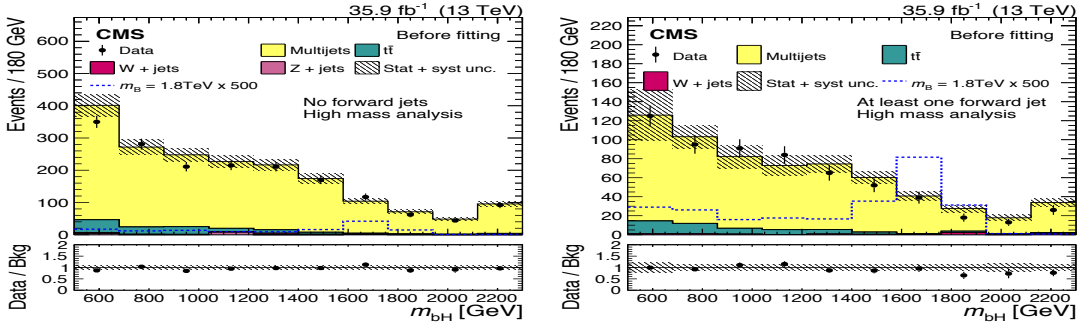
Backgrounds:
Multi Jet – from data
$t\bar{t}$, Z+Jets, W+Jets – from simulation

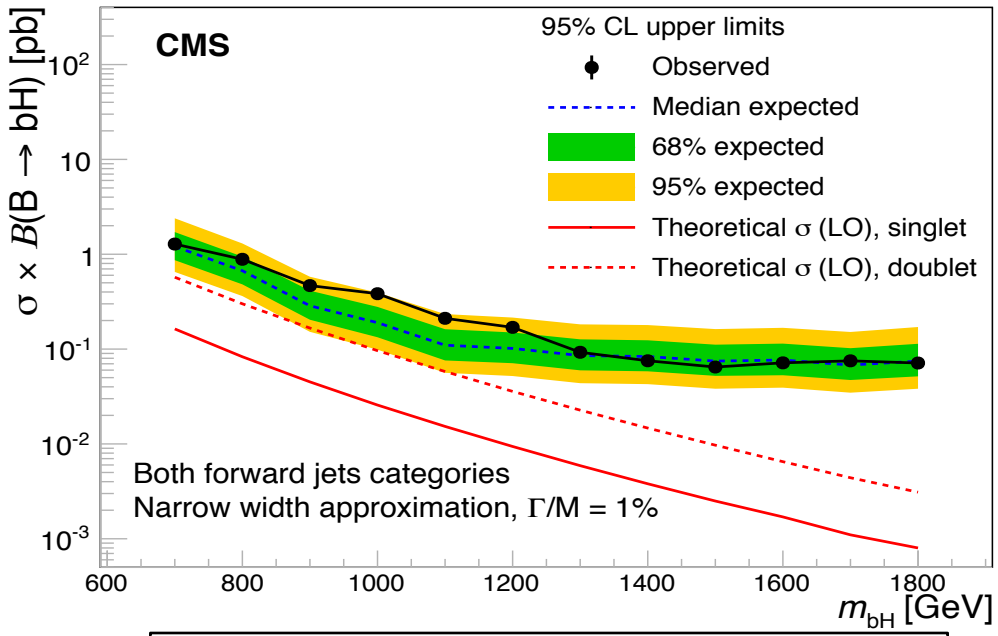
Low Purity | **High Purity**

Low Mass



High Mass





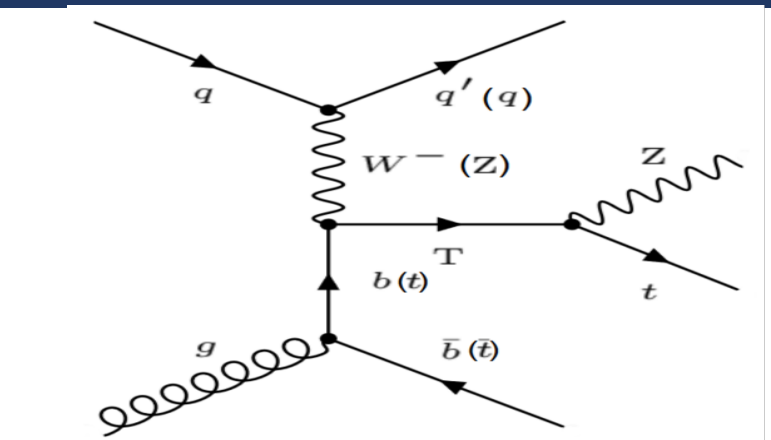
Expected Upper Limits

0.07 – 1.2 pb @ 95 % CL

C(bZ) = 0.5, $\mathcal{B}(B \rightarrow bH) = 25$ %

Single: $T_{2/3} \rightarrow tZ$, Di-leptons

Submitted to PLB

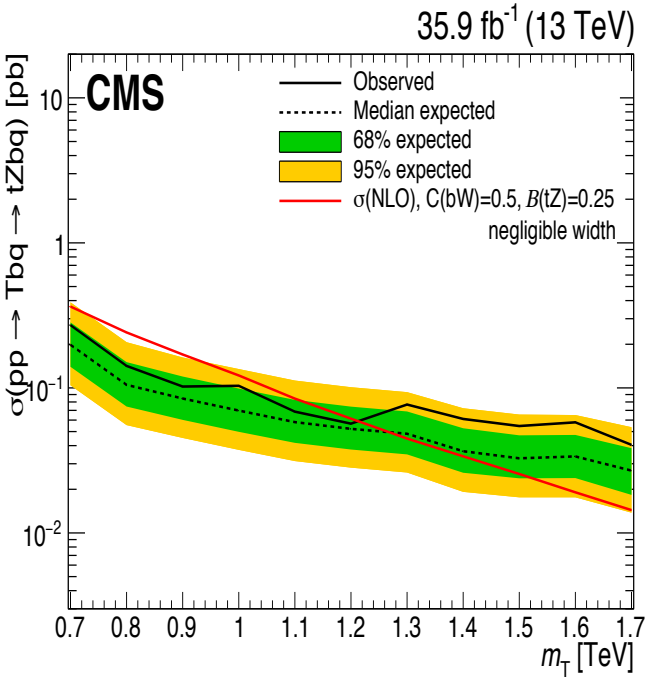


- 10 categories depending on Z decay, Hadronic Top reconstruction and number of forward jets
- reconstructed T mass (t, Z) for fitting

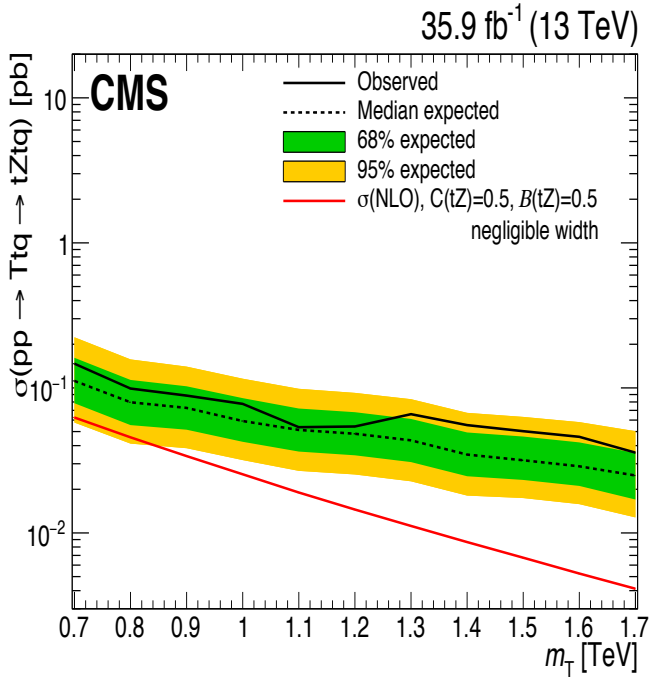
Category	Z boson	t quark	N(forward jets)
1	two muons	fully merged	≥0
2	two electrons	fully merged	≥0
3	two muons	partially merged	0
4	two muons	partially merged	≥1
5	two electrons	partially merged	0
6	two electrons	partially merged	≥1
7	two muons	resolved	0
8	two muons	resolved	≥1
9	two electrons	resolved	0
10	two electrons	resolved	≥1

Signal:
- 2 opposite sign di-leptons from Z
- t decays hadronically

Backgrounds:
All background – from data



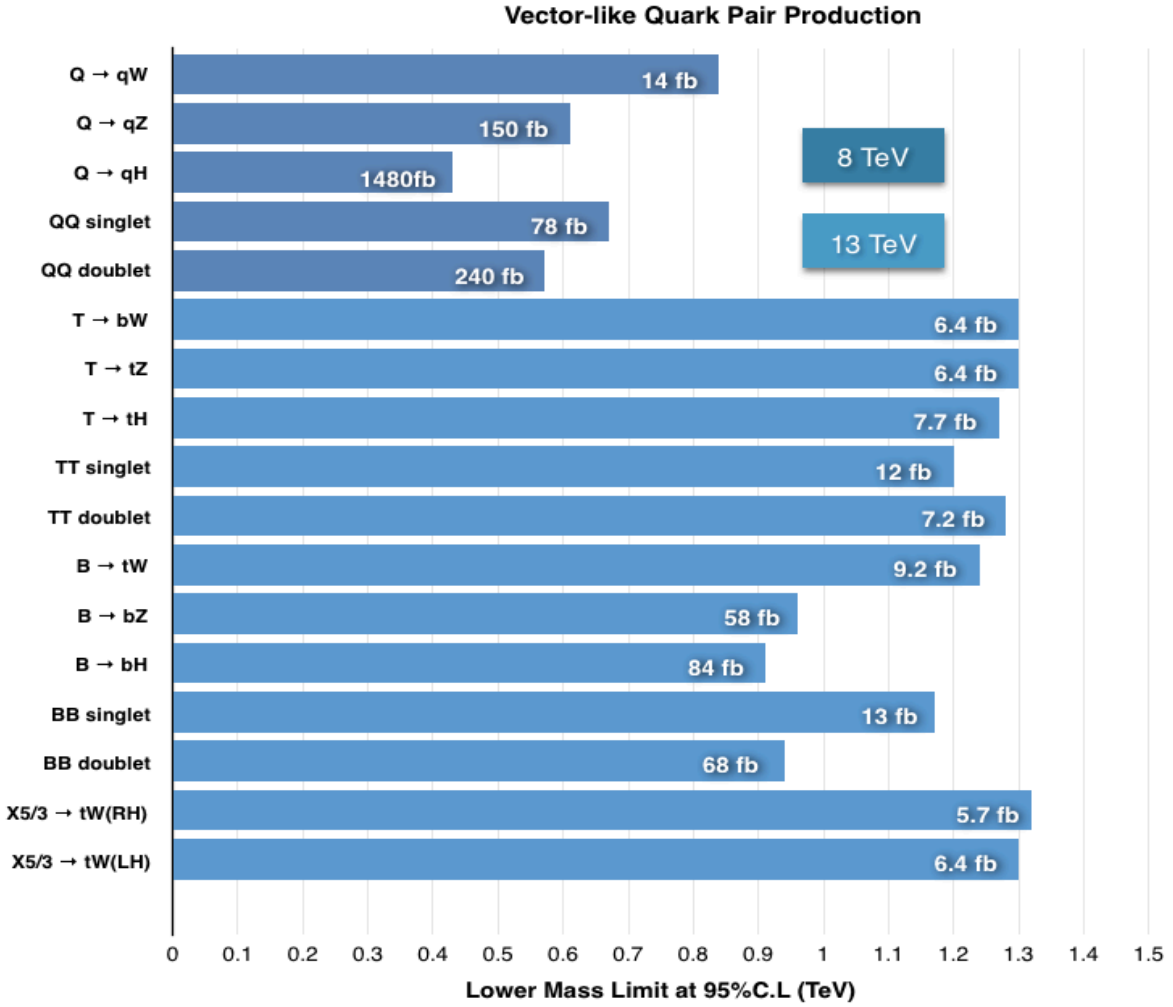
Upper Limits LH T(b)
xsec 0.27 – 0.04 pb
M_T >1.2 TeV @ 95% CL
C(bW) = 0.5

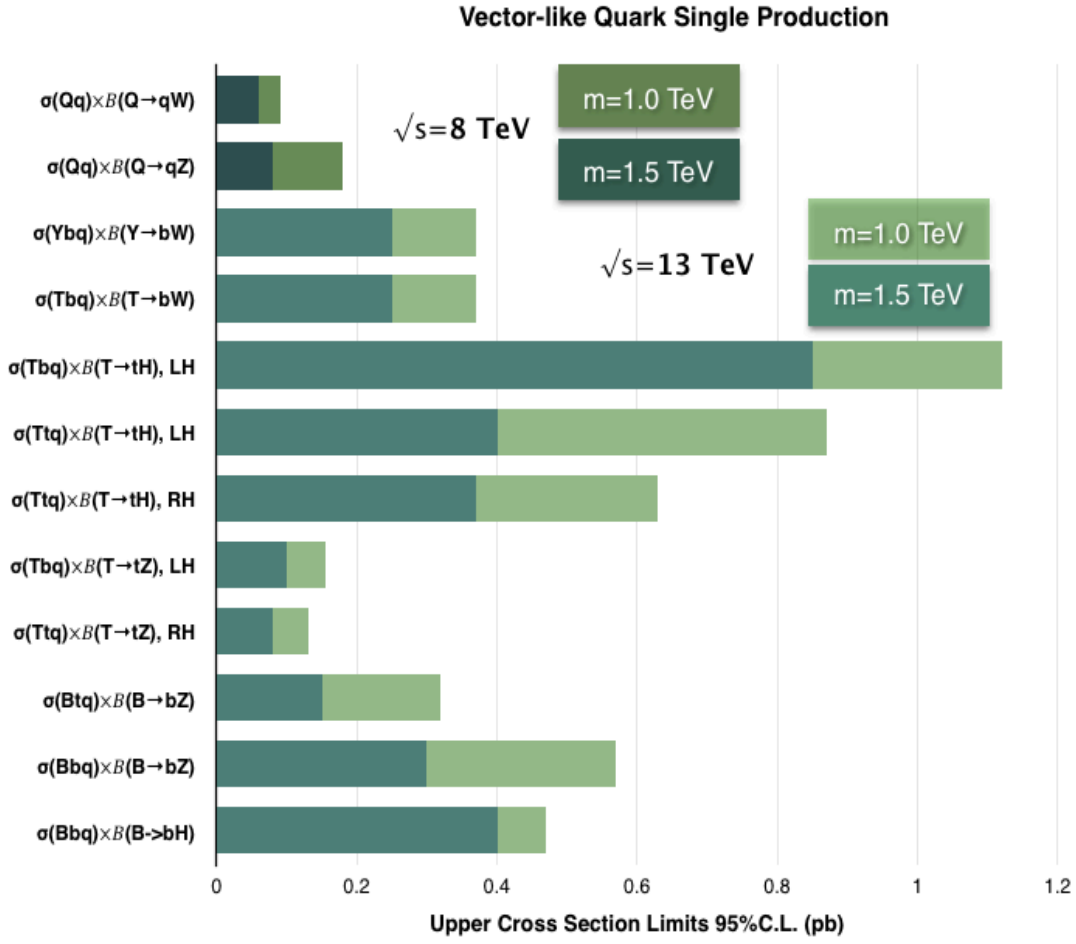


Upper Limits RH T(t)
xsec 0.15 – 0.04 pb
@ 95% CL
C(tZ) = 0.5

Summary

- Presented the status of VLQ searches in CMS using full 2016 data
- Setting stronger limits on both single and pair production





Thank you ……!!!!!

Back Up

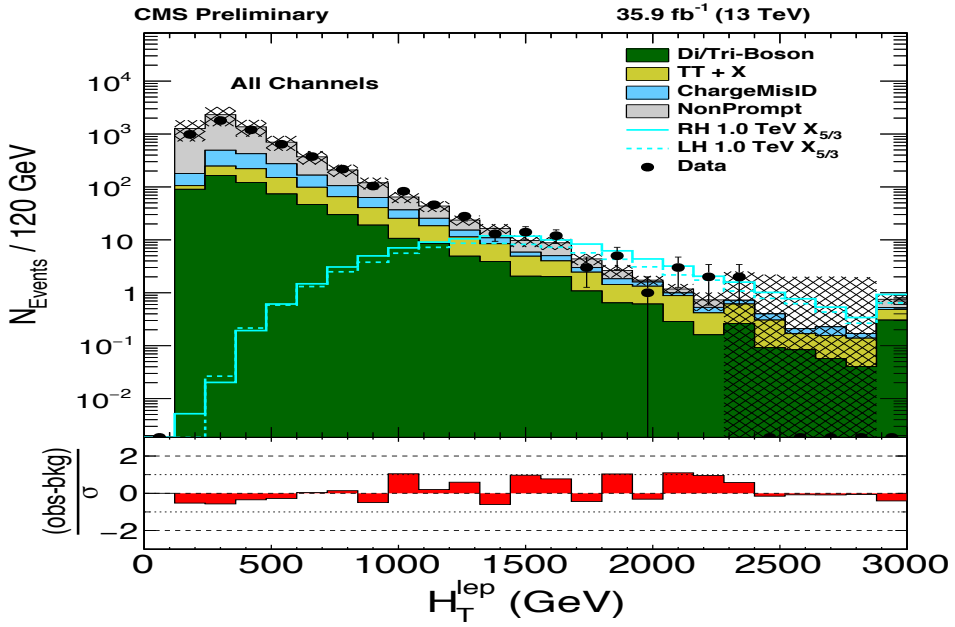
Pair: $X_{5/3} \rightarrow tW$, Same Sign di-lepton CMS-PAS-B2G-16-019

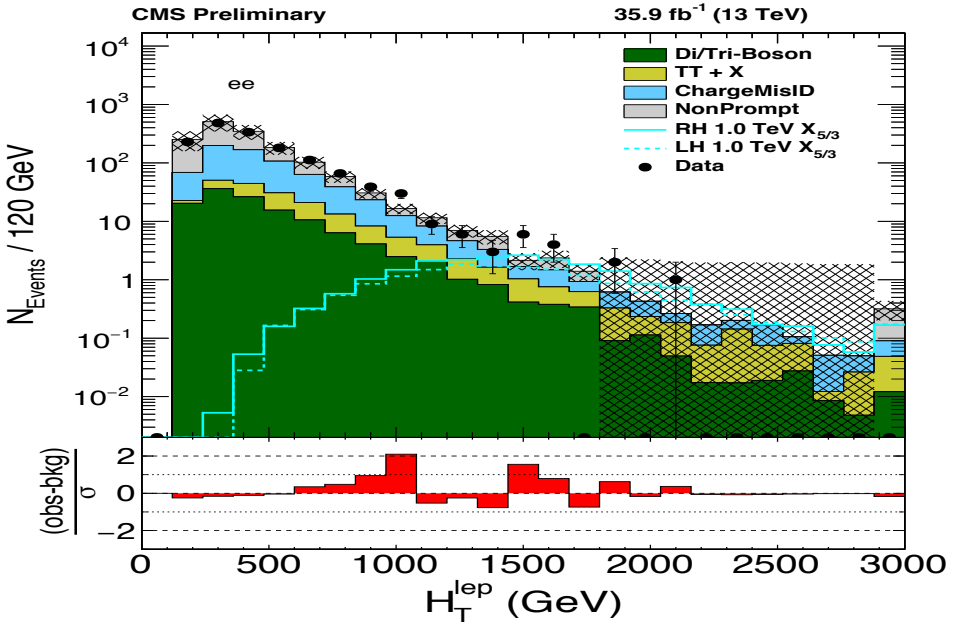
Event Selection:

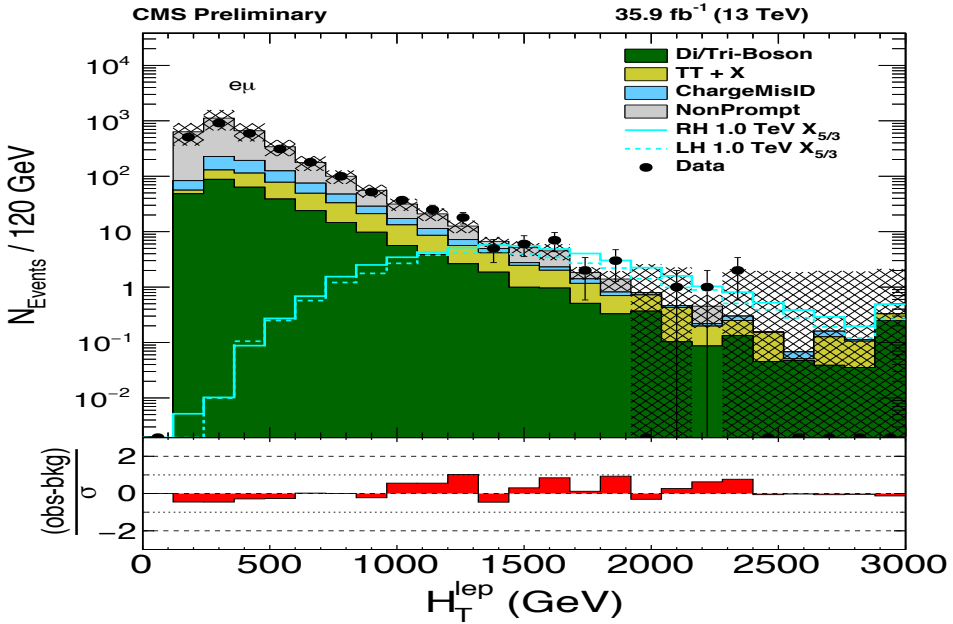
1. Two tight same sign leptons
2. Quarkonia veto :
   - $M_{ll} > 20$ GeV
3. Associate Z Boson veto :
   - veto events with $M_{ll'}$ within 15 GeV of Z mass
4. Primary Z Boson veto :
   - $M_{ll} > 106.1$ GeV and $M_{ll} < 76.1$ GeV (only for ee)
5. No. of constituents ≥ 5
   - No. of jets + No. of other leptons (leptons not from same sign pair)
6. $H_T^{lep} > 1200$ GeV
   - H_T^{lep} = sum P_T ($jets + tight\ leptons\ in\ event$)

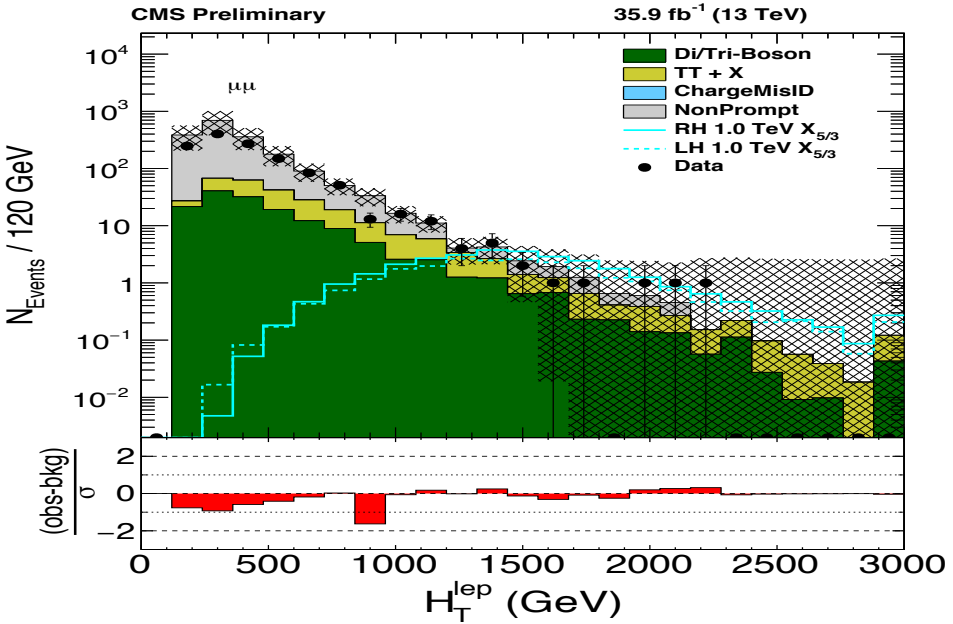
Pair: $X_{5/3} \rightarrow tW$, Same Sign di-lepton

CMS-PAS-B2G-16-019









Pair: $X_{5/3} \rightarrow tW$, Single lepton

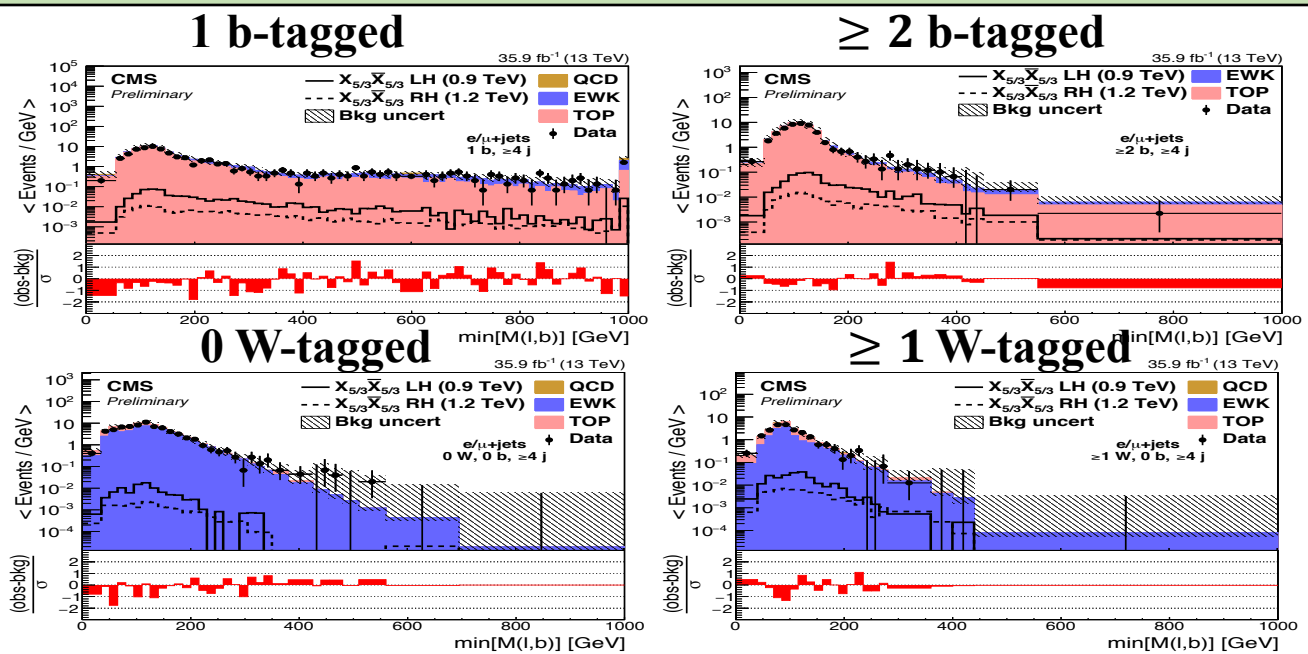
CMS-PAS-B2G-17-008

Event Selection:

1. One tight lepton with $p_T > 80$ GeV (no loose leptons with $p_T > 10$ GeV)
2. $E_T^{miss} > 100$ GeV (reduce multijet background)
3. NAK4 ≥ 4 (Leading Jet Transverse momentum > 450 , 2nd leading Jet Transverse momentum > 150)
4. Nbjets ≥ 1
5. dR (lepton , closest jet) > 0.4 or lepton p_T perpendicular to jet axis > 40 GeV (reduce residual multijet contamination)
6. dR(lepton , j2) > 1.0 (good discriminator for both signal and control regions)

$t\bar{t}$ control region

W + jets control region



Pair: $X_{5/3} \rightarrow tW$, Single lepton

CMS-PAS-B2G-17-008

0 t - tagged

≥ 1 t - tagged

=1 b

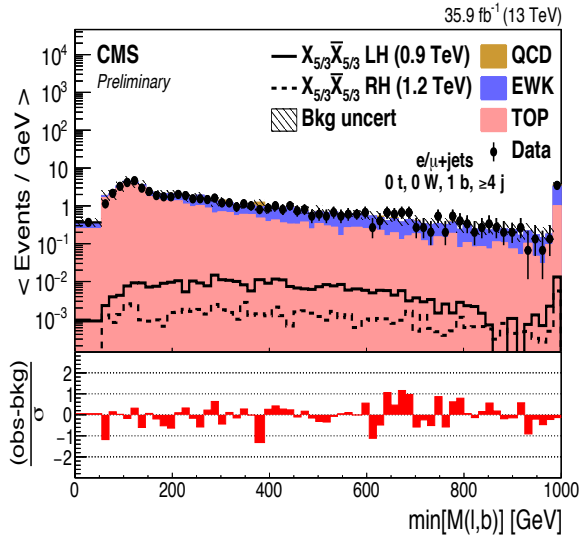
≥ 2 b

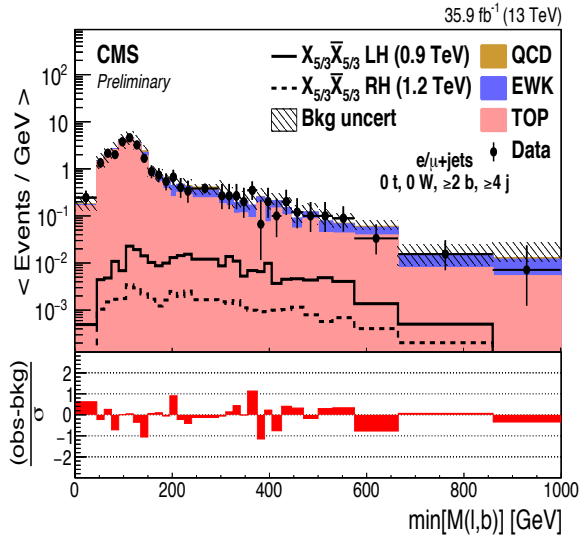
=1 b

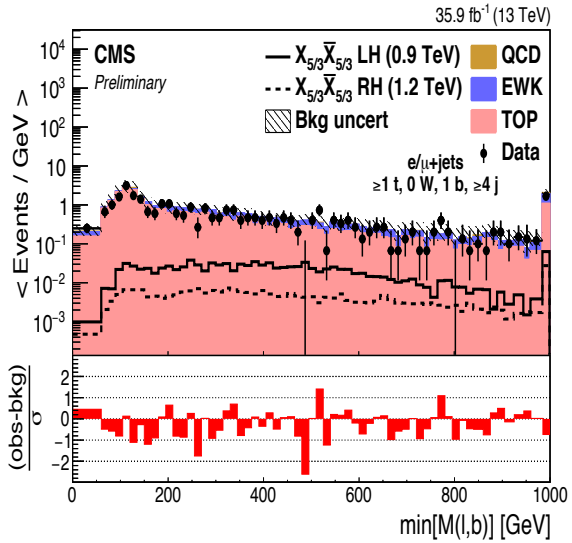
≥ 2 b

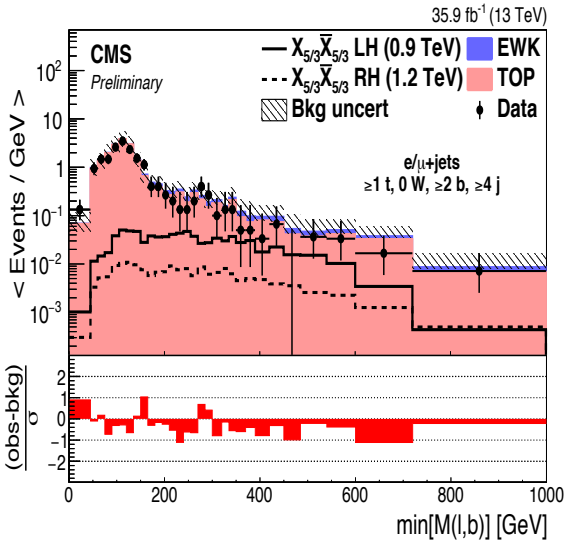
0 W

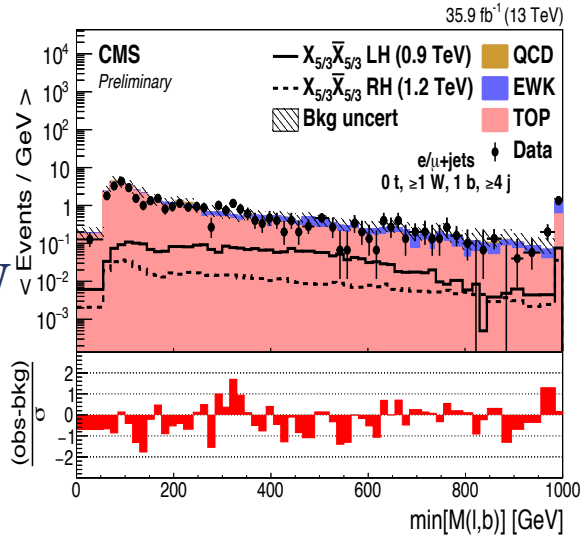
≥ 1W

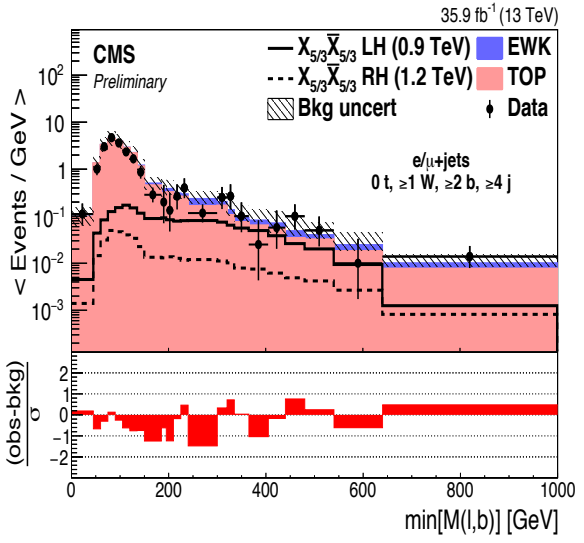


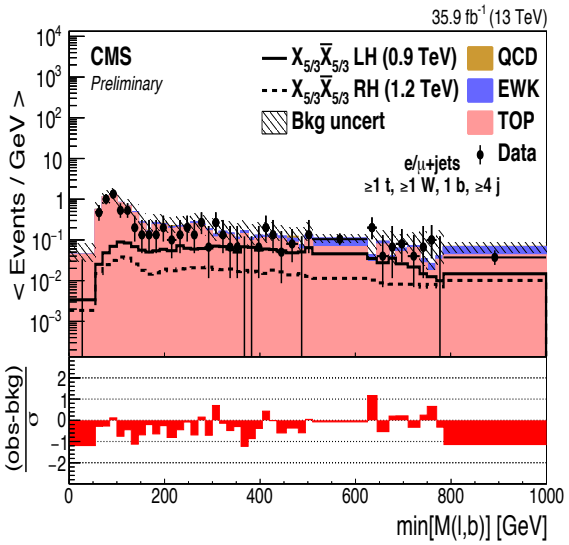


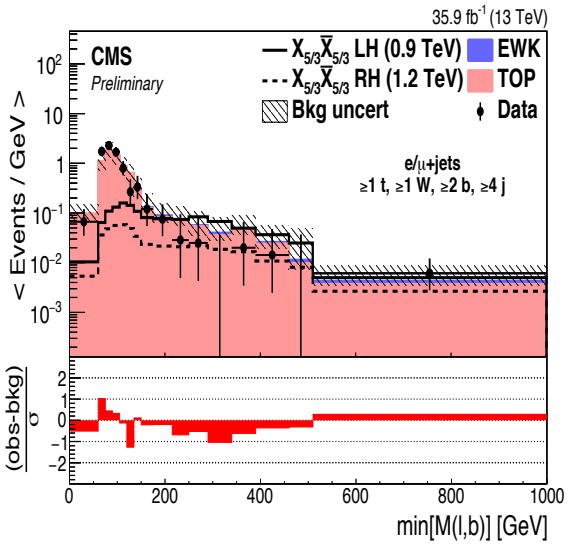






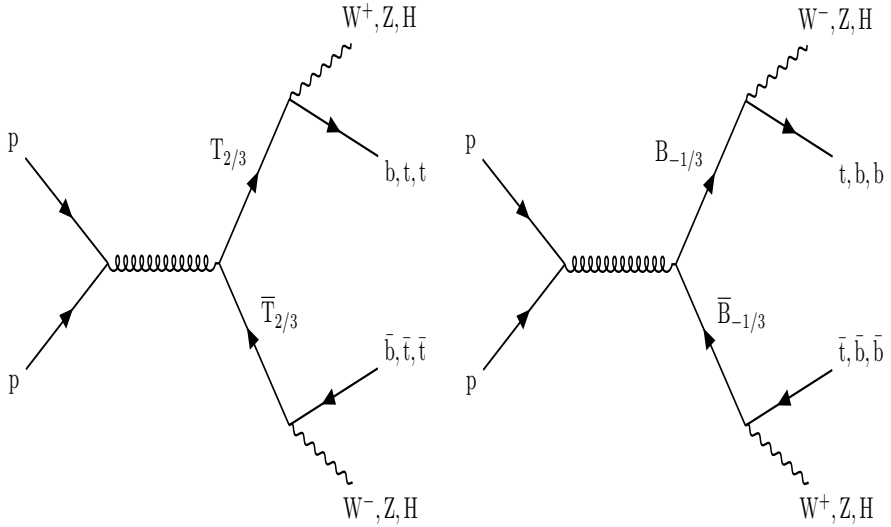






Pair: $T_{2/3}(B_{-1/3})\rightarrow$ Leptonic final states

CMS-PAS-B2G-17-011



Signal:

- Single lepton - sensitive to T(B) → bW,tH (tW, bH)
- same sign di-leptons - sensitive to T(B) → tH (tW)
- Tri-leptons - sensitive to T(B) → tZ (bZ)

Backgrounds:

- Single lepton - All Backgrounds from simulation
- Same sign di-leptons –
  1. Same-sign prompt leptons – from simulation
  2. Opposite-sign prompt leptons – data driven method
  3. Same-sign non- prompt leptons – data driven method
- Tri – leptons
  1. Prompt background – from simulation
  2. Non-prompt background – data driven method

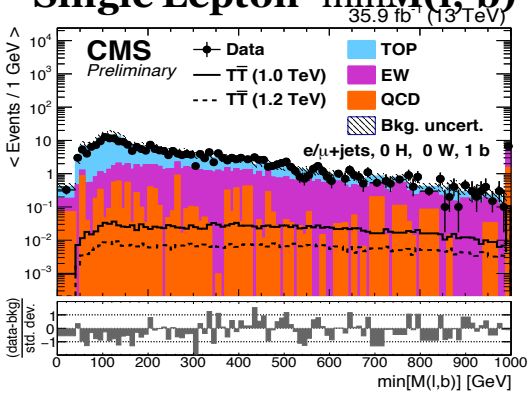
Search Variables

- **Single Lepton**
- 16 categories according to lepton flavor and number of H tagged, W tagged and b tagged jets
- For W categories - min**M(l, b)**
- For H Categories - $\mathbf{S_T}$

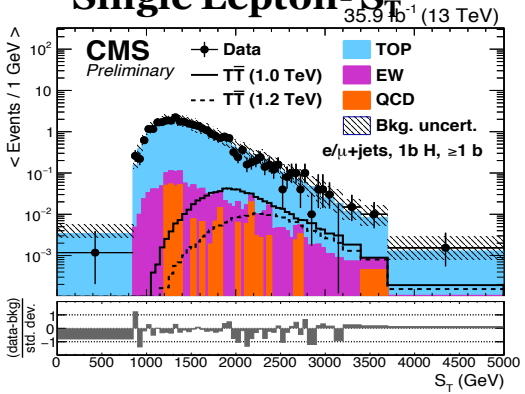
- **Same-sign di-leptons** - H_T^{lep}

$\mathbf{S_T} \equiv \sum_{all\ jets+leptons+MET} \mathbf{P_T}$

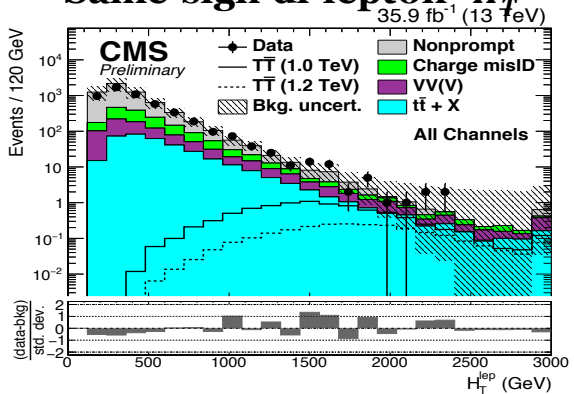
Single Lepton- minM(l, b)



Single Lepton- S_T

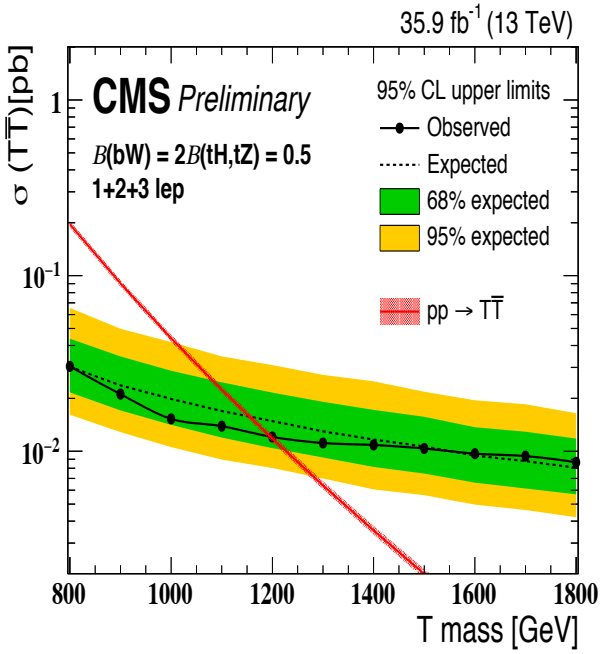


Same-sign di-lepton- H_T^{lep}

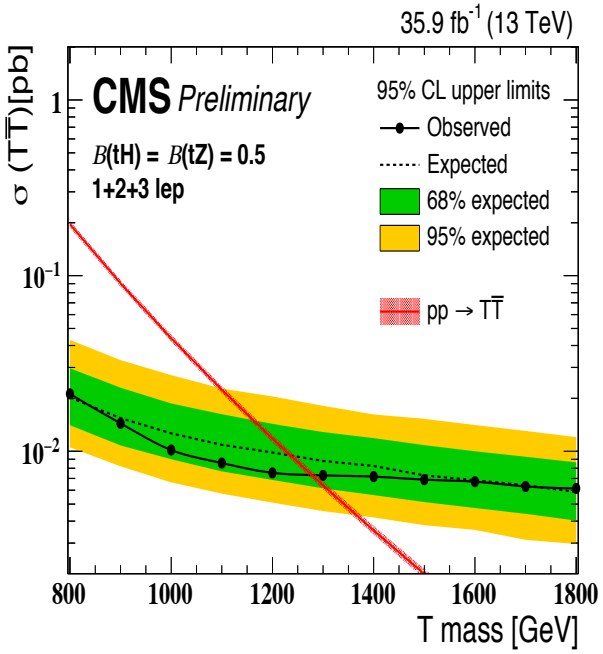


Pair: $T_{2/3}(B_{-1/3})\rightarrow$ Leptonic final states CMS-PAS-B2G-17-011

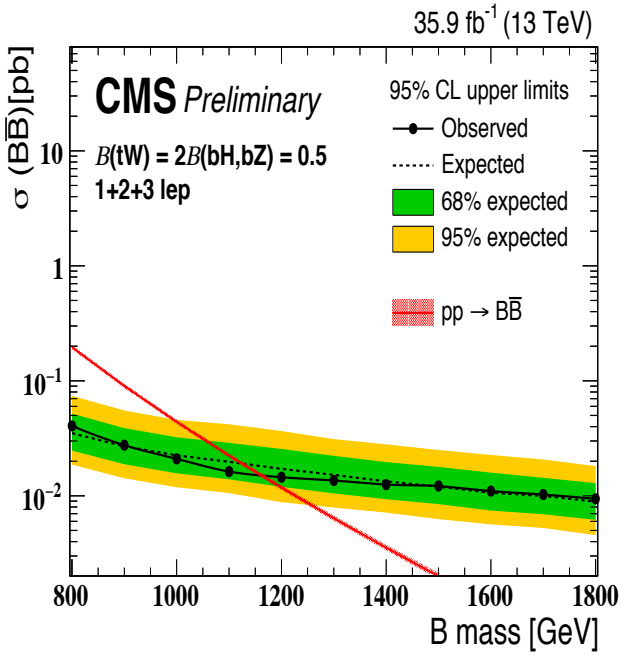
T Singlet Model



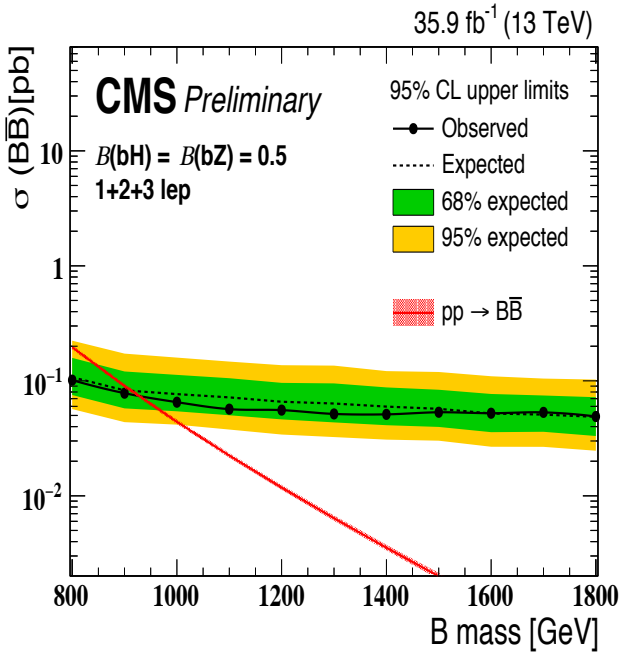
T Doublet Model



B Singlet Model



B Doublet Model

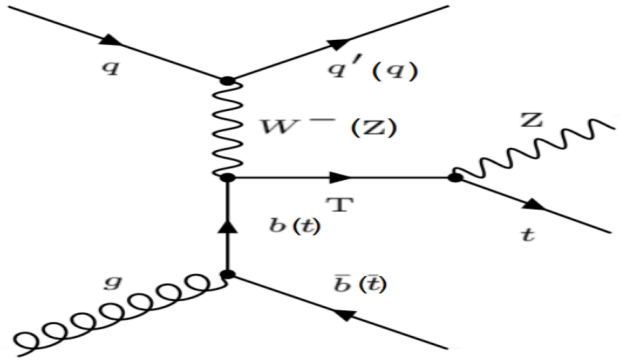


M_T >1200 GeV @ 95 % CL $\mathcal{B}(T \rightarrow bW) = 50$ % $\mathcal{B}(T \rightarrow tZ, tH) = 25$ %	M_T >1280 GeV @ 95 % CL $\mathcal{B}(T \rightarrow tZ, tH) = 50$ %

M_B >1170 GeV @ 95 % CL $\mathcal{B}(B \rightarrow tW) = 50$ % $\mathcal{B}(B \rightarrow bZ, bH) = 25$ %	M_B > 940 GeV @ 95 % CL $\mathcal{B}(B \rightarrow bZ, bH) = 50$ %

Single: $T_{2/3} \rightarrow tZ$, Di-leptons

Submitted to PLB



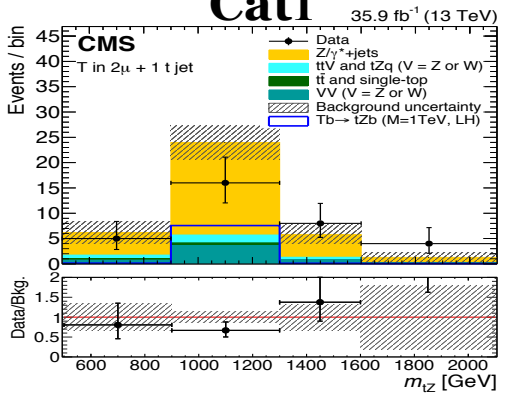
Signal:
- 2 opposite sign di-leptons from Z
- t decays hadronically

Backgrounds:
All background – from data

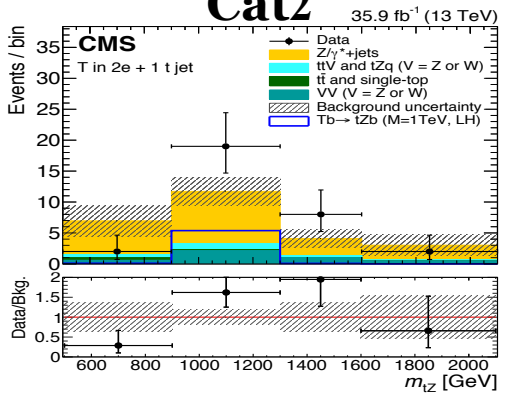
- 10 categories depending on Z decay, Hadronic Top reconstruction and number of forward jets
- reconstructed T mass (t, Z) for fitting

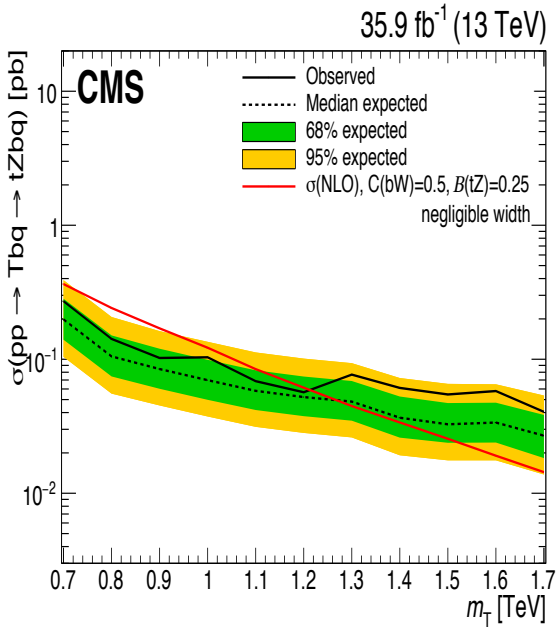
Category	Z boson	t quark	N(forward jets)
1	two muons	fully merged	≥ 0
2	two electrons	fully merged	≥ 0
3	two muons	partially merged	0
4	two muons	partially merged	≥ 1
5	two electrons	partially merged	0
6	two electrons	partially merged	≥ 1
7	two muons	resolved	0
8	two muons	resolved	≥ 1
9	two electrons	resolved	0
10	two electrons	resolved	≥ 1

Cat1

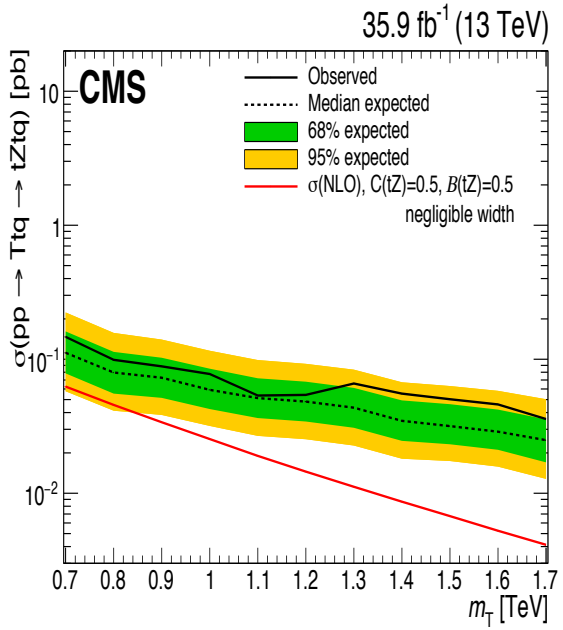


Cat2





Upper Limits LH T(b)
xsec 0.27 – 0.04 pb
M_T >1.2 TeV @ 95% CL
C(bW) = 0.5



Upper Limits RH T(t)
xsec 0.15 – 0.04 pb
@ 95% CL
C(tZ) = 0.5