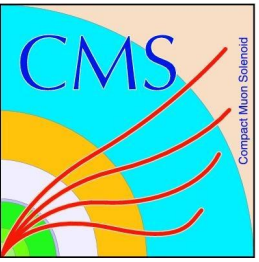
# Searches for vector-like quarks at CMS

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**On behalf of the CMS Collaboration**


SUSY 2021

23-28 August 2021

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# Outline

- Recent results on the searches for vector-like quarks (VLQ) at the CMS detector at LHC
  - LHC Run II collision data, 13 TeV
- First results on full Run II dataset:
  - Bottom-type VLQ pair production in fully hadronic final state. B2G-19-005
  - Single production of VLQ T decaying to a top quark and Z boson, with the Z boson decaying to neutrinos. B2G-19-004
  - W' boson decaying to a VLQ and a top or a bottom quark in all hadronic final state. B2G-20-002
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

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# Vector-like quarks (VLQs)

Several extensions of the Standard Model (SM) predict the existence of VLQs

- Spin ½ fermions
- Left-handed and right-handed components behave in the same way under the SM symmetry group
- Vector current couplings to the weak gauge bosons
- Non-Yukawa coupling mass-terms for VLQs are allowed.

| Type | Charge |
|---|---|
| X | +5/3 |
| T | +2/3 |
| B | -1/3 |
| Y | -4/3 |

| SU(2) Multiplets | |
|---|---|
| Singlets | T,B |
| Doublets | (T,B),(X,T),(B,Y) |
| Triplets | (X,T,B),(T,B,Y) |

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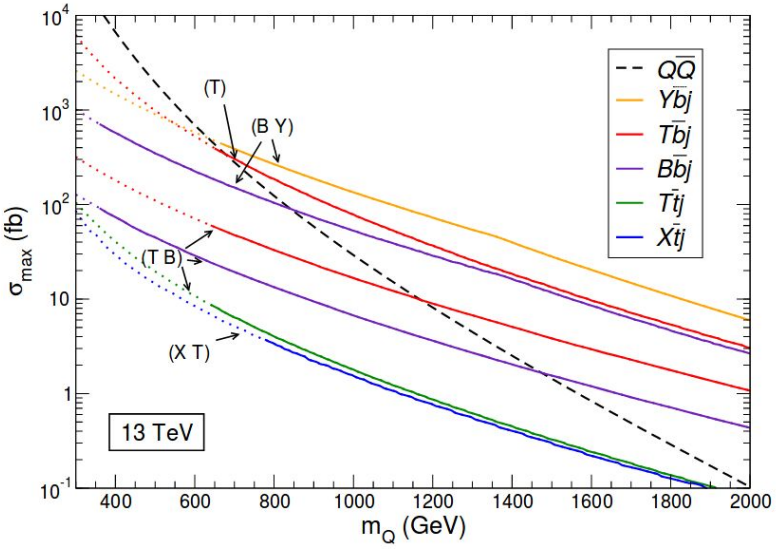
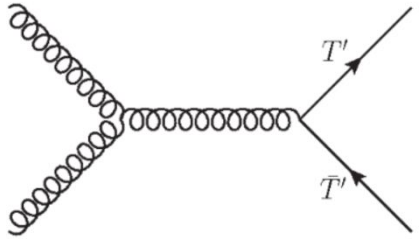
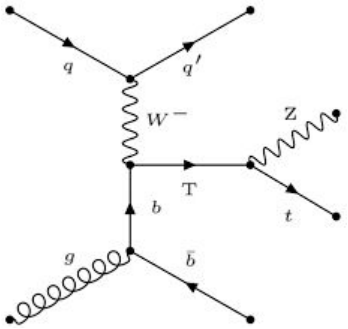
# VLQ production and decay

Both the pair and the single production of VLQs is considered :

- Pair production
  - Strong interaction processes
  - Model independent cross section, suppressed for large VLQ mass
- Single production
  - Electroweak processes
  - Cross section depending on VLQ mass and coupling to SM particles
  - Models foresee preferential mixing with 3rd generation SM quarks




| Type | Decay channel |
|---|---|
| X | tW |
| T | tZ,tH,bW |
| B | bZ,bH,tW |
| Y | bW |

**BR depending on VLQ mass and model**

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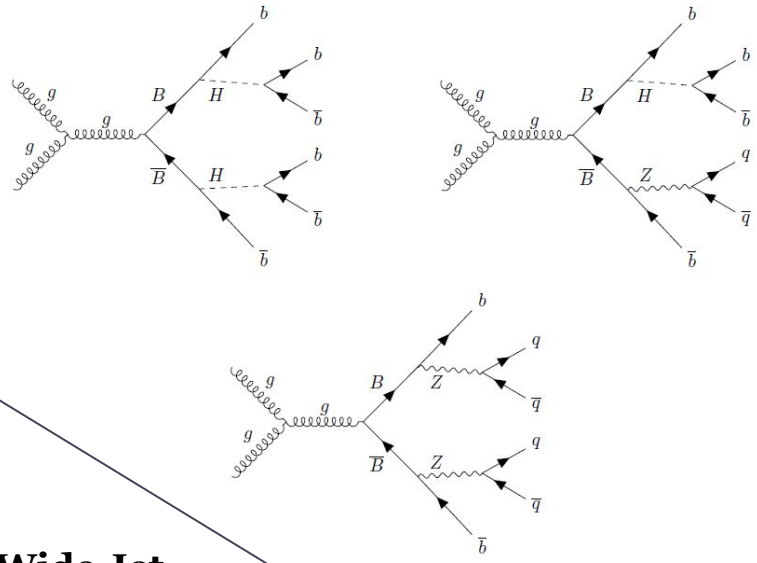
# Search for BB in full hadronic

First Full Run2 result for pair production, 137 $fb^{-1}$ , considering 3 different decays of the BB pair

B2G-19-005




Masses above 1 TeV are investigated

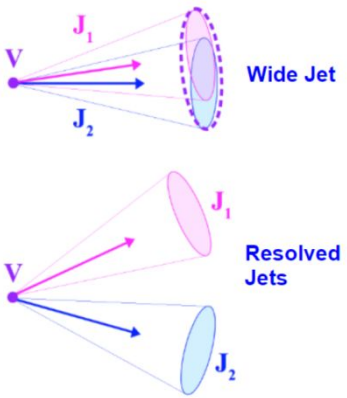
- jets, products of B decay, may overlap in one wide jet or in two resolved jets

Signal selection:

- 4, 5 or 6 high $p_T$ jets in the final state
- $H_T$ > 1350 GeV
- jets b-tagging

**Wide Jet**
**anti-kt R=0.8**
**$p_T$ >200 GeV**

**Narrow Jet**
**anti-kt R=0.4**
**$p_T$ >50 GeV**




**According to the number and the type of reconstructed of jets 9 event categories are defined**

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# Search for BB in full hadronic

$\chi^2$-like metrics for the reconstruction of the decay channel and category assignment:

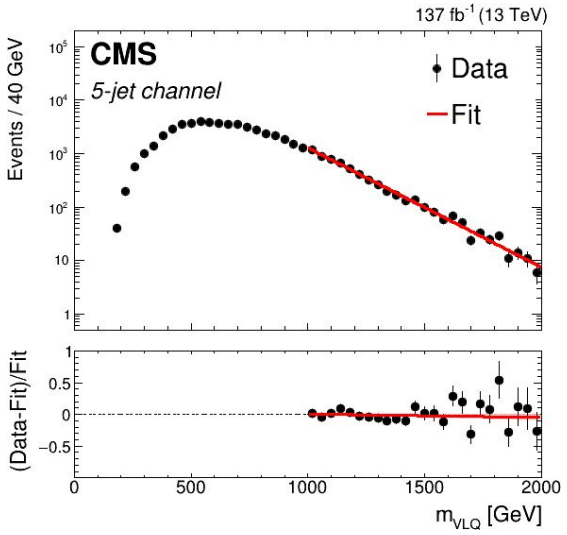
• invariant mass of the dijet or wide jet compatible with the boson mass and equal invariant mass of the reconstructed B candidates

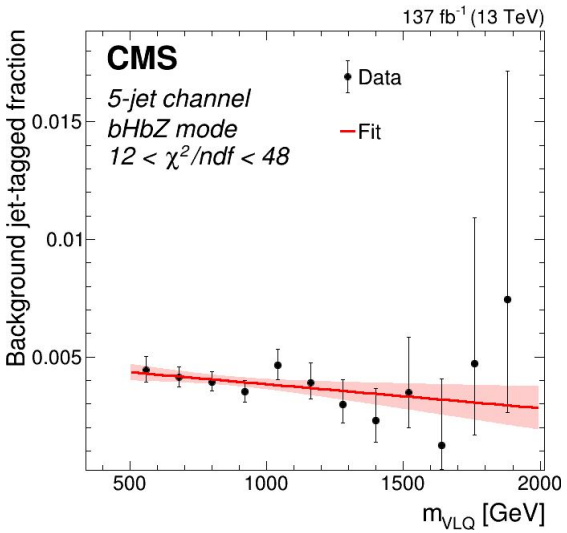
The main background is QCD multijet production, it has been determined from data:

•Exponential fit to the B mass distribution before b-tagging

•Estimation from low $m_{VLQ}$ sideband region of the background rate jets passing the tagging

•Background tagged fraction propagated to high mass using a high $\chi^2$ control region



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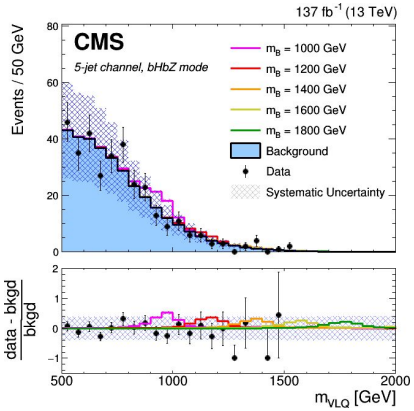
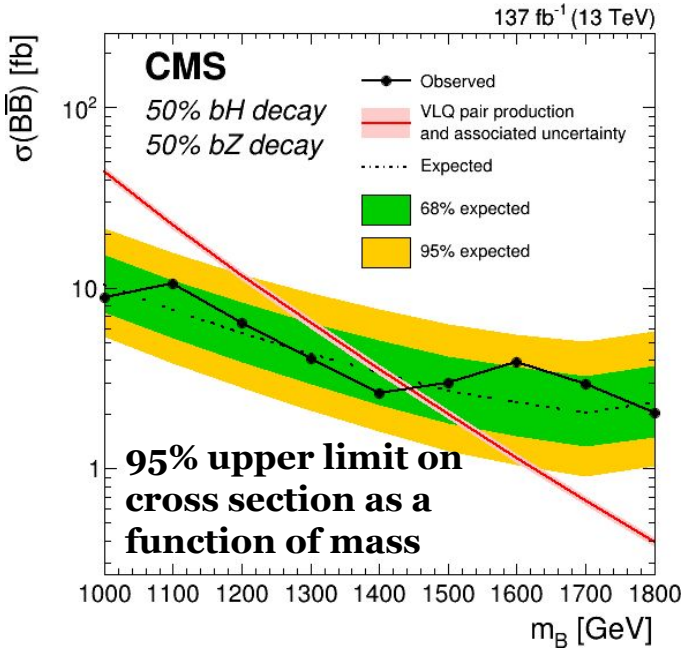
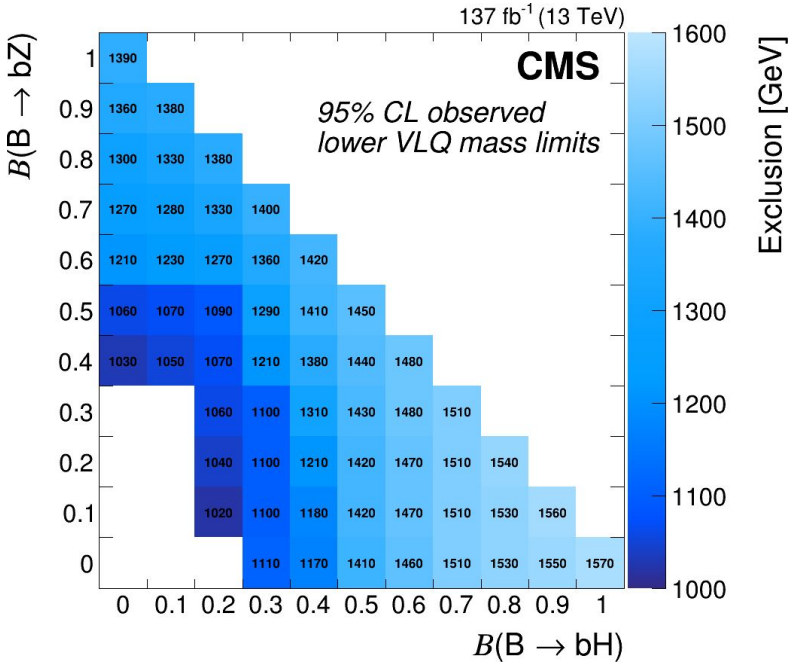
# Search for BB in full hadronic

No significant excess of data with respect to the expected background

95% CL upper limits on cross section as a function of B mass and BR of bZ and bH decay channels have been obtained



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# Single T->tZ(νν)

First Full Run2 result for single production, 136 $fb^{-1}$ , considering Tbq production channel

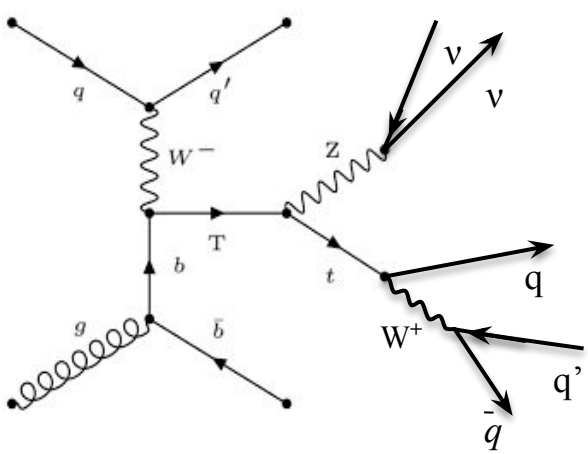
The mass range investigated is $m_T$ [600,1800] GeV

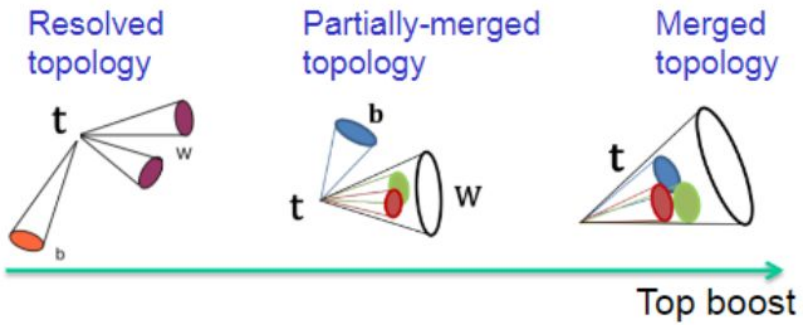
- Products of top quark decay:
  - 3 narrow jets
  - 1 large jet (W) and 1 narrow jet(b)
  - 1 large jet (t)

Signal selection:

- MET > 200 GeV
- Lepton veto
- jet b-tagged from top decay
- min ΔΦ(MET,Jets)>0.6

B2G-19-004




**According to the type of reconstructed top and the presence of a forward jet 6 event categories are defined**

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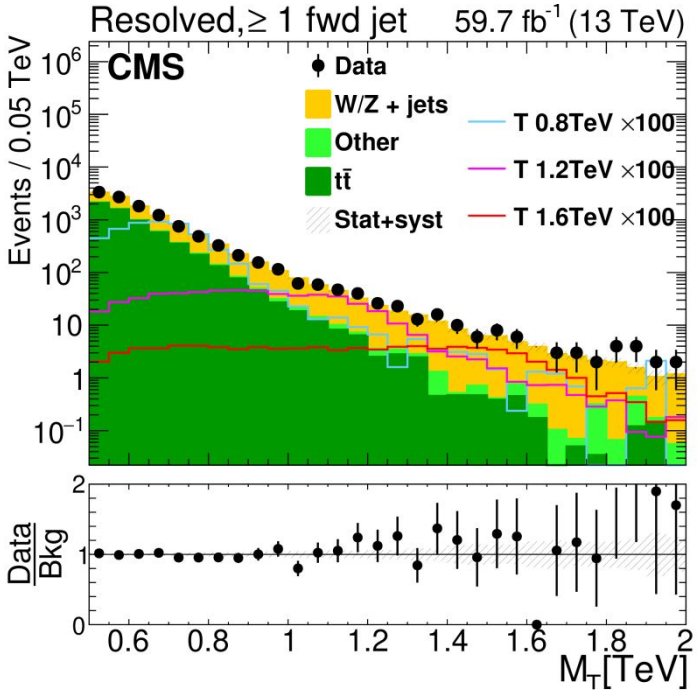
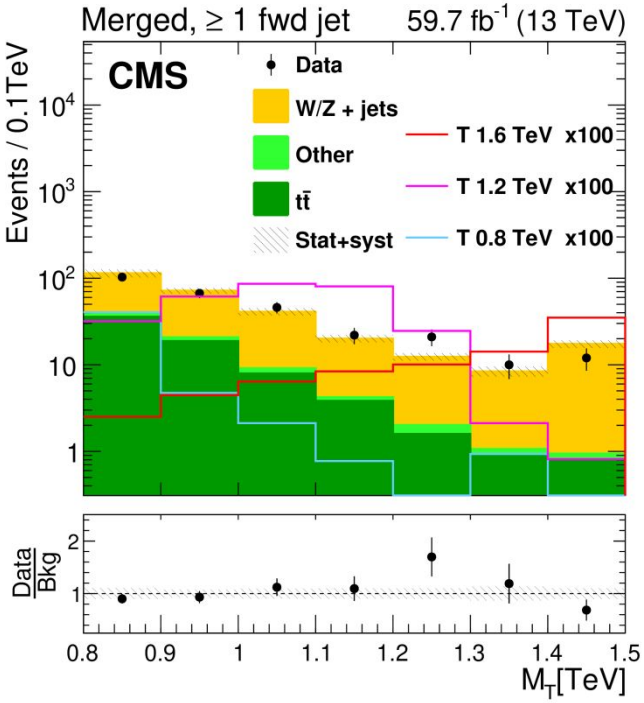
# Single T->tZ(νν)

For the signal extraction it was fitted simultaneously the transverse mass of the top and MET in each category:

$$M_T = \sqrt{2 p_T^t p_T^{miss} (1 - \cos \Delta\phi_{t, p_T^{miss}})}$$




The main backgrounds in the signal region are ttbar, W+jets, and Z+jets events:

- Data-driven correction to background $M_T$ distribution extracted from control regions

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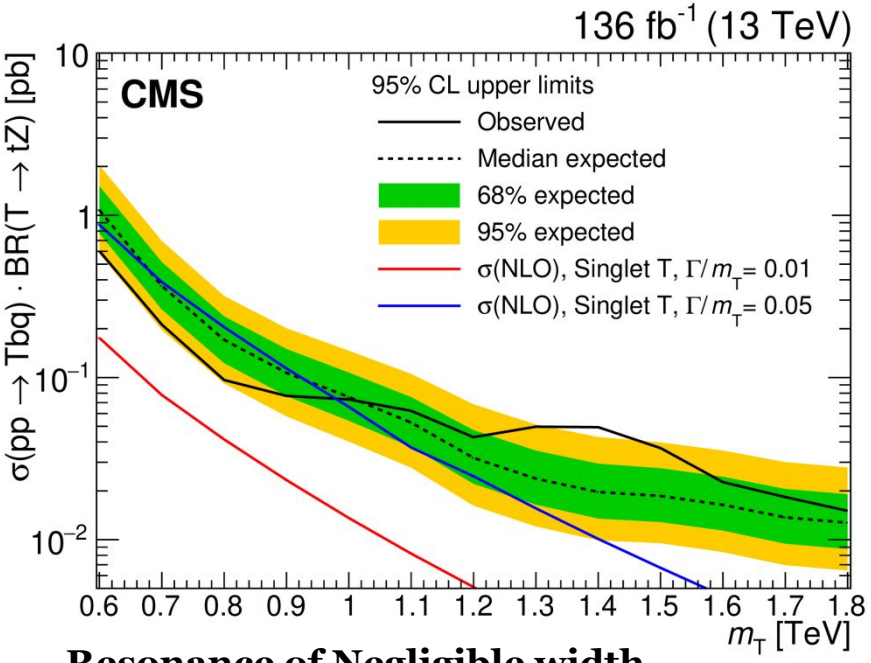
# Single T->tZ(νν)

Signal Resonance width: [0.01,0.3] $m_T$

**Limit as a function of mass**

$m_T$ <0.98 TeV excluded for $\Gamma/ m_T = 0.05$

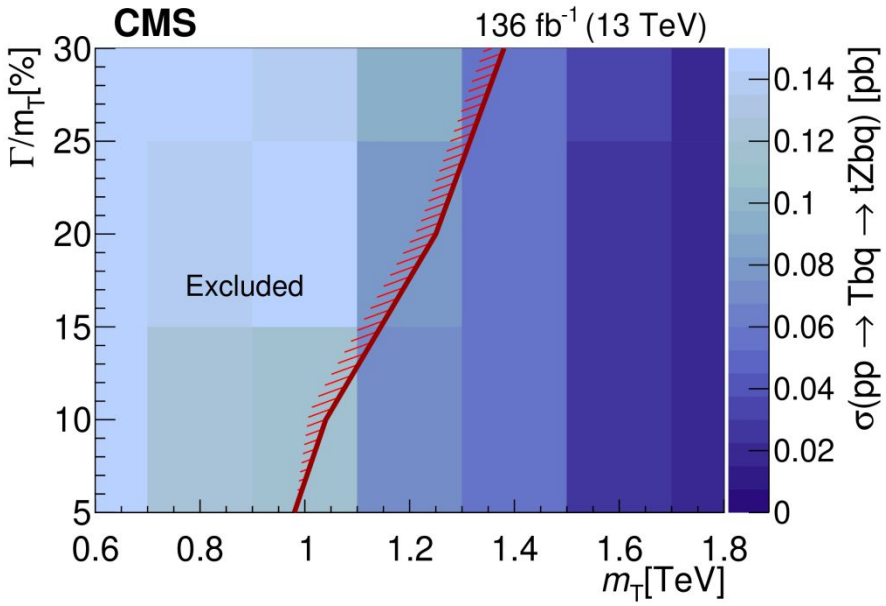
Excess in data observed in resolved category, 2.4 σ for $m_T = 1.4$ TeV




**Resonance of Negligible width**

**Limit as a function of mass and resonance width**

$m_T$ <1.4 TeV excluded for $\Gamma/ m_T = 0.3$



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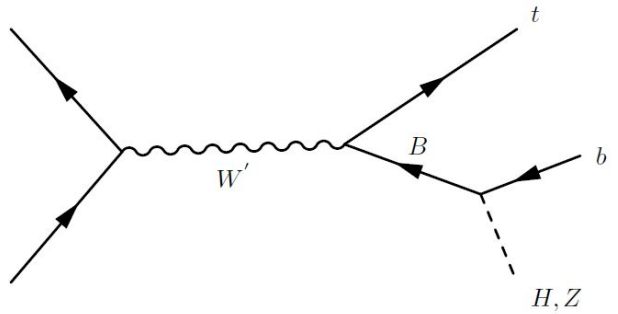
# Search for W'->tB/Tb full hadronic

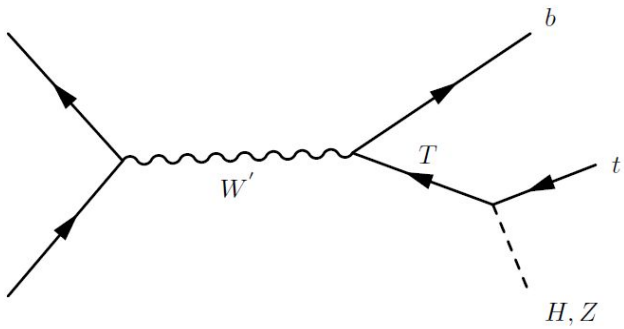
Full Run2 result for single production, 137 $fb^{-1}$ , considering different decay of of the W' boson to VLQ, depending on the ratio $m_{W'}/m_{VLQ}$

B2G-20-002




Signal selection:

- 2 high $p_T$ wide jets in the final state for Z/H and top tagging
- $H_T$ > 1000 GeV
- High $p_T$ narrow jet is b-tagging
- No overlap between the final state jets (t,b,H/Z)




**ΔR(H/Z,t)>1.6**

**ΔR(H/Z/t,b)>1.2**

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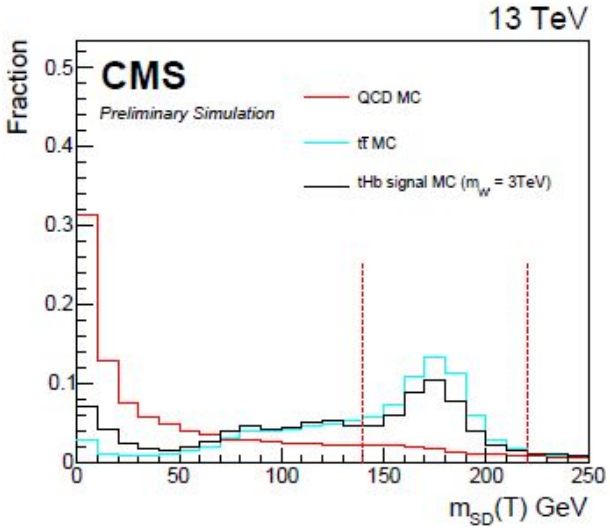
# Search for W'->tB/Tb full hadronic

Signal jets tagging to distinguish from the SM multijet background:

- Top: $m_{SD}$ under the top peak, $\text{ImageTop}_{MD}$

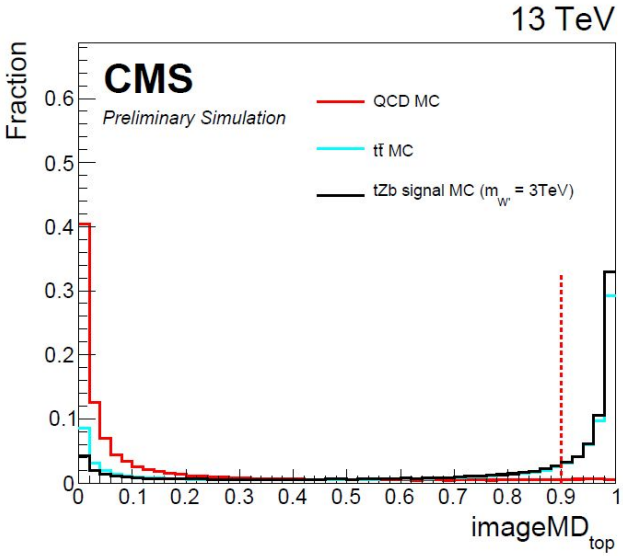
- Higgs: $m_{SD}$ under the Higgs peak, double b-tag substructure

- Z: $m_{SD}$ under the Z peak, 2-prong $\tau_{21}$




Selection regions:

| Label | Tag | Discriminator | Mass |
|---|---|---|---|
| Tight | H | $0.6 < \text{Dbtag}$ | $105 < m_{SD}(H) < 140\,\text{GeV}$ |
| | Z | $\tau_{21} < 0.45$ | $65 < m_{SD}(Z) < 105\,\text{GeV}$ |
| | t | $0.9 < \text{imageTop}_{MD}$ | $140 < m_{SD}(t) < 220\,\text{GeV}$ |
| Medium | H | $0.0 < \text{Dbtag} < 0.6$ | $105 < m_{SD}(H) < 140\,\text{GeV}$ |
| | Z | $0.45 < \tau_{21} < 0.6$ | $65 < m_{SD}(Z) < 105\,\text{GeV}$ |
| | t | $0.3 < \text{imageTop}_{MD} < 0.9$ | $140 < m_{SD}(t) < 220\,\text{GeV}$ |
| Loose | H | $-1.0 < \text{Dbtag} < 0.0$ | $5 < m_{SD}(H) < 30\,\text{GeV}$ |
| | Z | $0.6 < \tau_{21} < 1.0$ | $5 < m_{SD}(Z) < 30\,\text{GeV}$ |
| | t | $0.0 < \text{imageTop}_{MD} < 0.3$ | $30 < m_{SD}(t) < 65\,\text{GeV}$ |



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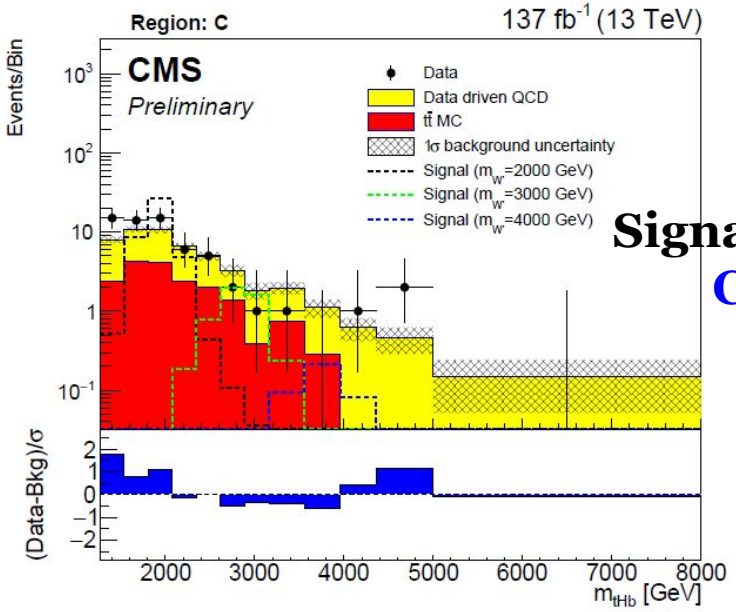
# Search for W'->tB/Tb full hadronic

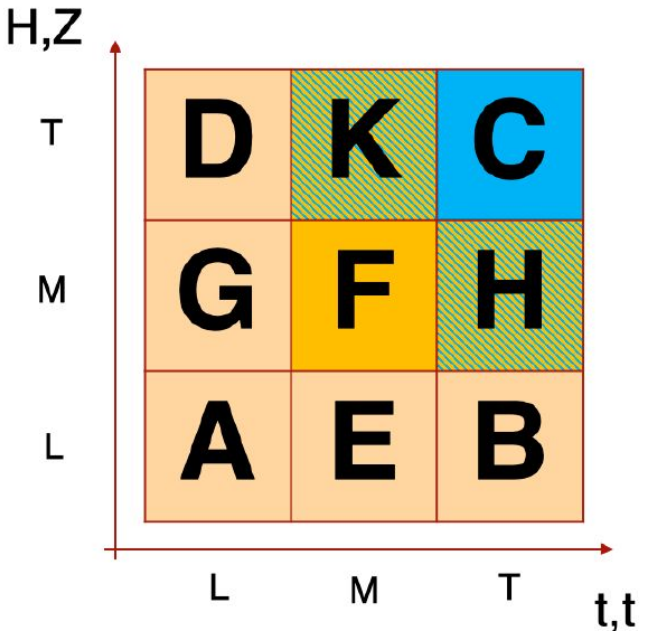
The main SM backgrounds are ttbar and QCD multijet:

•ttbar: template from MC simulation

• QCD multijet: data-driven method
Transfer function TF($p_T$,η) derived in top-antitag region




**Signal Region C tHb**




Extraction of QCD component in the signal region C:

$$TF(p_T,\eta) = (B_{Data}-B_{tt})/(A_{Data}-A_{tt})$$

$$C_{QCD} \simeq (D_{Data}-D_{tt}) \times TF(p_T,\eta)$$

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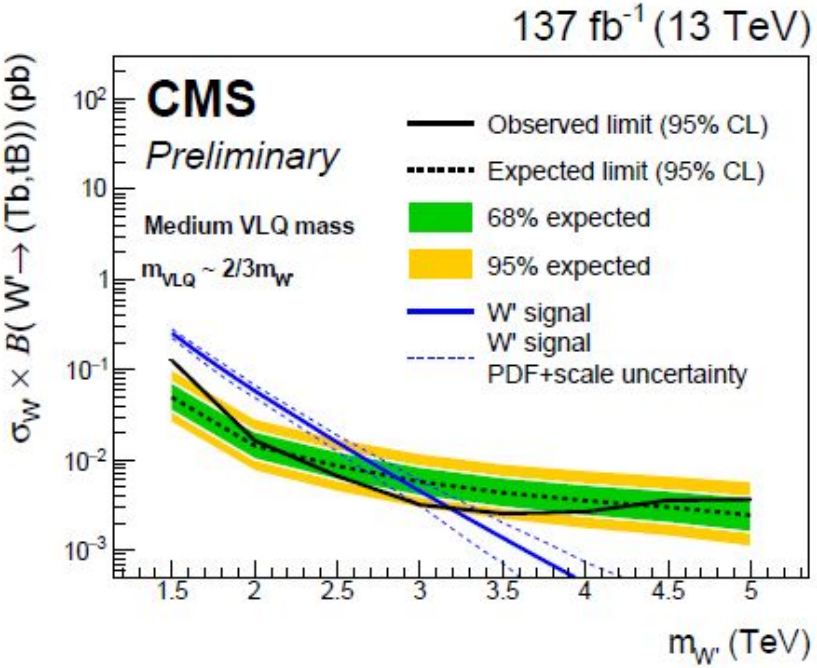
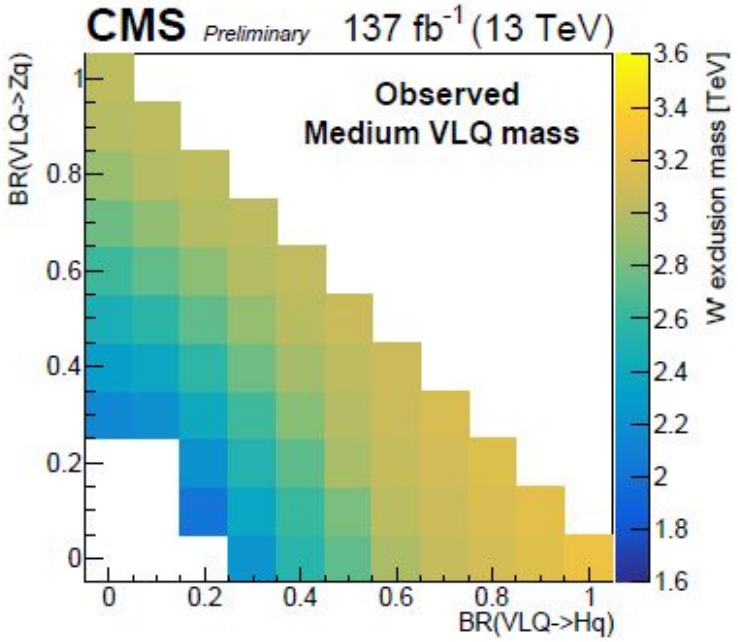
# Search for W'->tB/Tb full hadronic

**Limit as a function of W' mass**

$m_{W'}$ >3.2 TeV with $m_{VLQ} \approx 2/3\ m_{W'}$




**W' mass limit as a function of BR(VLQ->Zq) vs BR(VLQ->Hq)**



# Conclusions

- Presented recent results on the searches for vector-like quarks (VLQ) at the CMS detector at LHC
  - LHC Run II collision data, 13 TeV
- No evidence of VLQs
  - Stringent exclusion limits on VLQ mass provided by pair production searches.
  - First result single production of VLQ T decaying to a top quark and Z boson, with the Z boson decaying to neutrinos, providing stringent mass exclusion.
  - Limit on the VLQ mass depending on BR, considering W' boson decaying to a VLQ in all hadronic final state.

# THANK YOU!

# BACKUP

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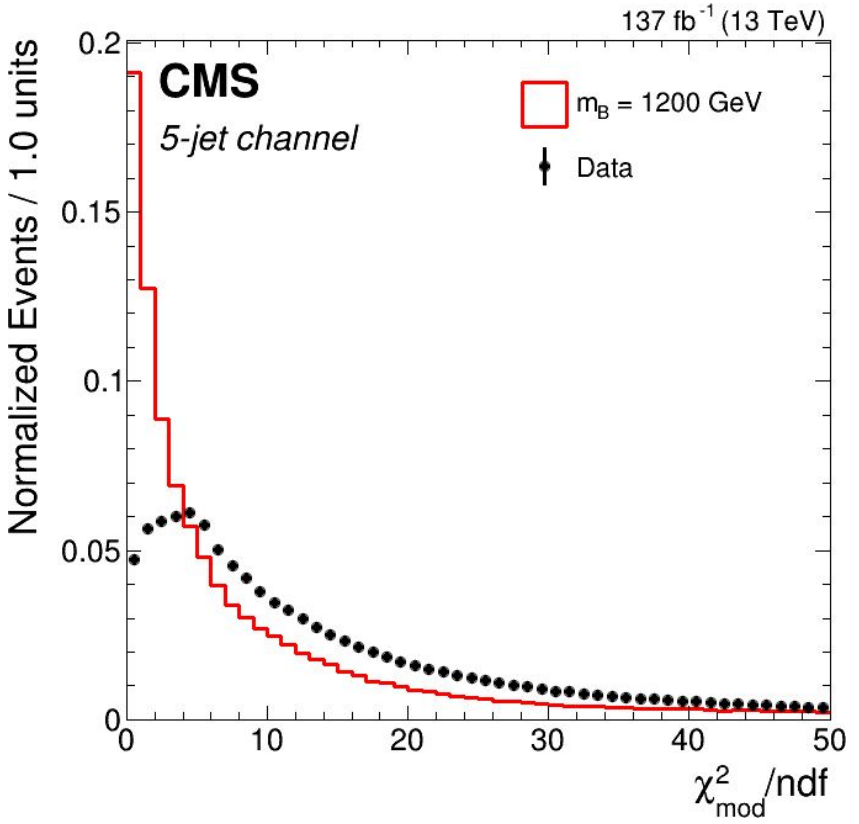
# Search for BB in full hadronic

$\chi^2$-like metrics for the reconstruction of the decay channel and category assignment:

• invariant mass of the dijet or wide jet compatible with the boson mass and equal invariant mass of the reconstructed B candidates




5-jet events:

$$\chi^2_{\text{mod}} = \frac{(m_{dijet} - \overline{m}_{dijet})^2}{\sigma^2_{m_{dijet}}} + \frac{(m_{merged} - \overline{m}_{merged})^2}{\sigma^2_{merged}} + \frac{(m_{\Delta VLQ} - \overline{m}_{\Delta VLQ})^2}{\sigma^2_{\Delta VLQ}}$$

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# Search for BB in full hadronic

Systematics uncertainties

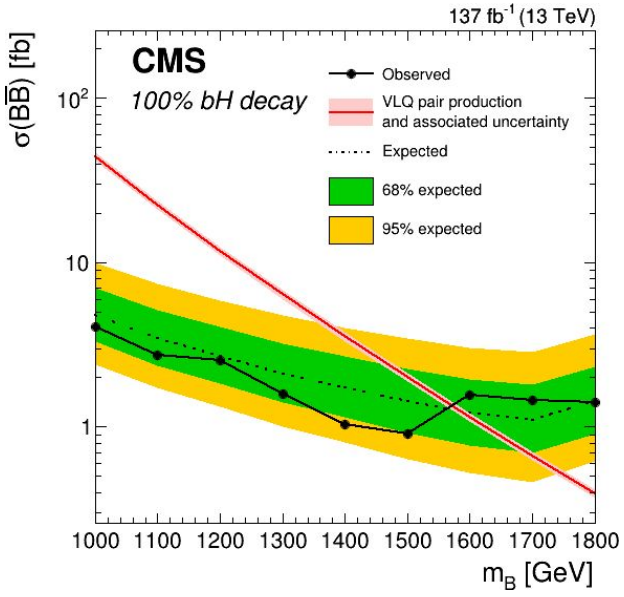
In common →

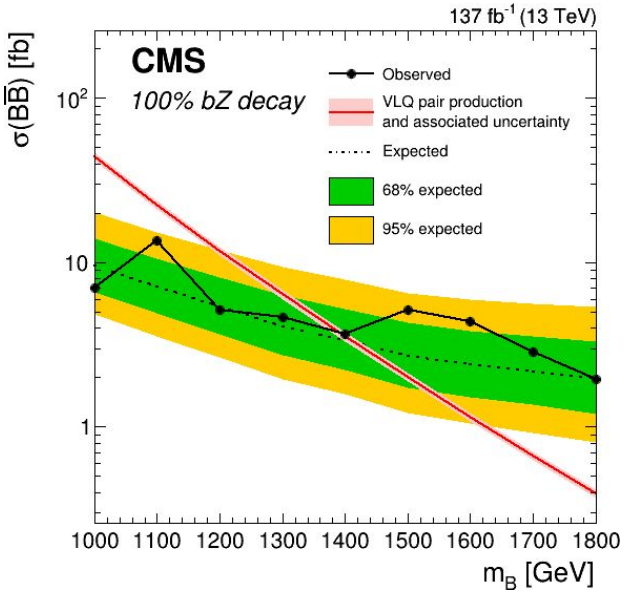
| Type | Signal/Background | Uncertainty |
|---|---|---|
| Integrated luminosity | Signal | 1.8% |
| Trigger efficiency | Signal | 0.02% |
| Choice of fit function | Background | 4.9% |

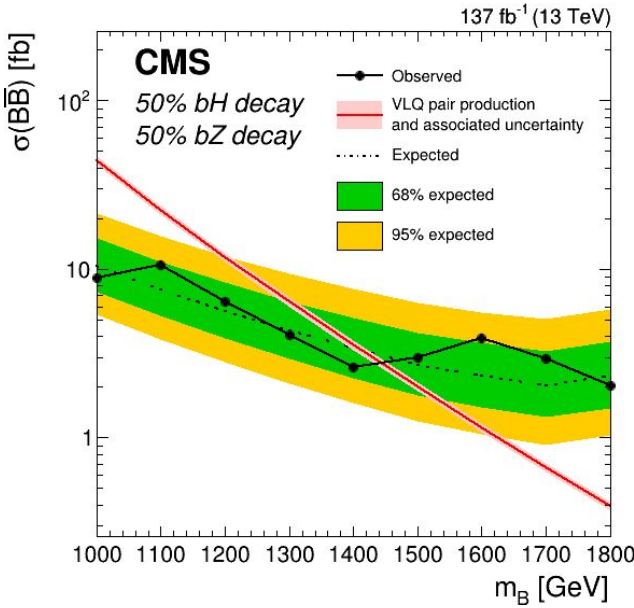
bHbH mode →

| Type | Signal/Background | Rate/Shape | 4 jets | 5 jets | 6 jets |
|---|---|---|---|---|---|
| | | *bHbH event mode* | | | |
| Background fit $p_0$ | Background | Shape | 59% | 14% | 13% |
| Background fit $p_1$ | Background | Shape | 78% | 18% | 16% |
| BJTF $m$ dependence $p_0$ | Background | Shape | 1.3% | 5.9% | 4.5% |
| BJTF $m$ dependence $p_1$ | Background | Shape | 19% | 25% | 17% |
| Low-mass BJTF | Background | Rate | 34% | 9.7% | 11% |
| Jet tag scale factors | Signal | Shape | 16% | 15% | 17% |
| Jet energy scale | Signal | Shape | 4.0% | 5.3% | 6.4% |
| Jet energy resolution | Signal | Shape | 2.4% | 1.5% | 1.6% |
| Pileup | Signal | Shape | 28% | 28% | 27% |
| PDF | Signal | Rate | 1.5% | 1.5% | 1.5% |

# Search for BB in full hadronic



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# Single T->tZ(νν)

Systematics uncertainties

| Source | Effect | Correlation | Type |
|---|---|---|---|
| Luminosity | 2.3–2.5% | Uncorrelated | yield |
| Pileup | 0.2–3% | Correlated | yield |
| b tagging | 0.5–1.2% | Correlated | yield |
| top tagging | 9–10% | Correlated | yield, shape |
| W tagging | 7–8% | Correlated | yield, shape |
| Trigger efficiency | 1–3% | Correlated | yield, shape |
| ECAL L1 trigger inefficiency | 0.2–3% | Uncorrelated | yield, shape |
| Jet energy scale | 2–18% | Correlated | yield, shape |
| Jet energy resolution | 2–5% | Correlated | yield, shape |
| PDF | 1–5% | Correlated | yield |
| $\mu_R$, $\mu_F$ | 10–30% | Correlated | yield, shape |
| Background scale factors | 5–50% | Uncorrelated | yield, shape |

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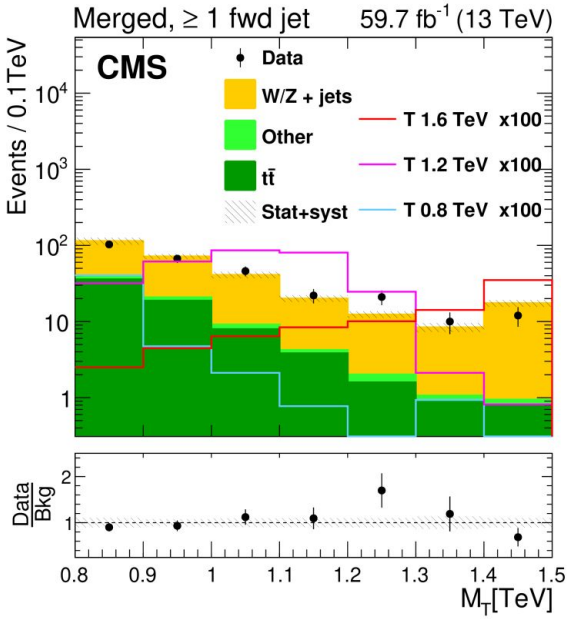
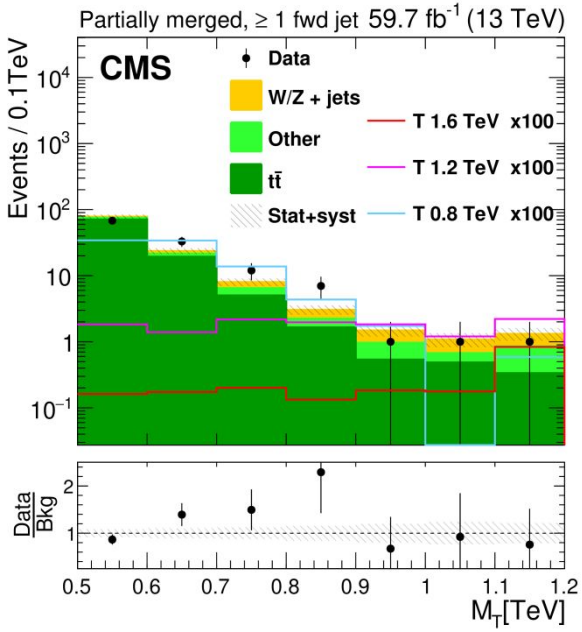
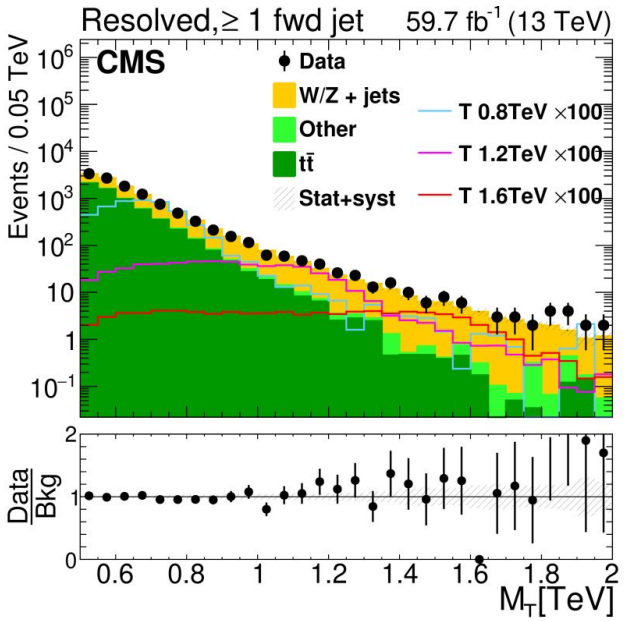
# Single T->tZ(νν)

**$M_T$ distribution in the signal region:**

- **1 fwd jet**
- **1 jet merged, partially merged or resolved**



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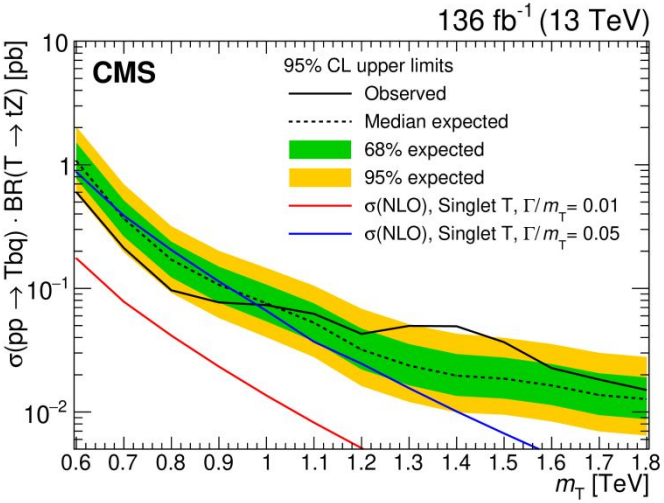
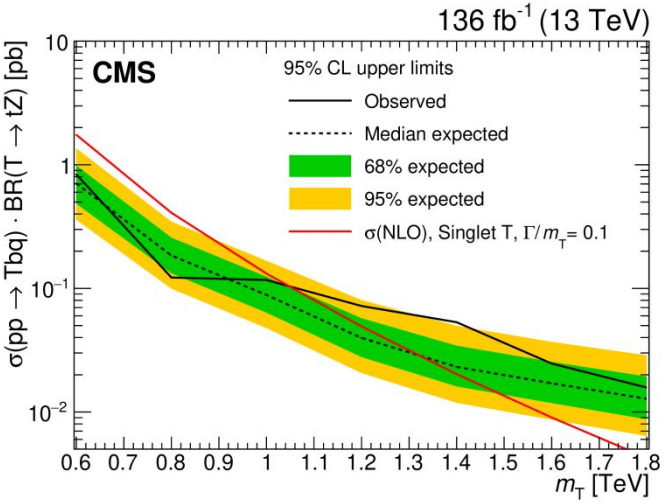
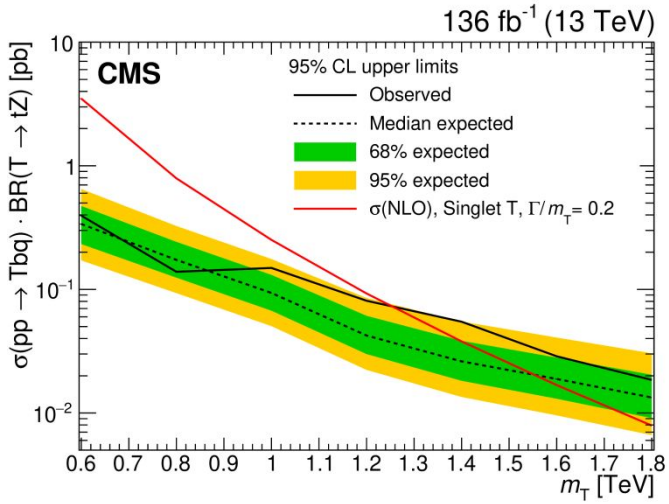
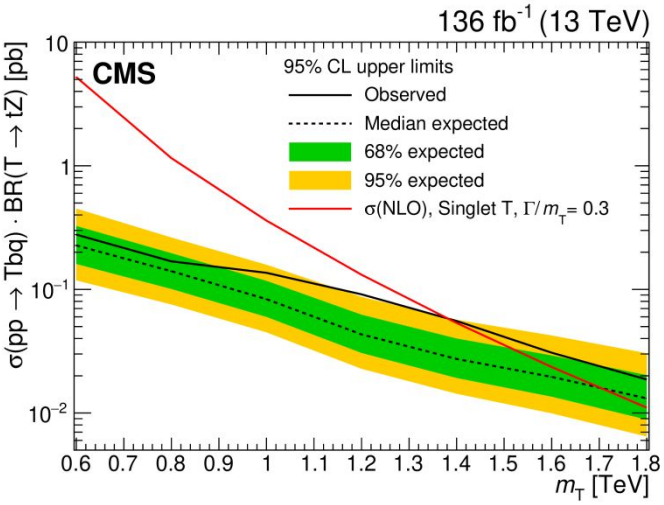
# Single T->tZ(νν)



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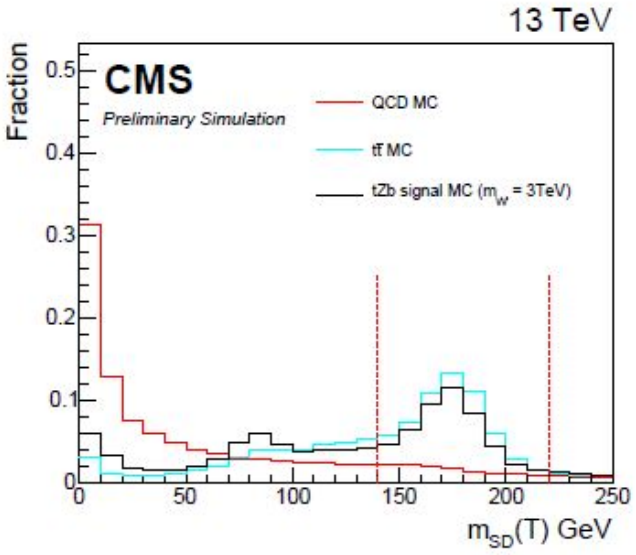
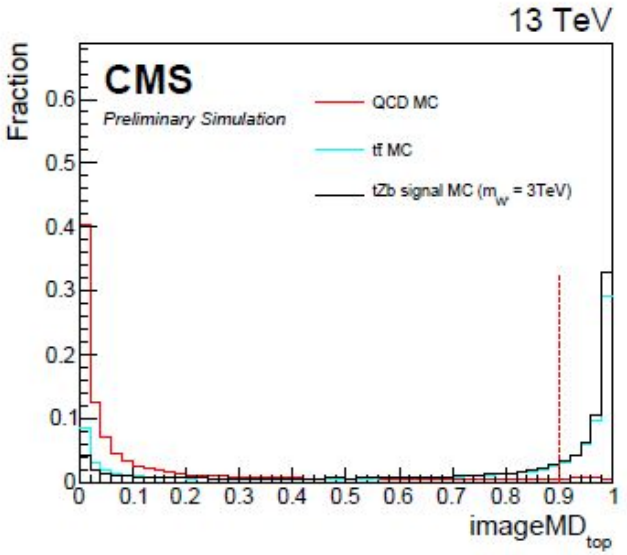
# Search for W'->tB/Tb full hadronic

| Label | Tag | Discriminator | Mass |
|---|---|---|---|
| Tight | H | $0.6 < \text{Dbtag}$ | $105 < m_{SD}(H) < 140\,\text{GeV}$ |
| | Z | $\tau_{21} < 0.45$ | $65 < m_{SD}(Z) < 105\,\text{GeV}$ |
| | t | $0.9 < \text{imageTop}_{MD}$ | $140 < m_{SD}(t) < 220\,\text{GeV}$ |
| Medium | H | $0.0 < \text{Dbtag} < 0.6$ | $105 < m_{SD}(H) < 140\,\text{GeV}$ |
| | Z | $0.45 < \tau_{21} < 0.6$ | $65 < m_{SD}(Z) < 105\,\text{GeV}$ |
| | t | $0.3 < \text{imageTop}_{MD} < 0.9$ | $140 < m_{SD}(t) < 220\,\text{GeV}$ |
| Loose | H | $-1.0 < \text{Dbtag} < 0.0$ | $5 < m_{SD}(H) < 30\,\text{GeV}$ |
| | Z | $0.6 < \tau_{21} < 1.0$ | $5 < m_{SD}(Z) < 30\,\text{GeV}$ |
| | t | $0.0 < \text{imageTop}_{MD} < 0.3$ | $30 < m_{SD}(t) < 65\,\text{GeV}$ |



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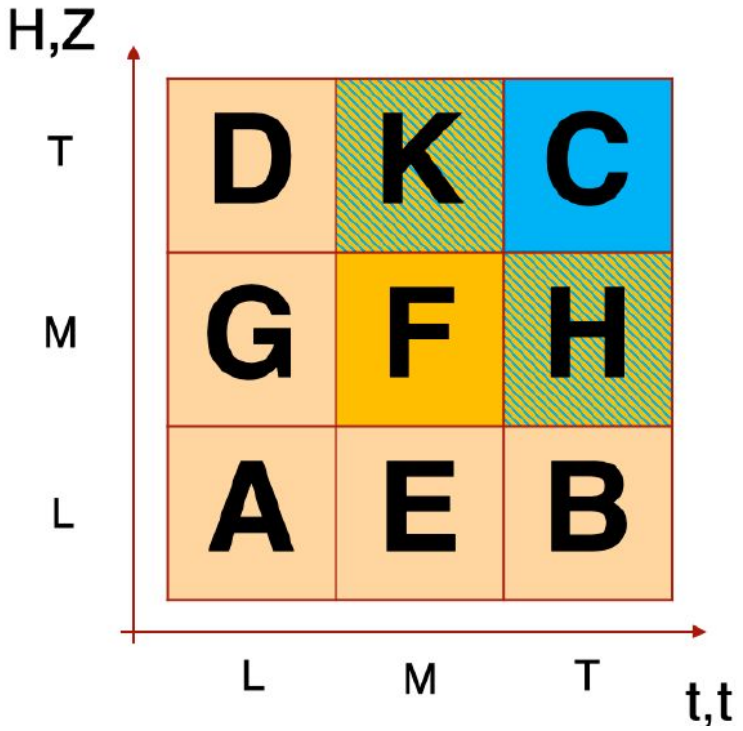
# Search for W'->tB/Tb full hadronic

$$TF(p_T,\eta) \equiv (B_{data} - B_{t\bar{t}})/(A_{data} - A_{t\bar{t}}),$$
$$TF_v(p_T,\eta) \equiv (E_{data} - E_{t\bar{t}})/(A_{data} - A_{t\bar{t}}),$$
$$C_{qcd} \simeq (D_{data} - D_{t\bar{t}}) \times TF(p_T,\eta),$$
$$H_{qcd} \simeq (G_{data} - G_{t\bar{t}}) \times TF(p_T,\eta),$$
$$K_{qcd} \simeq (D_{data} - D_{t\bar{t}}) \times TF_v(p_T,\eta),$$
$$F_{qcd} \simeq (G_{data} - G_{t\bar{t}}) \times TF_v(p_T,\eta).$$

**Signal region: C**



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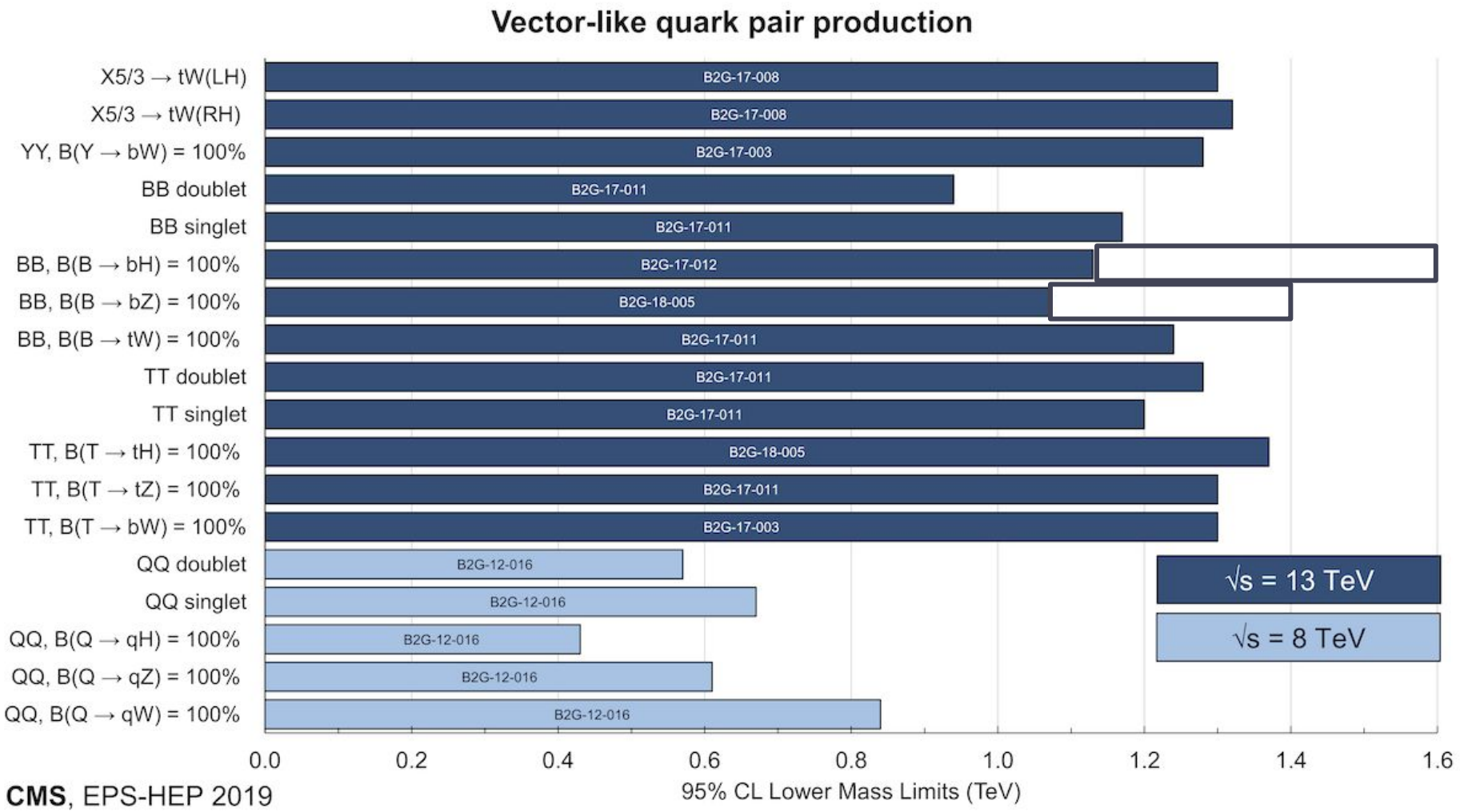
# Search for W'->tB/Tb full hadronic

**Systematics uncertainties**

| Source | Variation | Process |
|---|---|---|
| Integrated luminosity | ±2.3-2.5% | signal, $t\bar{t}$, single top |
| Top jet tagging | $\pm1\sigma(p_T)$ | signal, $t\bar{t}$, single top |
| Jet energy scale | . $\pm1\sigma(p_T,\eta)$ | signal, $t\bar{t}$, single top |
| Jet energy resolution | $\pm1\sigma(p_T,\eta)$ | signal, $t\bar{t}$, single top |
| Jet mass scale | $\pm1\sigma(m_{SD})$ | signal, $t\bar{t}$, single top |
| Jet mass resolution | $\pm1\sigma(m_{SD})$ | signal, $t\bar{t}$, single top |
| B tagging | $\pm1\sigma(p_T)$ | signal, $t\bar{t}$, single top |
| B mistagging | $\pm1\sigma(p_T)$ | signal, $t\bar{t}$, single top |
| Dbtag | $\pm1\sigma(p_T)$ | signal |
| Dbtag mistagging | $\pm1\sigma(p_T)$ | signal, $t\bar{t}$, single top |
| W tagging | $\pm1\sigma(p_T)$ | signal |
| Pileup | $\pm1\sigma$ ($\sigma_{mb}$) | signal,$t\bar{t}$, single top |
| PDF,$\alpha_s$ | $\pm1\sigma$ | signal, single top |
| $Q^2$ | $\pm1\sigma$ | signal, single top |
| ISR/FSR | $\pm1\sigma$ | single top |
| $t\bar{t}$ normalization | $\pm1\sigma(H_T)$ | $t\bar{t}$ |
| trigger | $\pm1\sigma(H_T)$ | signal, $t\bar{t}$, single top |
| $TF(p_T,\eta)$ | $\pm1\sigma(p_T,\eta)$ | QCD |
| $t\bar{t}$ contamination | $\pm1\sigma(p_T,\eta)$ | QCD |

# VLQ Pair Production Summary



# VLQ Single Production Summary