LIO international workshop on Vector-like Fermions

Search for vector like fermions at CMS

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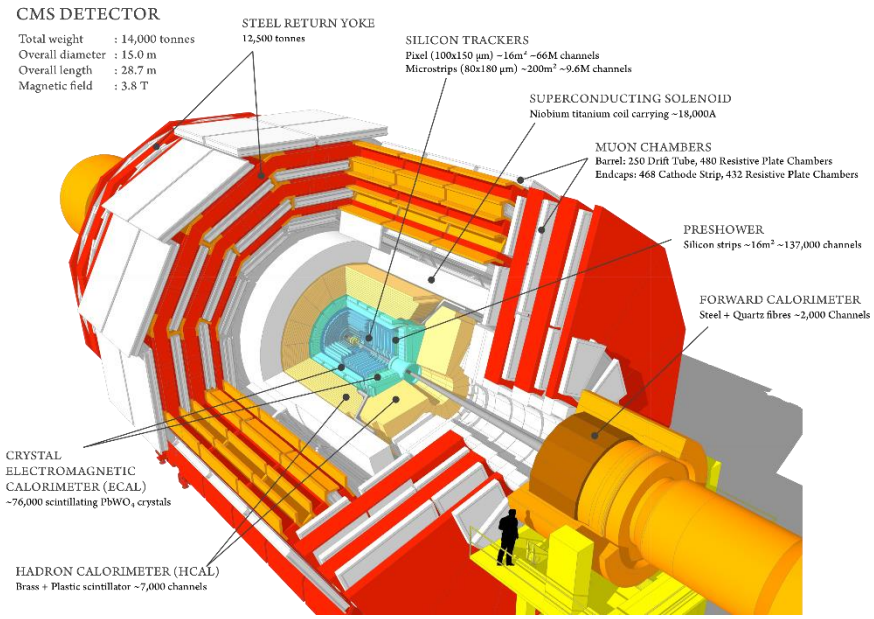
Introduction

- The **CMS experiment** has an extensive physics program devoted to the **search of vector-like quarks** since Run 1
- The physics group dedicated to VLQ (between other physics models) is the B2G group, i.e. **Beyond 2nd Generation**: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- Several analyses focusing on both **single and pair production**
- **In the next:**
  - discussion on how we present VLQ results in CMS
  - experimental strategy
  - selection of most recent analyses

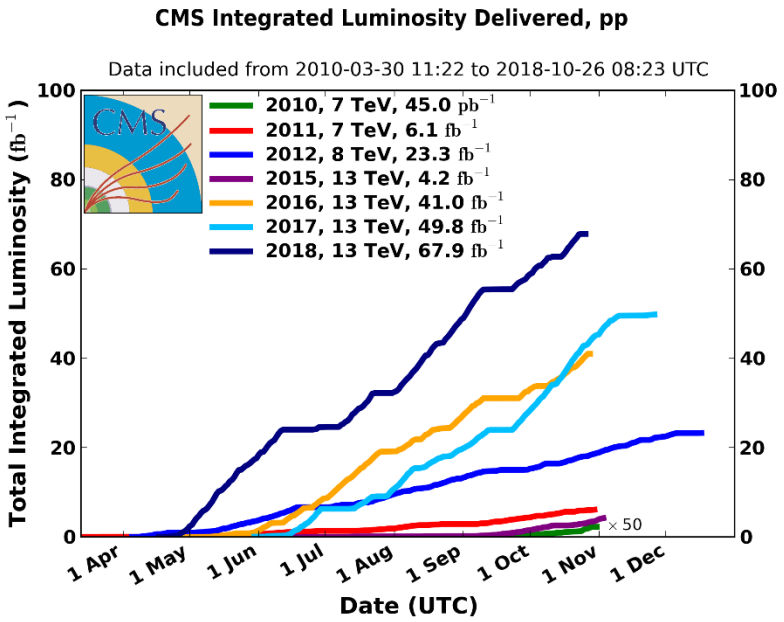
CMS detector



- General-purpose detector: investigate largest possible physics range
- Hermetic, many layers, and highly granular
- Designed to precisely reconstruct charged leptons, photons, hadronic jets, and missing energy

Delivered luminosity per year:

- 6 fb^{-1} @ 7 TeV (2011)
- 23 fb^{-1} @ 8 TeV (2012)
- 4 fb^{-1} @ 13 TeV (2015)
- 36 fb^{-1} @ 13 TeV (2016)
- 42 fb^{-1} @ 13 TeV (2017)
- 60 fb^{-1} @ 13 TeV (2018)



Vector-like quarks

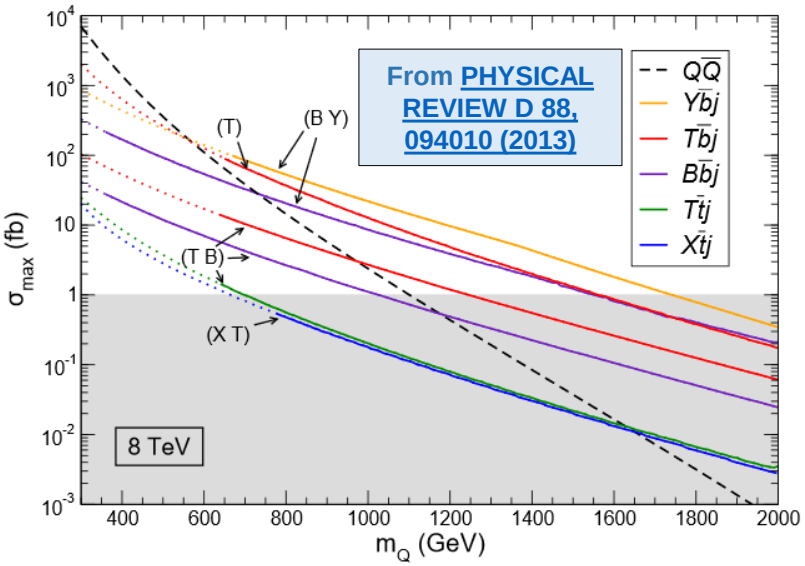
- Discovery of Higgs boson motivates **search for new physics**
- Possible explanations given by: little Higgs models, extra dimensions models, composite Higgs models, etc.
- These theories predict existence of **heavy vector-like quarks** (VLQ)
- Hypothetical new spin-1/2 particles: left- and right-handed chiralities transform in the same way under the standard model symmetry group

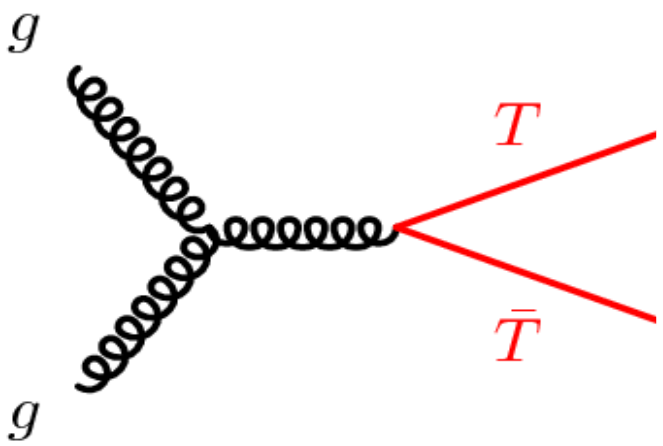
	$T \quad B$	$\begin{pmatrix} X \\ T \end{pmatrix} \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix} \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$ multiplet	1	2	3
Charge	2/3 -1/3	$\begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix} \begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix} \begin{pmatrix} -1/3 \\ -4/3 \end{pmatrix}$	$\begin{pmatrix} 5/3 \\ 2/3 \\ -1/3 \end{pmatrix} \begin{pmatrix} 2/3 \\ -1/3 \\ -4/3 \end{pmatrix}$

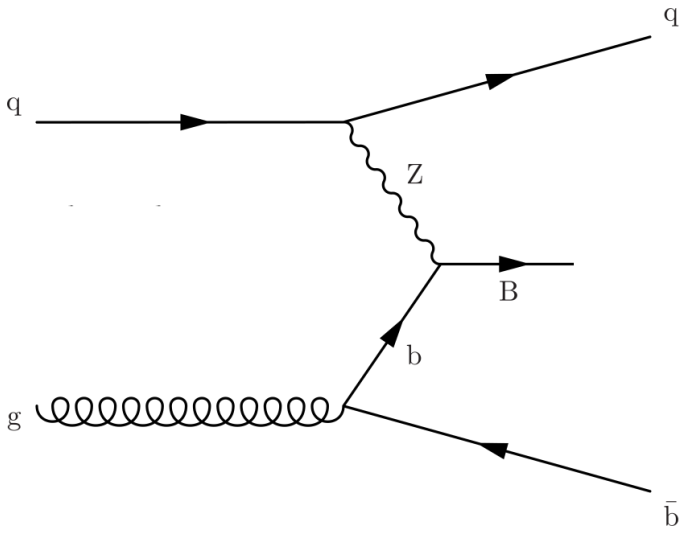
VLQ production

- **Pair-production**:
  strong mechanism, the cross section depends only on the **VLQ mass**
- **Single production**:
  electroweak mechanism, the cross section depends on **VLQ mass** and on its **couplings** with SM particles

Pair production cross section falls steeply with VLQ mass







VLQ decays

- Following decay modes are possible:
  - **T → Wb, Zt, and Ht**
  - **B → Wt, Zb, and Hb**
  - **X → Wt**
  - **Y → Wb**
- For single production, we use branching ratio of 25% or 50% (singlet or doublet scenario)
- For pair production, we scan over different branching ratios

VLQ at CMS

How do we look for VLQ at CMS?

Experimental point of view:

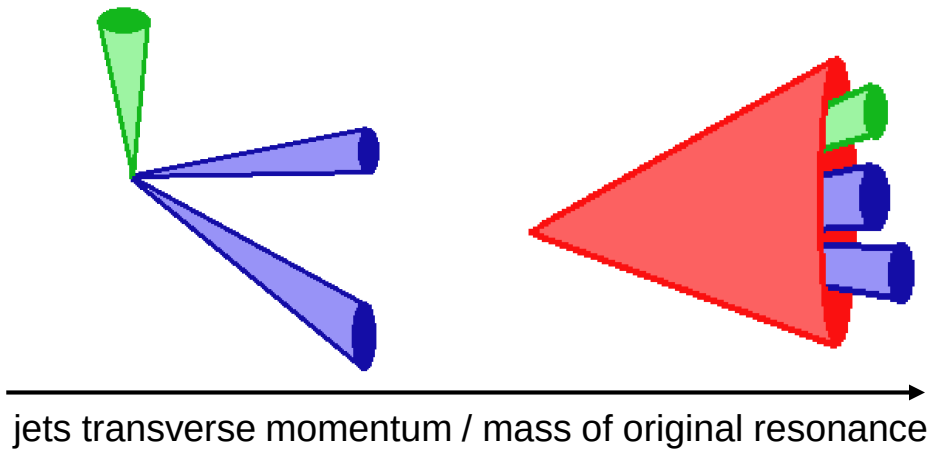
- VLQ are investigated at large mass, M(VLQ) ≥ 700 GeV
- W, Z, H and top, when decaying hadronically can be reconstructed as a single jet
- Investigation of **boosted topologies**

Theoretical interpretation:

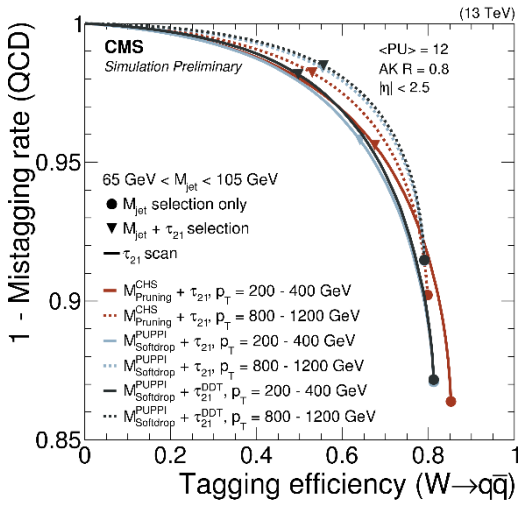
- Pair production → scan of **all possible BR**
- Single production → singlet and doublet hypotheses
  → study of the **VLQ width** (instead of the coupling)

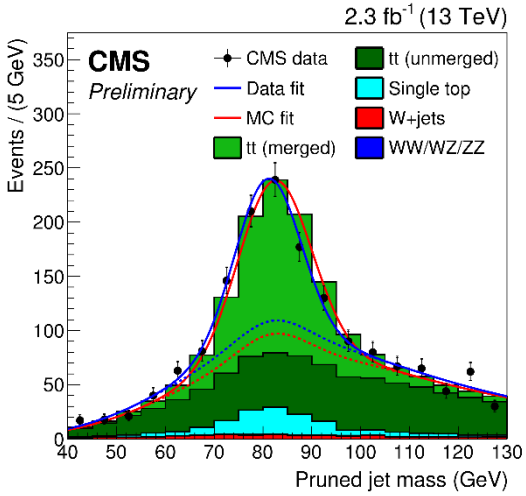
Reconstruction techniques

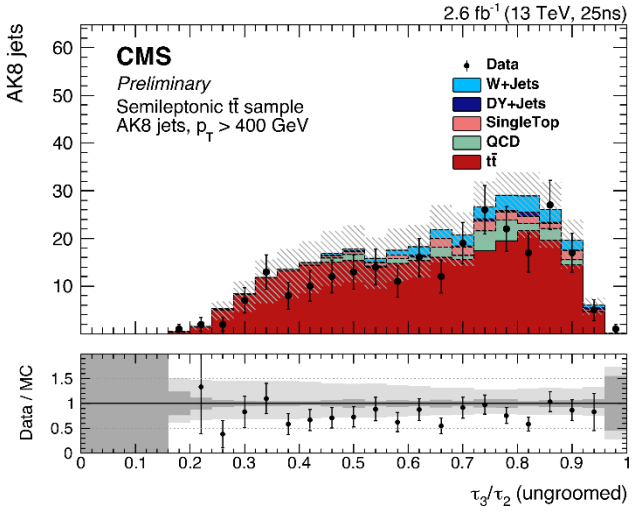
- Algorithms to tag **boosted** W/Z/H bosons and top quark decaying hadronically against QCD jets
- Usage of **wide jets** after *cleaning* from soft/far tracks (most likely not coming from V/top decay)
- **Jet substructure** to discriminate between 0/2/3 subjets inside the wide jet → N-subjettiness



CMS paper: *Jet algorithms performance in 13 TeV data*, link here



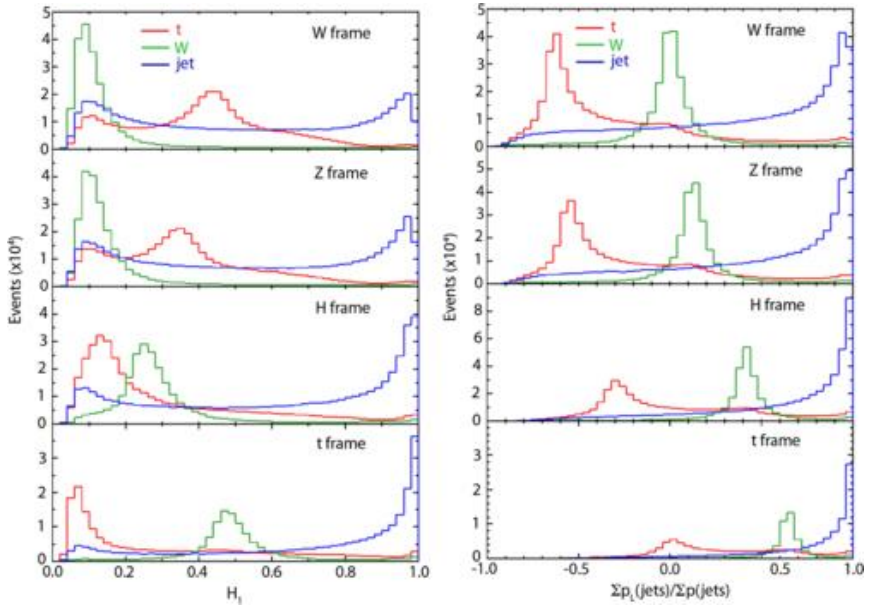


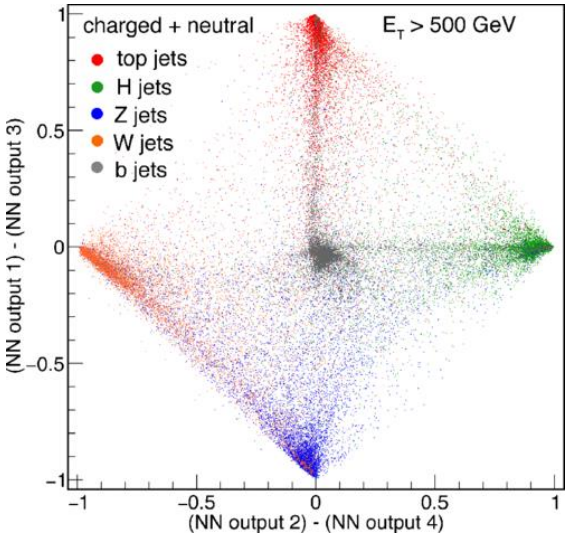


Reconstruction techniques

- **BEST algorithm** = Boosted Event Shape Tagger
- New approach in the identification of boosted massive particles: **machine learning algorithm**
- One single algorithm to classify a wide jet as: **W, Z, H, top, b or light quark jet**
- Main idea:
  - transformation to the **rest frame of the assumed particle**
  - use several variables to build a **neural network discriminant**

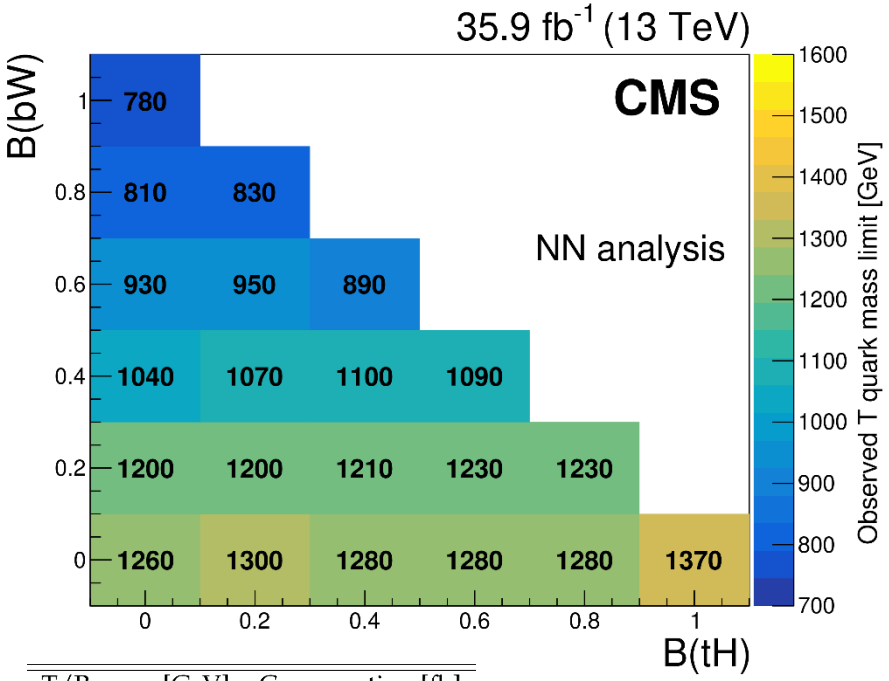
From Phys. Rev. D 94, 094027





Theoretical interpretation

How we show the results in CMS: VLQ pair production



T/B mass [GeV]	Cross section [fb]
700	455
800	196
900	90.4
1000	44.0
1100	22.0
1200	11.8
1300	6.4
1400	3.5
1500	2.0
1600	1.15
1700	0.67
1800	0.39

From B2G-18-005 (link here)

- Theoretical cross section calculated at NNLO with TOP++2.0 (link)
- Several combinations of branching ratio considered for the three possible decay

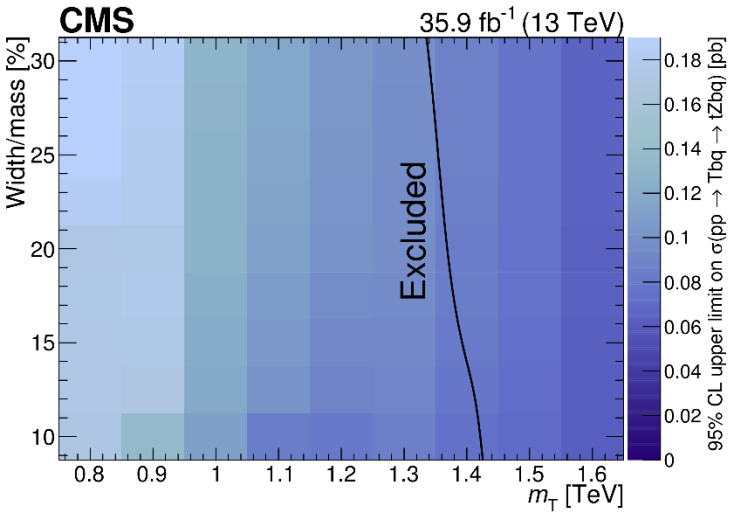
→ **Triangle plot**

Theoretical interpretation

How we show the results in CMS: VLQ single production

- Single production cross sections depends on the **coupling between the VLQ and the SM particles**
- Following the paper *"Single production of vector-like quarks with large width at the Large Hadron Collider"* (link here)
- We investigate the **VLQ width**, varying it between 1% and 30%

$$\sigma_S(C_1, C_2, M_Q, \Gamma_Q) = C_1^2\, C_2^2\, \hat{\sigma}_S(M_Q, \Gamma_Q)$$

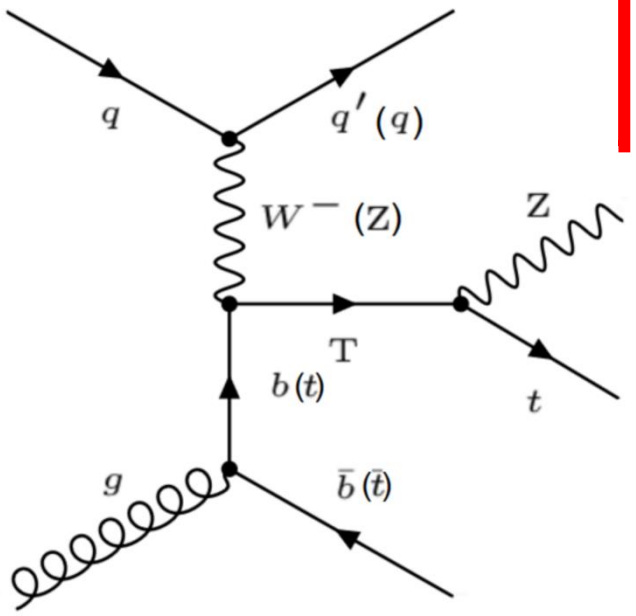


Separating the couplings from $\widehat{\sigma_S}$, which depends on VLQ mass and width

Single VLQ production

B2G-17-007: single T → tZ

- Single production of T quark, decaying to tZ with the **Z to leptons and the top quark to hadrons**
- The T quark can be singly produced with top or a b quark plus the *forward* quark
- **10 categories** defined, depending on the Z decays / top reconstruction / presence of forward jets



Leptonic Z: two muons **or** two electrons

Hadronic top:

a. fully-resolved topology → three ak4 jets are reconstructed

b. partially-merged topology → a W-jet and a b-jet are identified

c. fully-merged topology → decay products are within one top-jet

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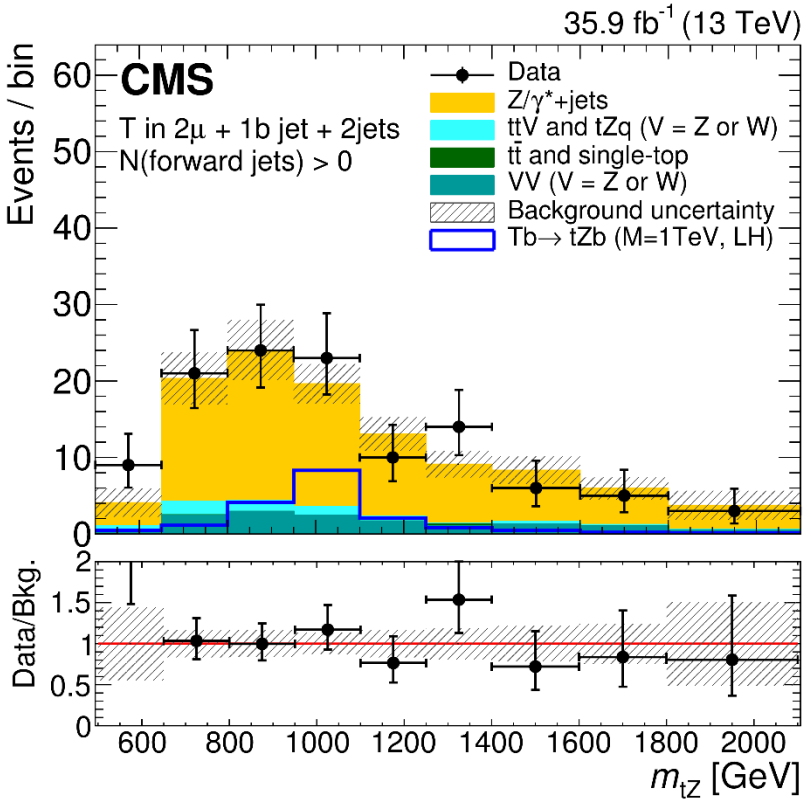
B2G-17-007: single T → tZ

- Optimized event selection: **ΔR(lep1, lep2) < 0.7** and **at least one b tagged jet**
- Main background given by **Z+jets events**
- In order to rely as little as possible on the MC, a predominantly data-driven prediction will be performed → **α-ratio method**

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

- Control region (cr) obtained asking for zero b tagged jets



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B2G-17-007: single T → tZ

- No deviations were observed relative to the expected standard model background
- T quark **width from negligible to 30%** of M(T) are studied
- Left-handed singlet T produced with a b quark excluded below the mass of 1.2 TeV (coupling of 0.5)
- Categories also sensitive to **Z' → Tt**: cross section above 0.13-0.06 pb excluded, for Z' (T) mass in the range [1.5, 2.5] TeV ([0.7, 1.5] TeV)

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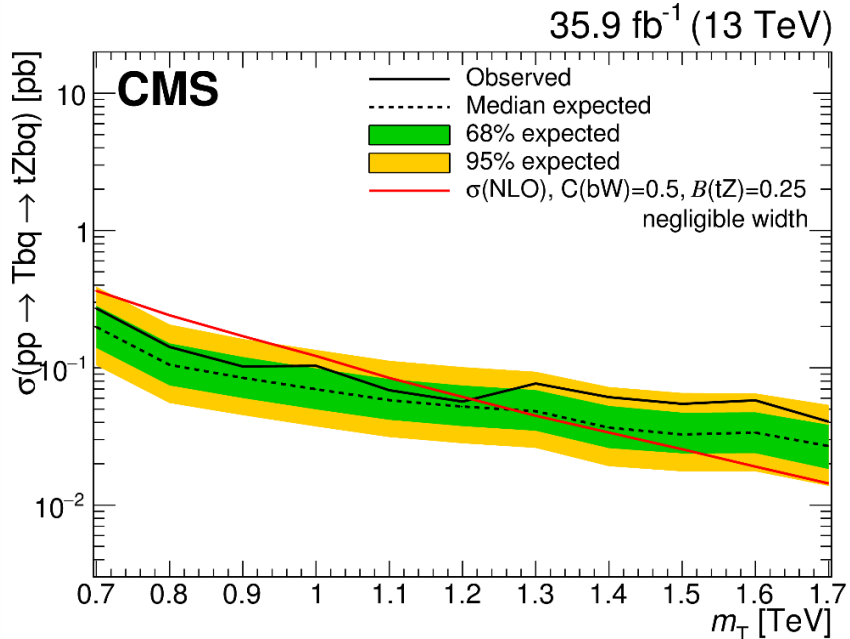
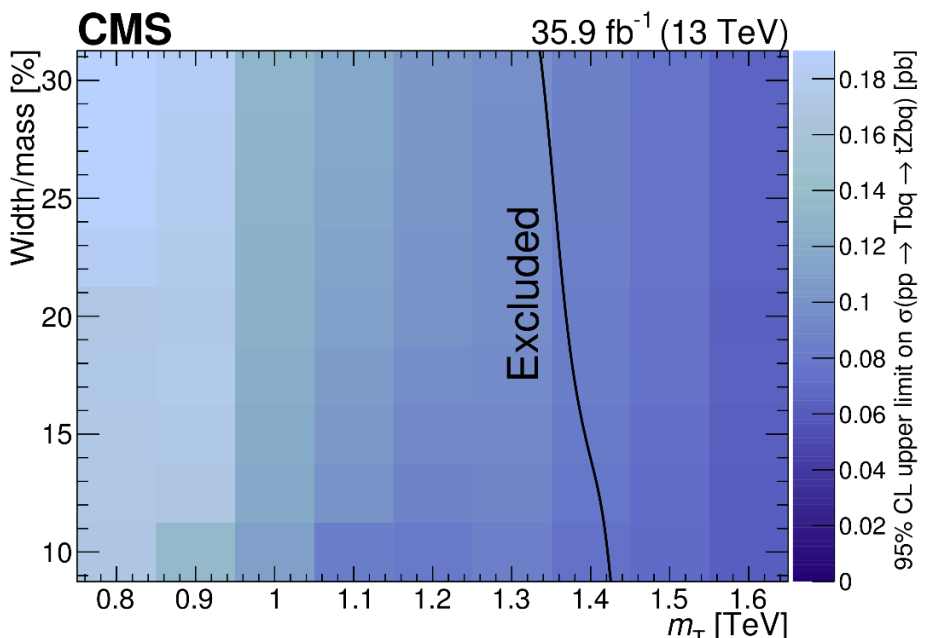
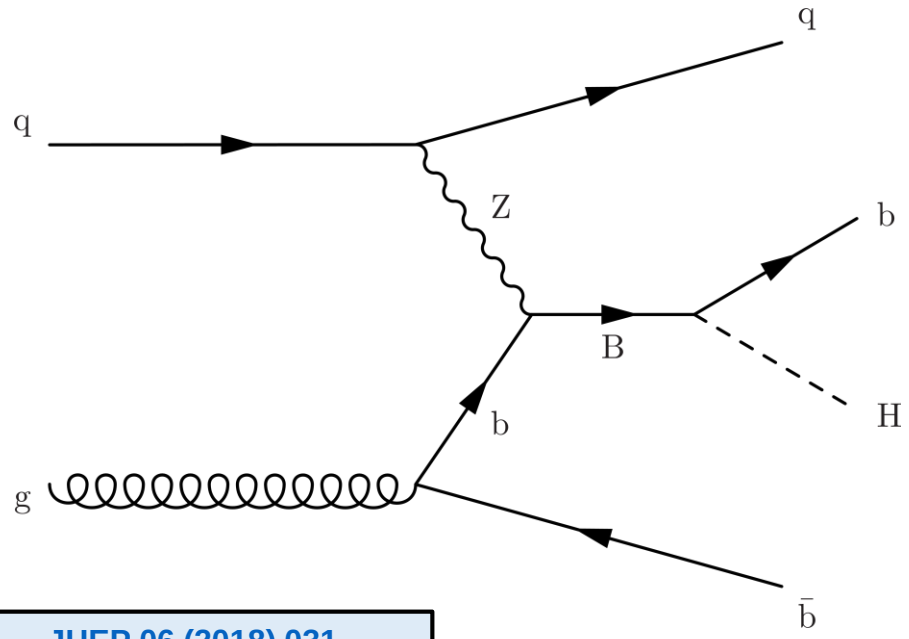
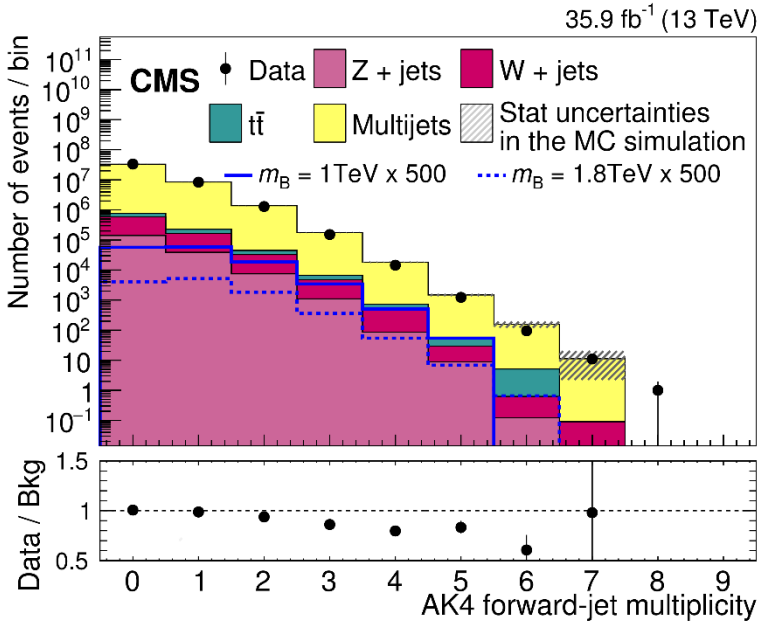




B2G-17-009: single B → bH

- Single production of **B quark**, decaying to **bH** with the H to bb
- Final state with:
  - **one high-pt b-tagged jet**
  - **one boosted Higgs to bb**
  - presence of **forward jets**
- Four categories: (low or high-mass) X (zero or at least one forward jet)





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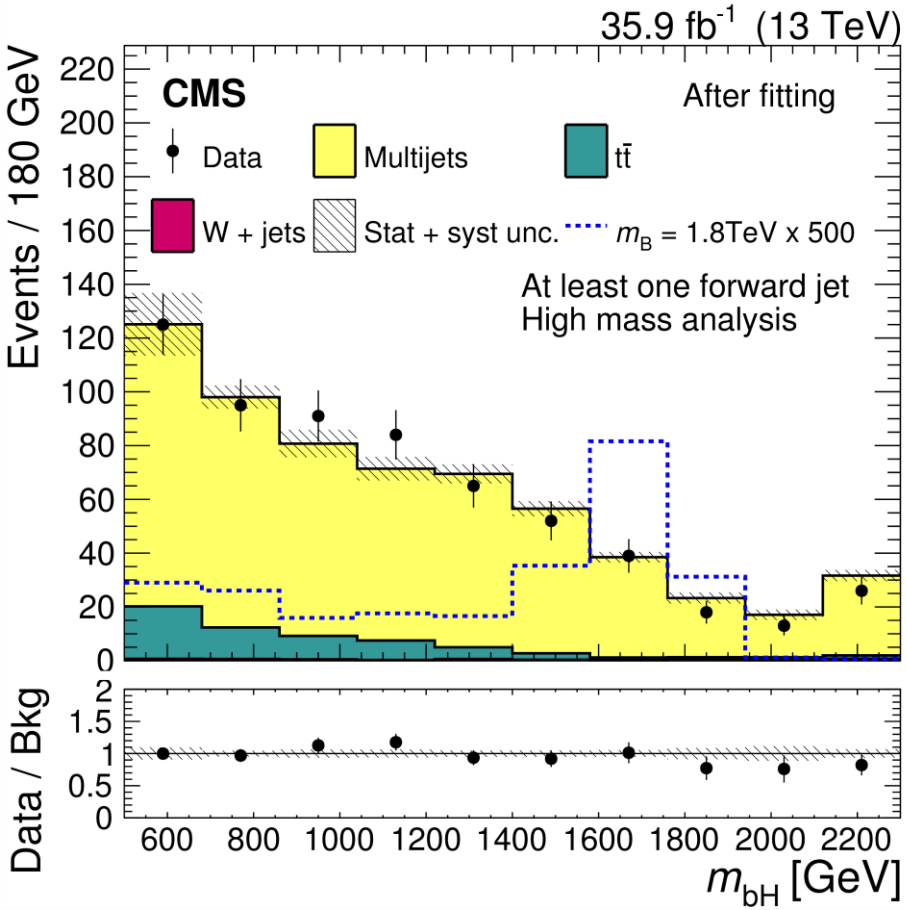
B2G-17-009: single B → bH



- **Main background from QCD multijets**
- Estimation done completely from data: ABCD method
- **Three control regions**, inverting the m_H and number of b tagged subjets cuts used to define the H to bb tagging

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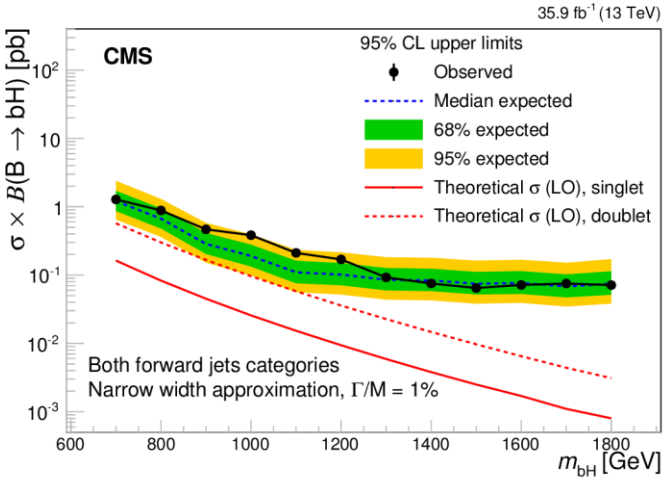
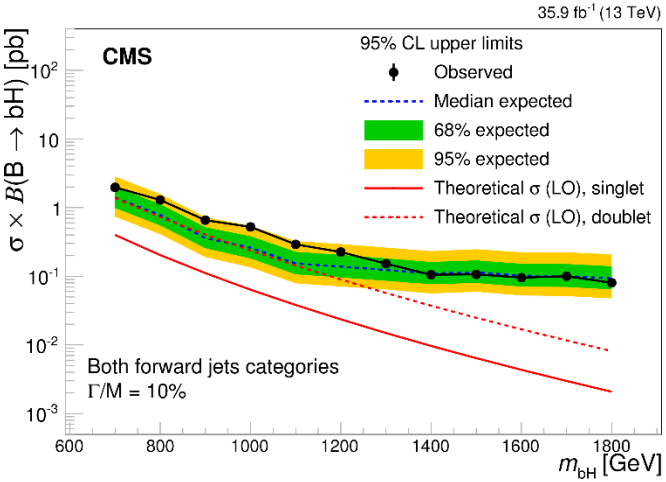
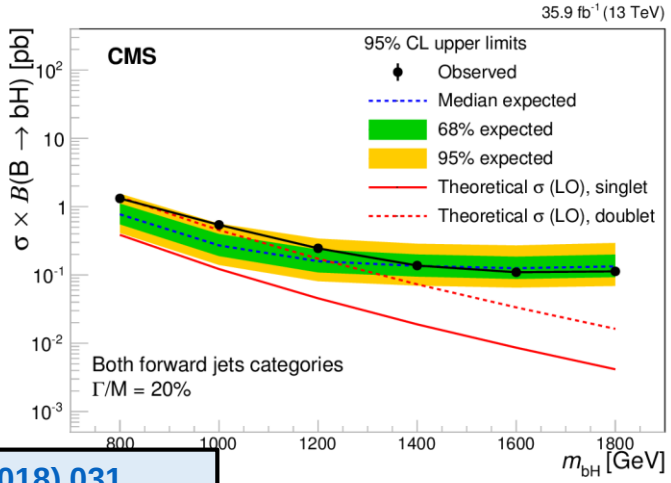
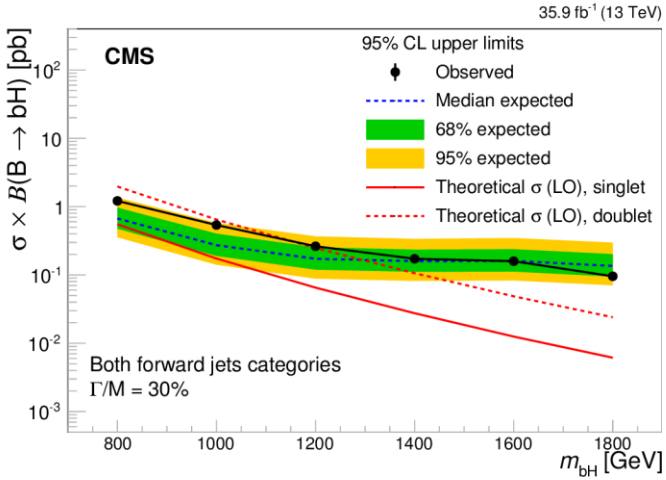
B2G-17-009: single B → bH

- Binned maximum likelihood fit performed to the m_{bH} distribution
- Observed distributions **consistent with background only hypothesis** in all the categories









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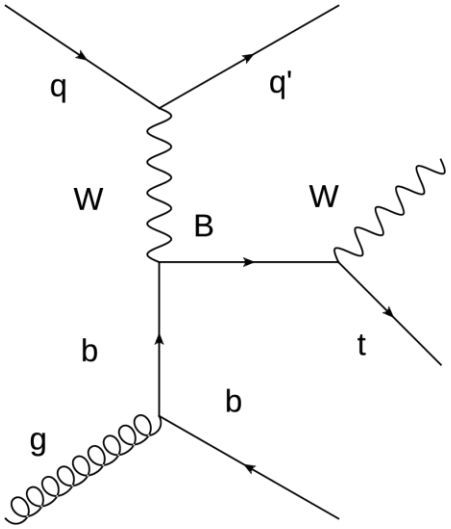
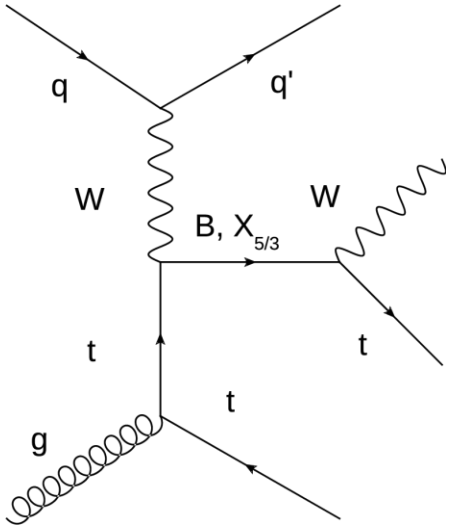
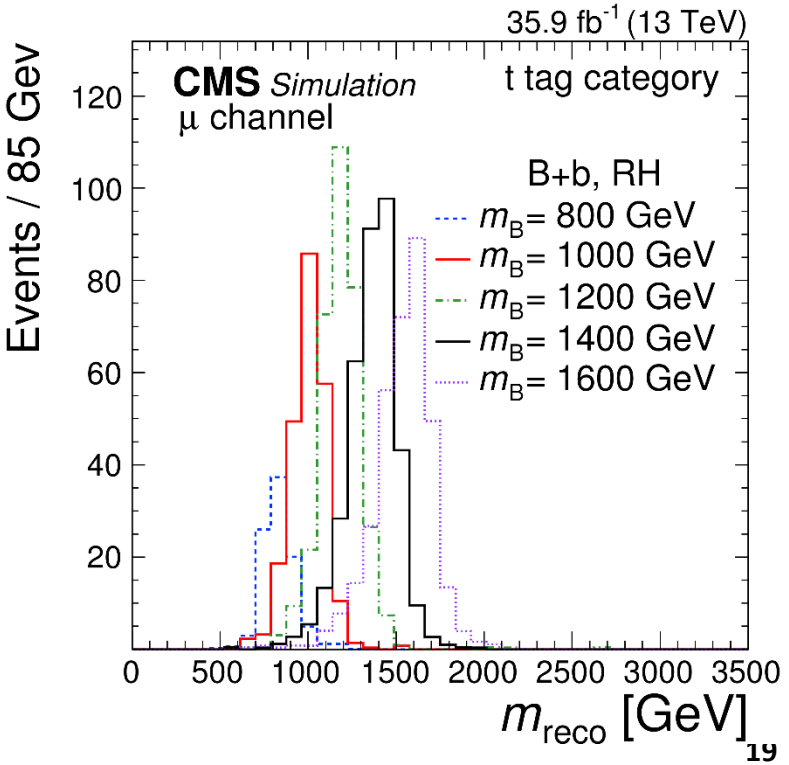
B2G-17-018: single B/X → tW

- Search for **single vector-like B or $X_{5/3}$** with the **VLQ decaying to tW**, with one muon or electron in the final state
- Ten categories depending on number of **top tagged jets**, **W tagged jets**, **b tagged jets**
- **Forward jet** required in the signal region
- Final discriminating variable is **m_{reco}**, mass of the reconstructed VLQ resonance







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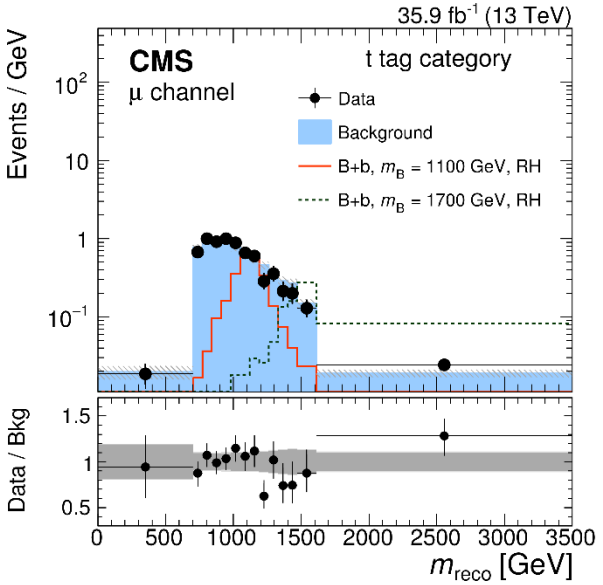
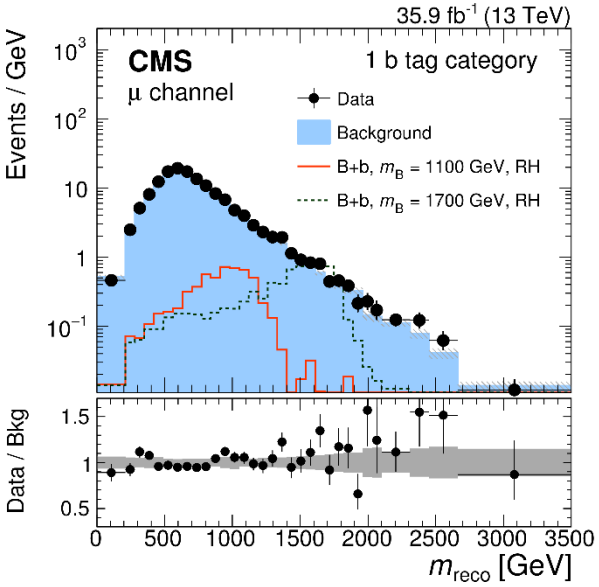
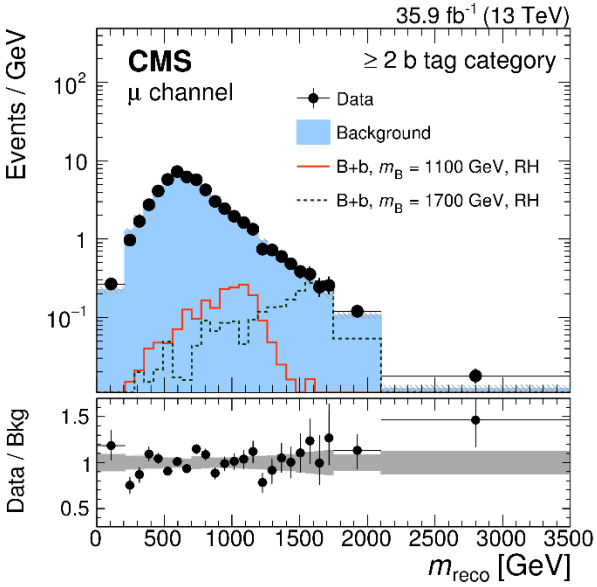
B2G-17-018: single B/X → tW

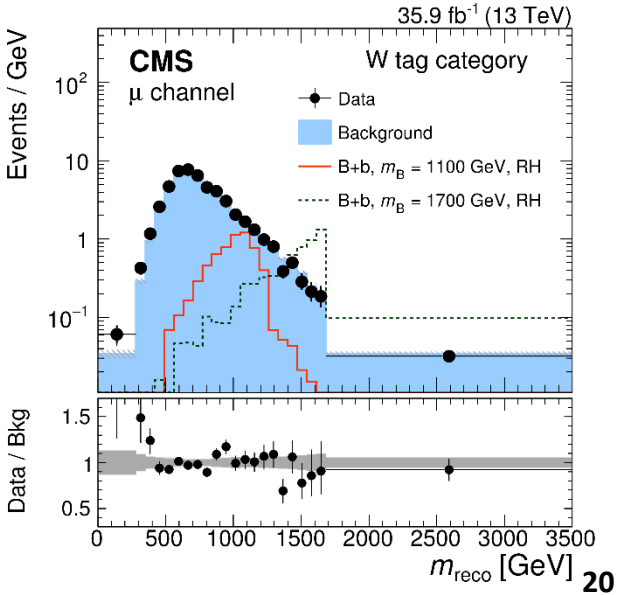
Eur. Phys. J. C 79 (2019) 90

- Background estimated from control region with zero jets in the forward region
- Shape taken from simulation, correction factor from the control region
- Method validated inverting cut on the chi2 reconstruction used to assign the correct jets to the top/W









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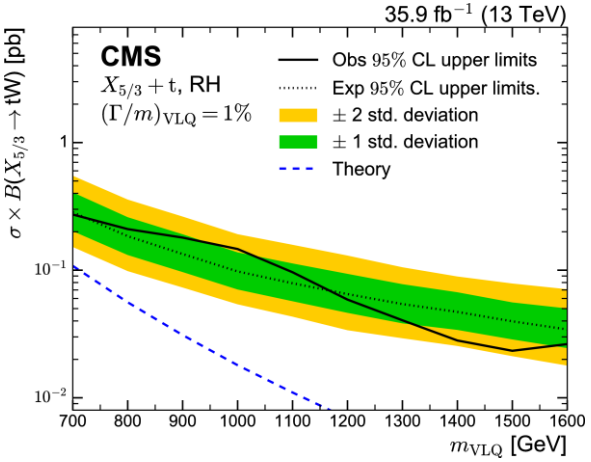
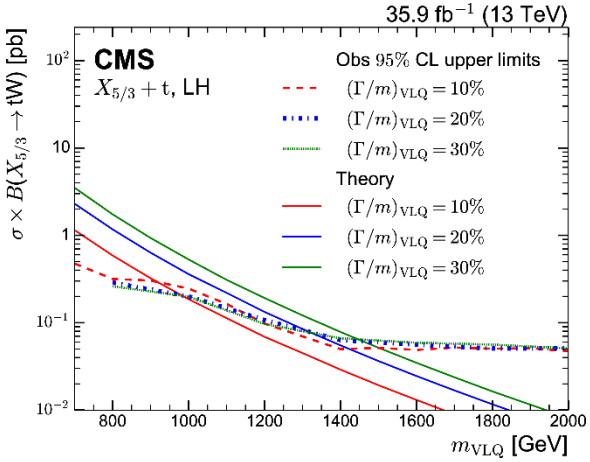
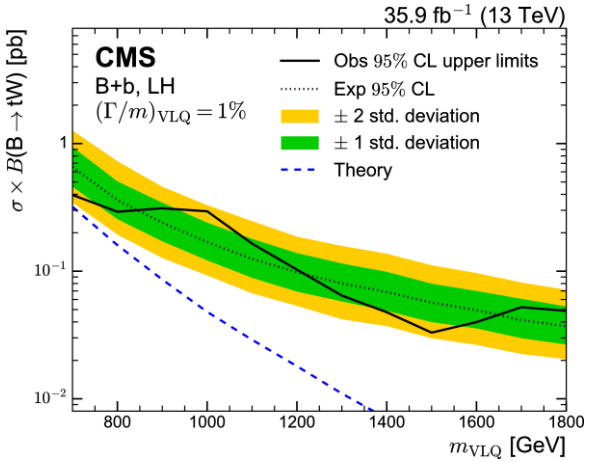
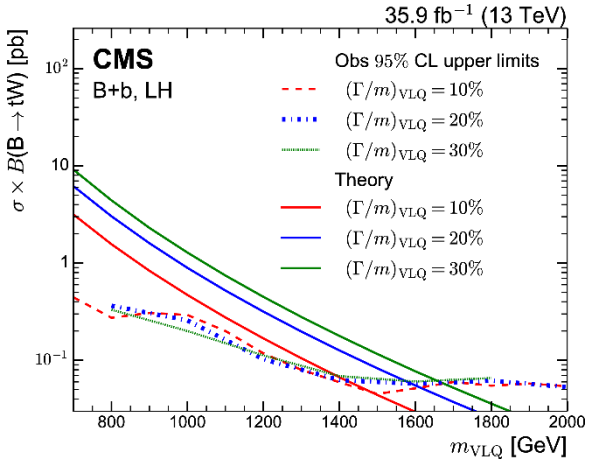




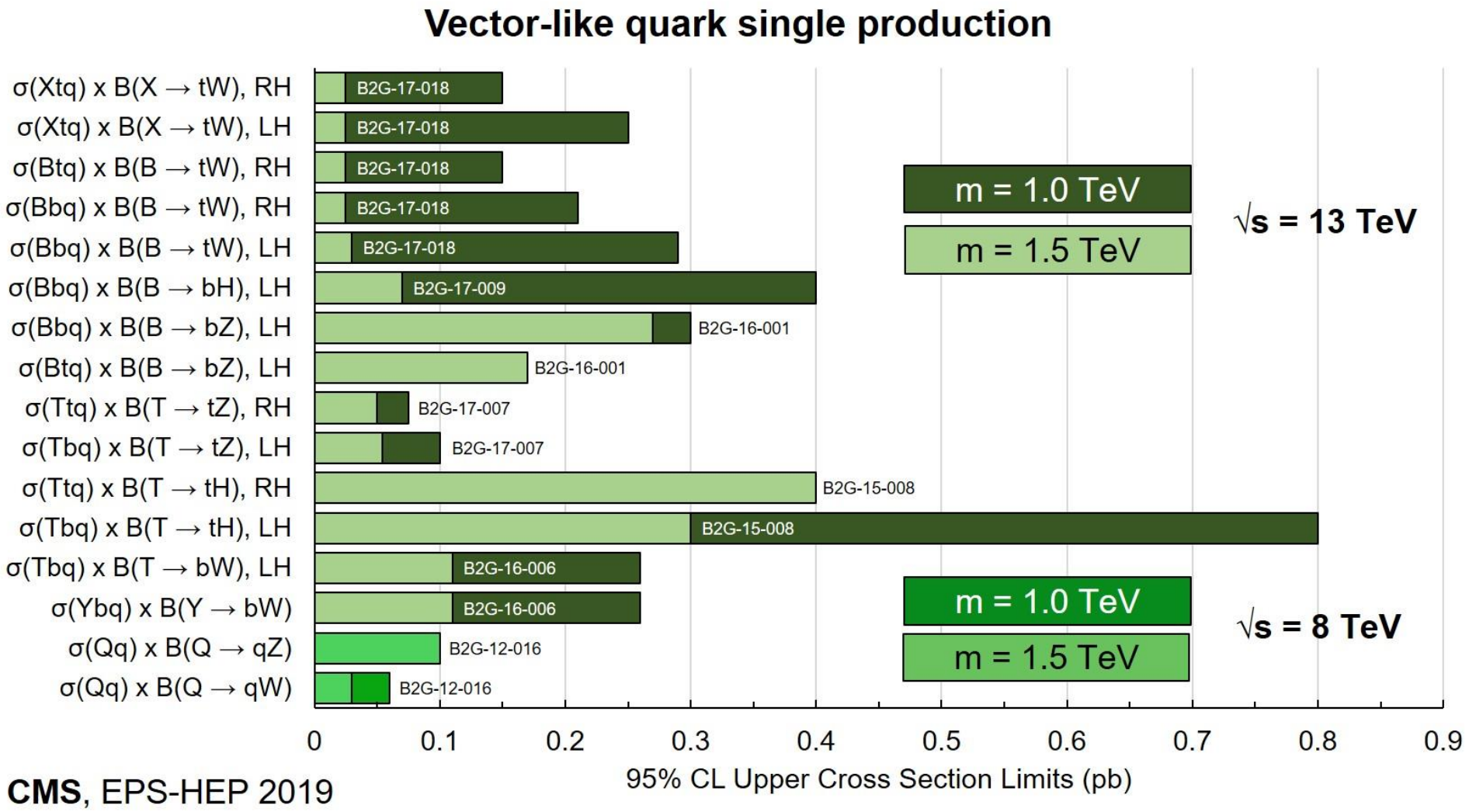




Limits for:

- B+b LH (width = 1%, 10%, 20%, 30%)
- B+b RH (width = 1%)
- B+t RH (width = 1%)
- $X_{5/3}$+t LH (width = 1%, 10%, 20%, 30%)

Summary

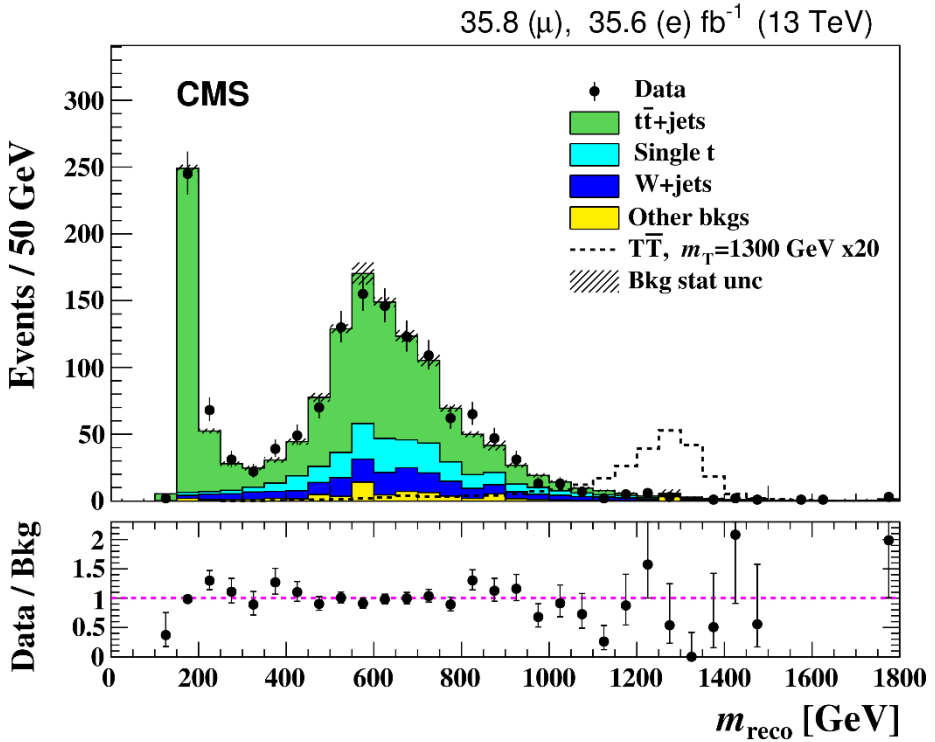


CMS, EPS-HEP 2019

Pair VLQ production

B2G-17-003: TT/YY → bWbW

- Search for: **pp → TT or YY → bWbW → blνbqq**
- Final states with a single isolated muon or electron, missing transverse momentum, and at least four jets with high transverse momenta
- W jet tagging is used to improve sensitivity at higher masses
- A **constrained kinematic fit** for the considered signal decay process is performed
- **Background** estimated from simulation with corrections from data



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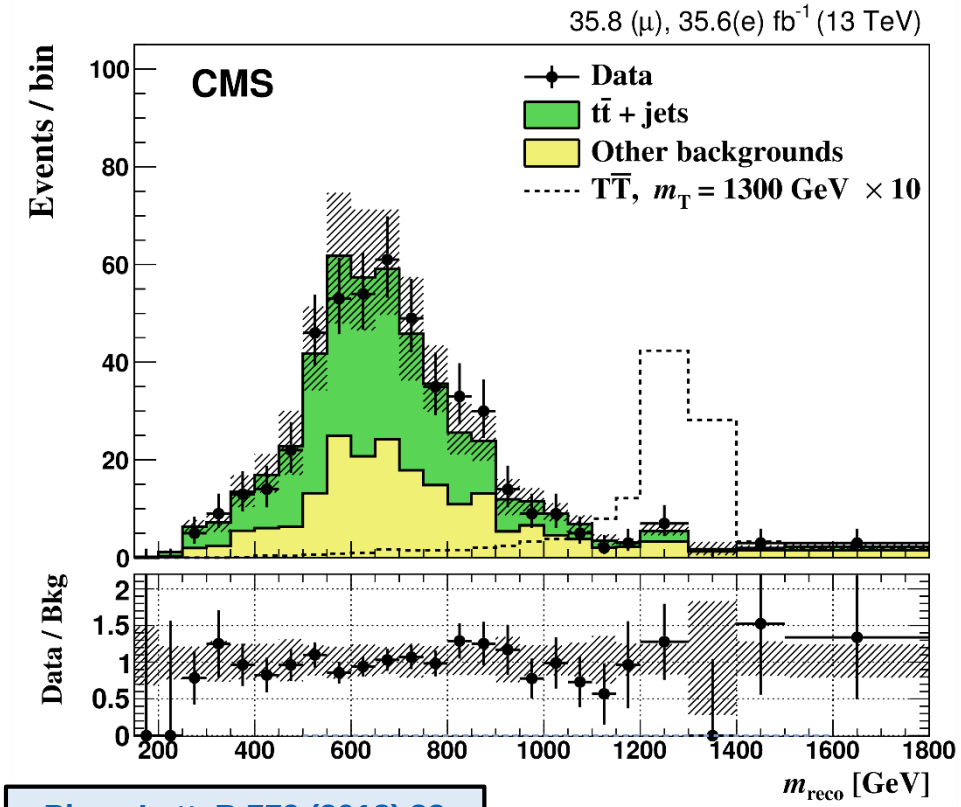
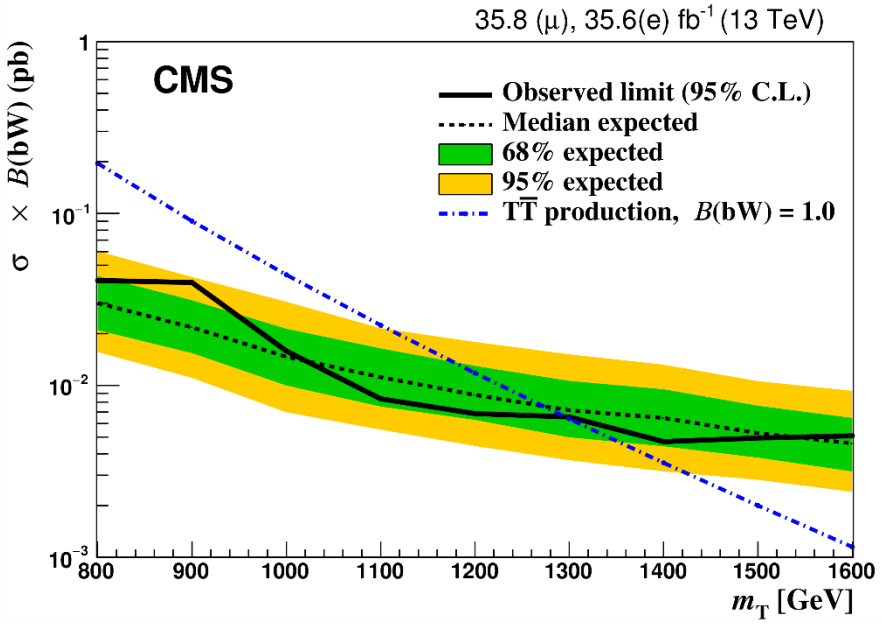
B2G-17-003: TT/YY → bWbW

- Exclusion limits on the TT/YY cross section, considering **BR(T/Y→bW) = 100%**
- Only categories with W tagged jets are used when setting limits
- T/Y quark masses are **excluded below 1295 GeV**





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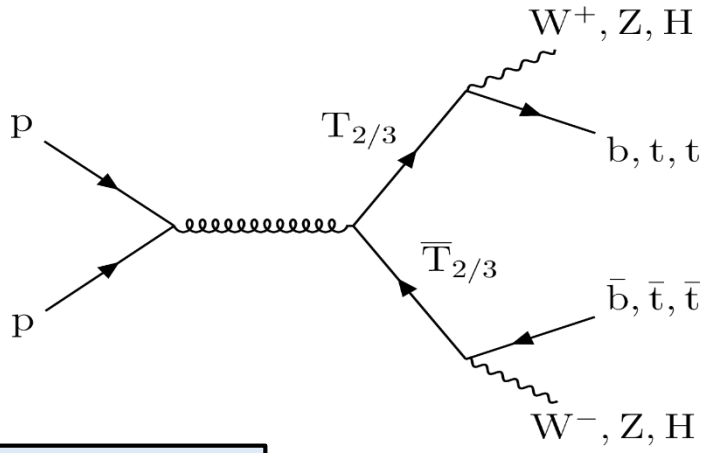
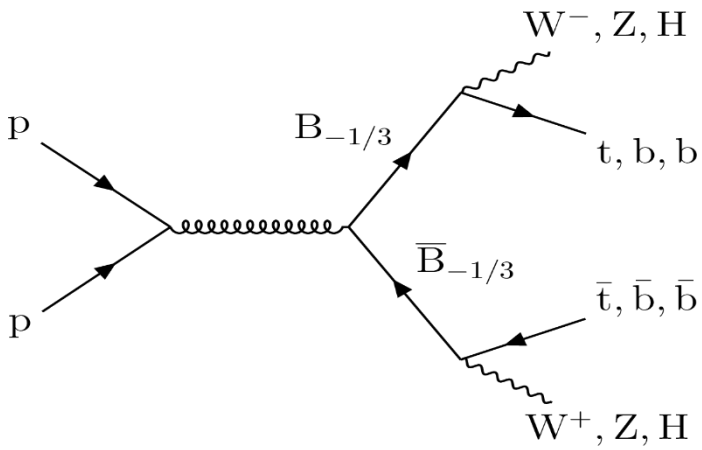
B2G-17-011: TT/BB → leptons

- Search for **TT or BB production**
- Three different channels:
  - **single lepton**, optimized for signal events with T → bW or T → tH, with a lepton from top decay and boosted W or H tagged jet
  - **same sign leptons**, most sensitive to signal events with T → tH, with the Higgs decaying to WW and one W decaying leptonically
  - **trilepton**, highly sensitive to VLQ pair production with at least one T → tZ, B → bZ, or B → tW decay





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B2G-17-011: TT/BB → leptons

- Each channel sensitive to different VLQ decay modes → strongest sensitivity to TT/BB achieved by combining the three channels:
  - **single-lepton** channel most sensitive to at least one **T → bW**
  - the **SS dilepton** channel most sensitive to at least one **B → tW**
  - the **trilepton** channel most sensitive to at least one **T → tZ**
- This search excludes **T (B) quark masses below 1140-1300 GeV (910-1240) GeV**, depending on the BR

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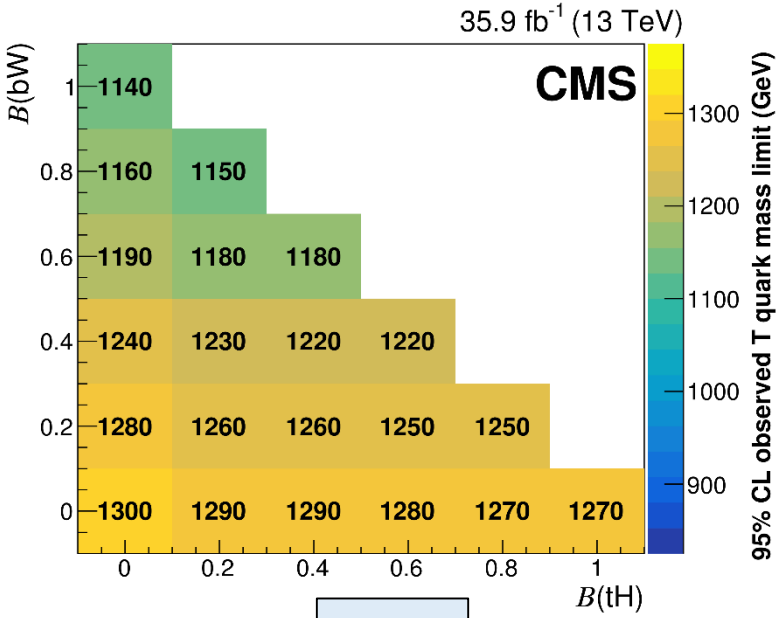
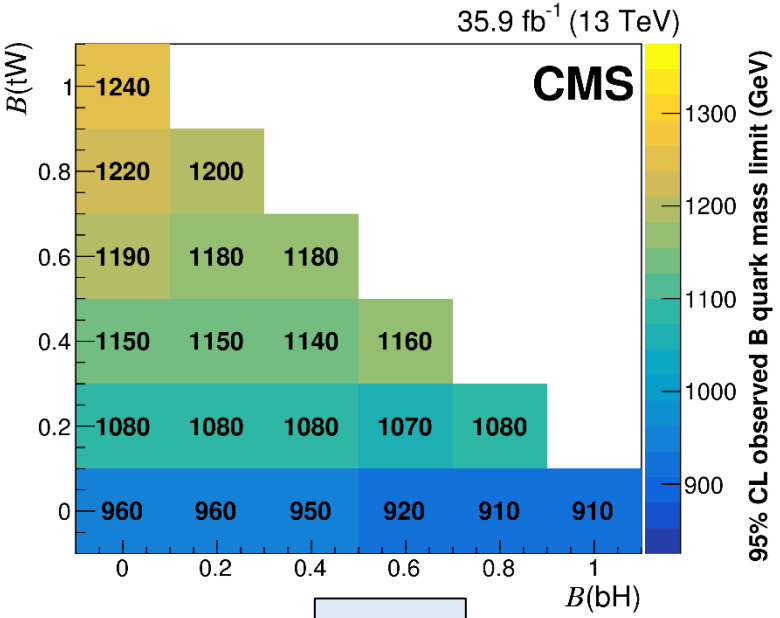


TT



BB

B2G-17-012: TT/BB → leptons

- Dedicated analysis looking for TT/BB in final state with **opposite sign dilepton**
- Analysis sensitive to final states with **T → tZ and B → bZ**
- Final states with boosted jets
- Assuming 100% BR to Z boson, **T (B) masses excluded below 1280 (1130) GeV**

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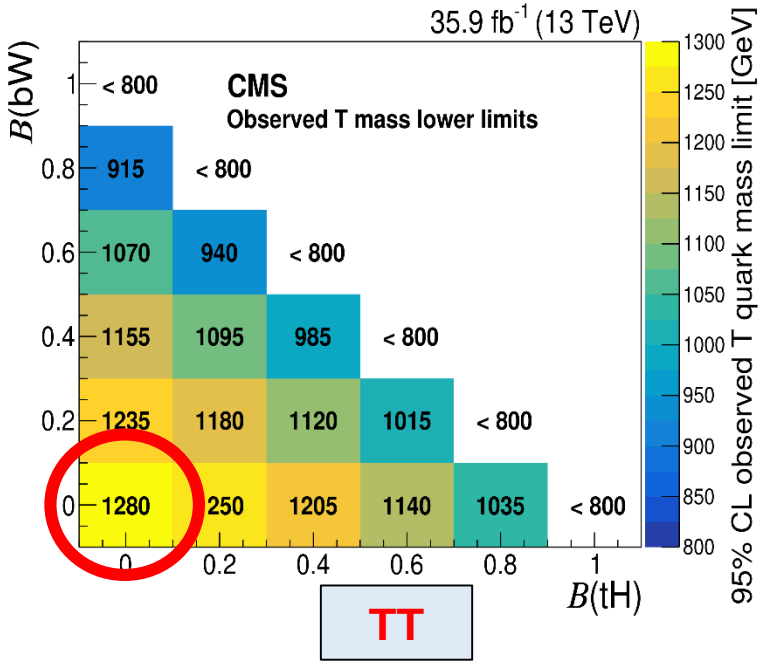
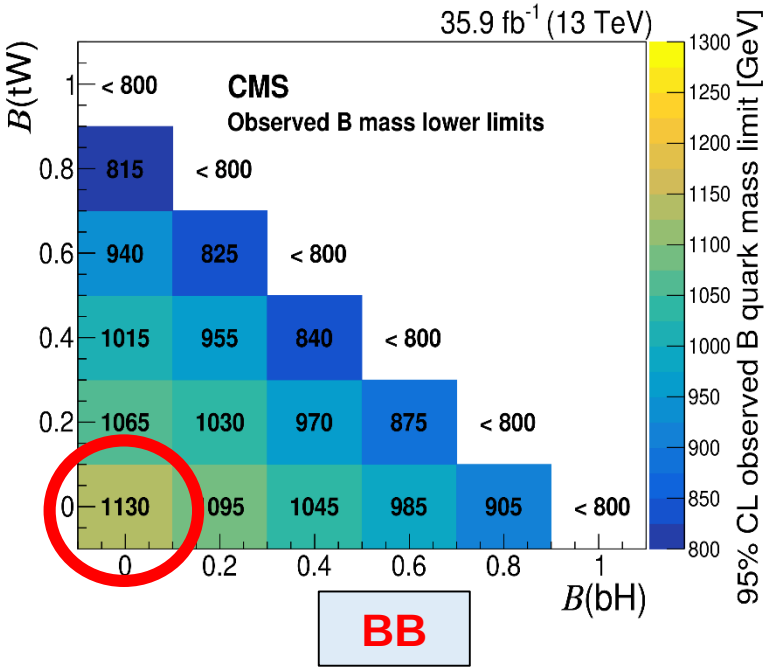


TT

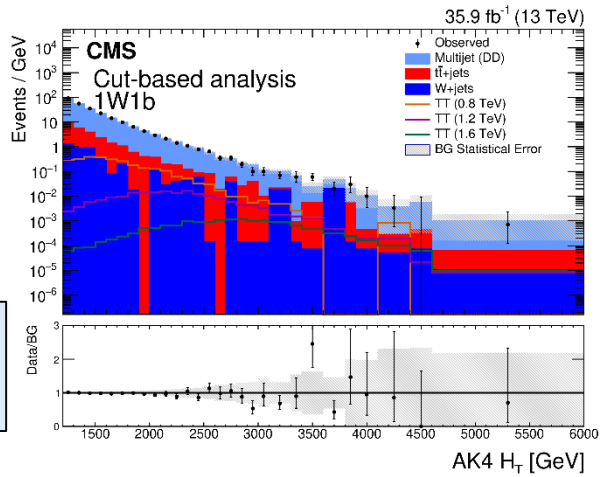


BB

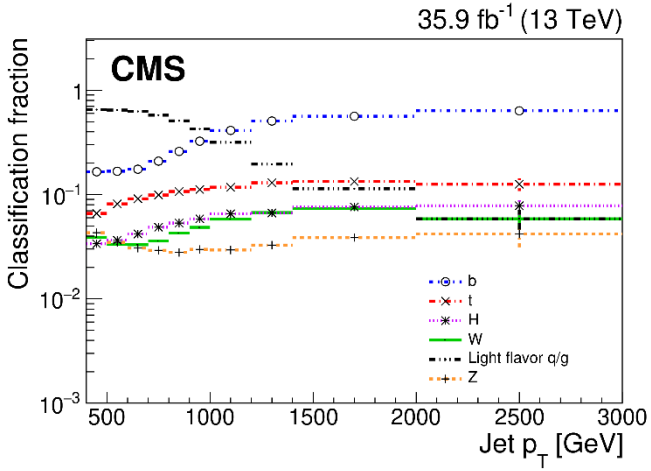
B2G-18-005: TT/BB → hadrons

- Results of two searches for pair production of vector-like T or B quarks in fully hadronic final states:
  1. **cut-based analysis targeting T → bW decay mode**
  2. **analysis based on NN algorithm, used to tag candidate jets as originating from top, b, light quarks, or W, Z, H bosons**
- Main background contribution is multijet events from QCD
- In the cut-based analysis, **control regions from data used to measure QCD multijet background** yields and shapes
- In the NN analysis, estimation from **the misidentification rates for each of the six categories of jets**

CMS-B2G-18-005



Cut based



Neural network

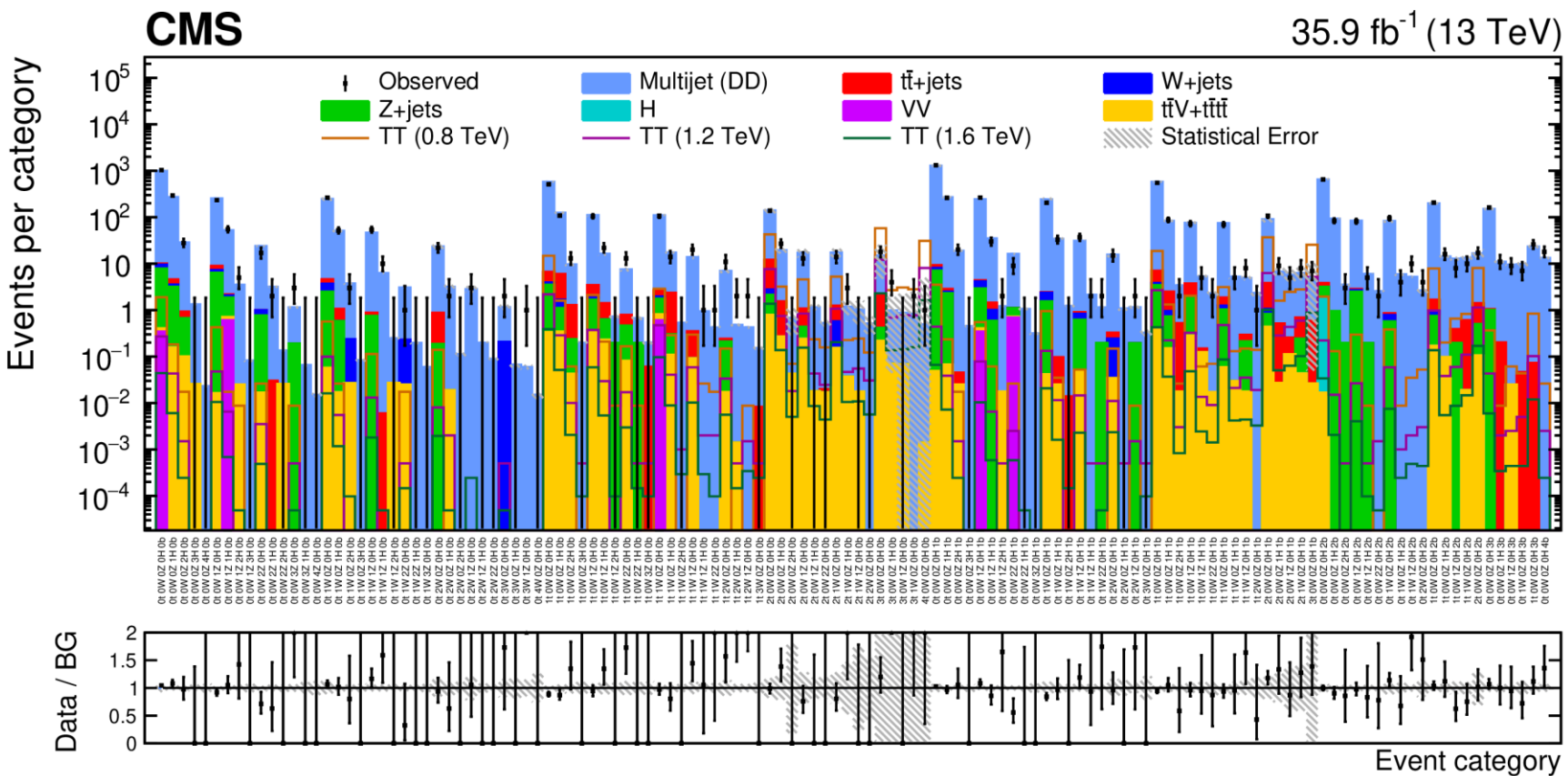
B2G-18-005: TT/BB → hadrons

Cut based analysis:

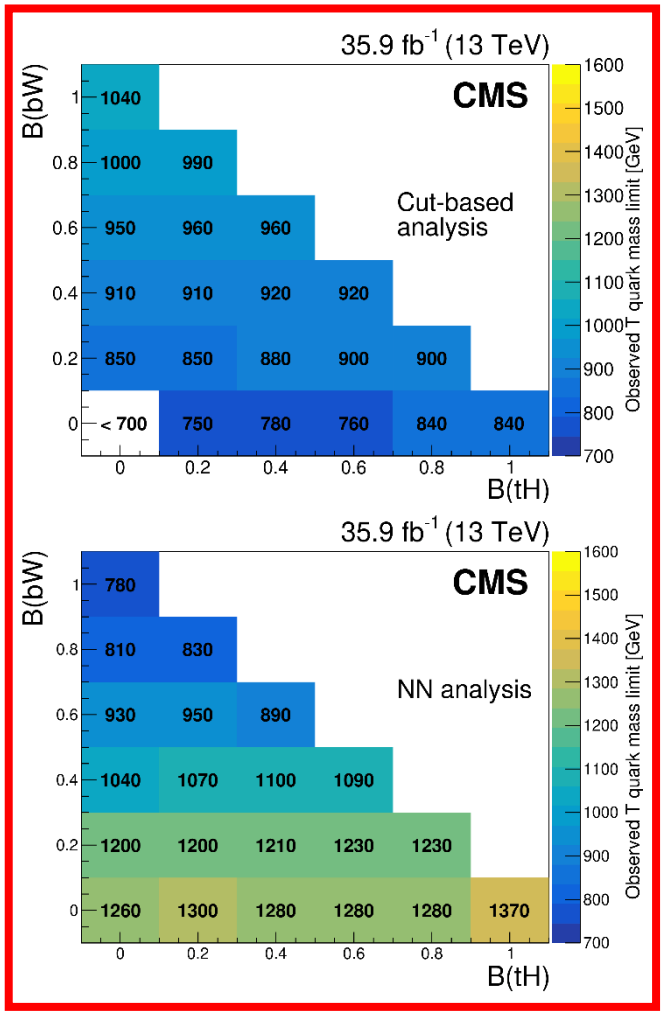
- At least 4 jets: 2 wide jets + 2 usual jets
- 4 categories: 1W1b, 2W1b, 1W2b, 2W2b

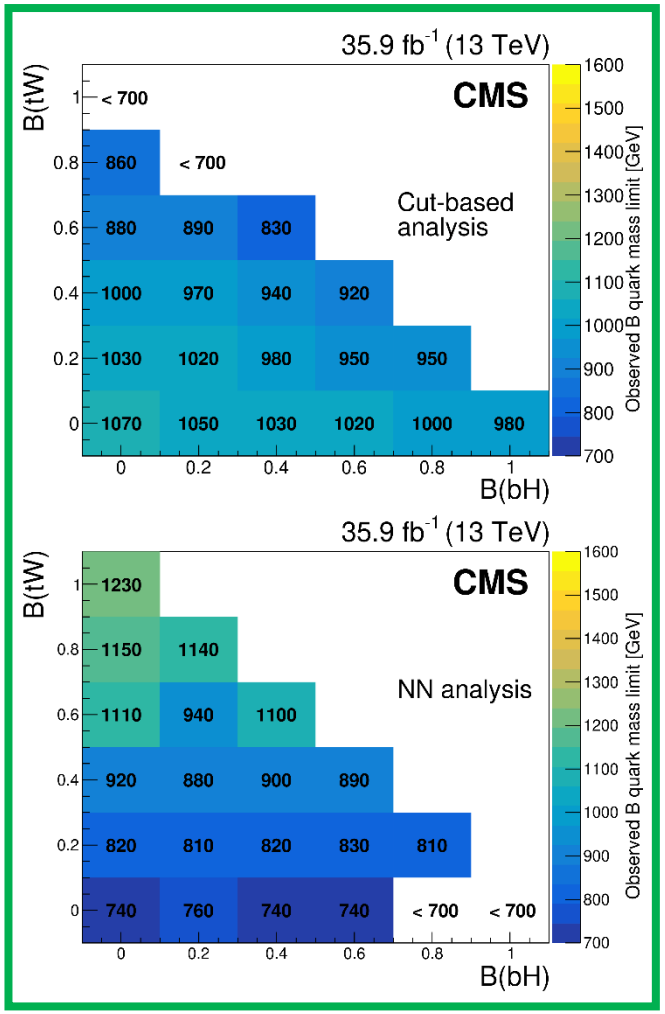
Neural network analysis:

- exactly 4 AK8 jets
- 126 categories, depending on the top, b, light quark, W, Z, H boson tagging



B2G-18-005: TT/BB → hadrons

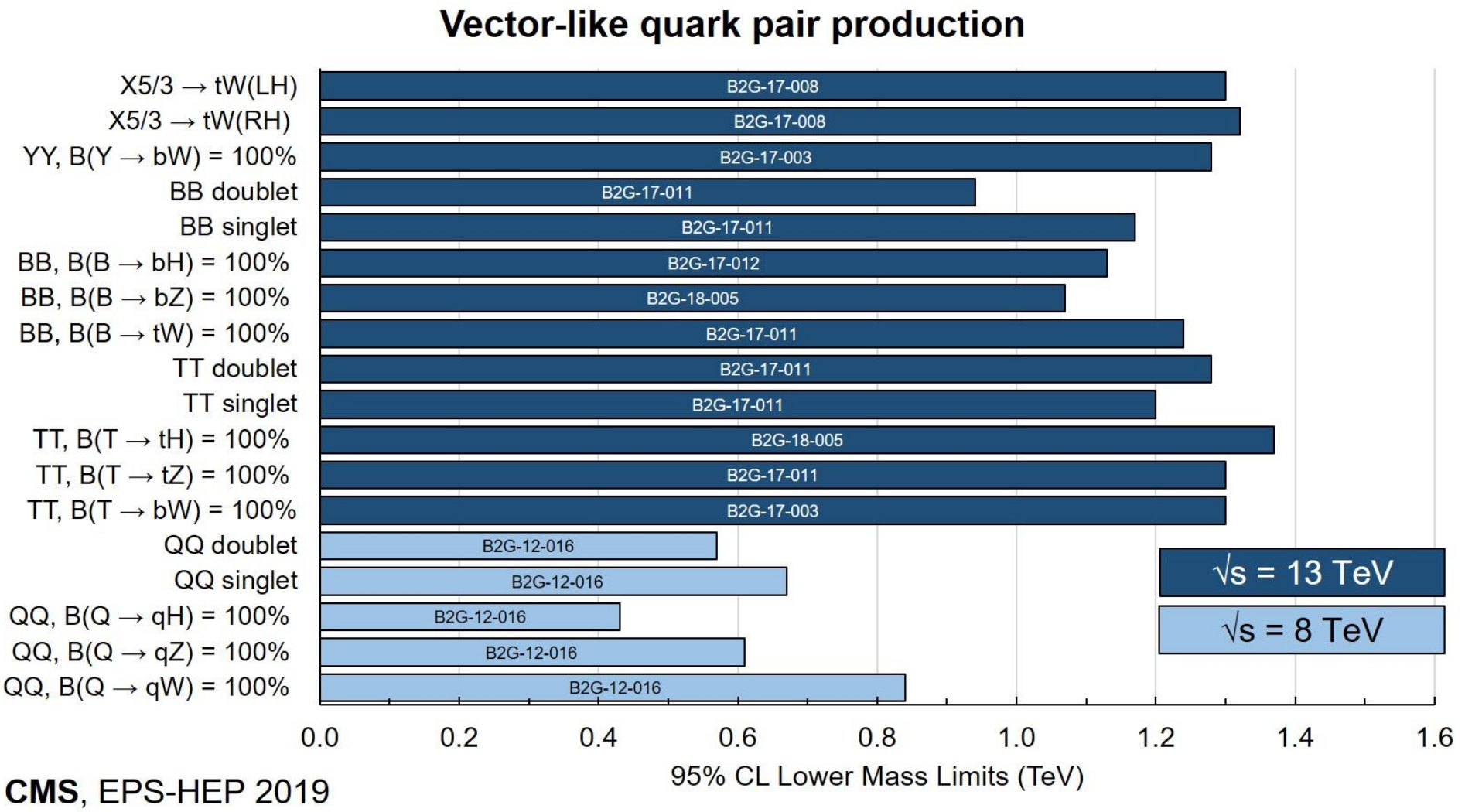




- **T search**: cut-based most sensitive to bW decay, NN to other decays
- **B search**: cut-based most sensitive to bZ decay, NN to tW

CMS-B2G-18-005

Summary



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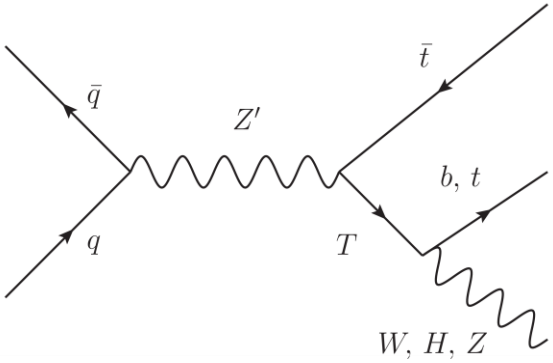
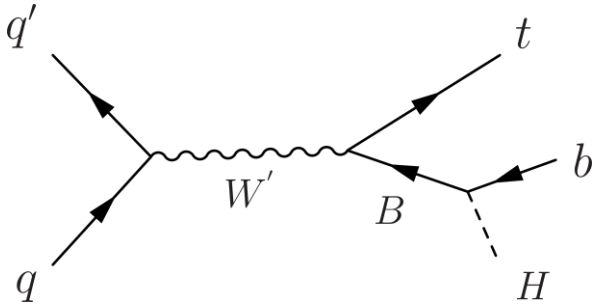
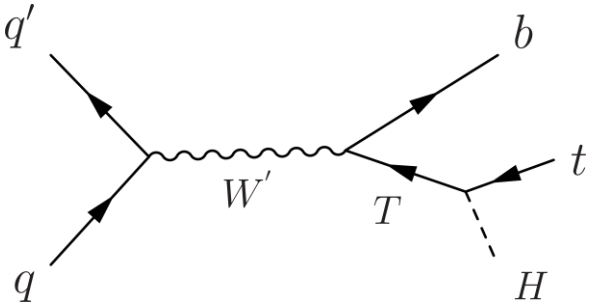
Resonances Z' and W' to VLQ

Resonances Z' and W' to VLQ

- Many extensions of the standard model (SM) predict the existence of heavy bosonic resonances
- Z'/W' couple with VLQ, decay modes are: Z' → Tt, W' → Bt, W' → Tb
- **G* model**: ten new VLQs predicted couple with the lightest spin-1 Kaluza-Klein excitation of the gluon (G*)
- **ρ^0 model**: heavy spin-1 resonance (ρ^0) couple with a multiplet of four new VLQs
- **W' to VLQ**: top and W' are superposition of elementary and composite modes that includes VLQs

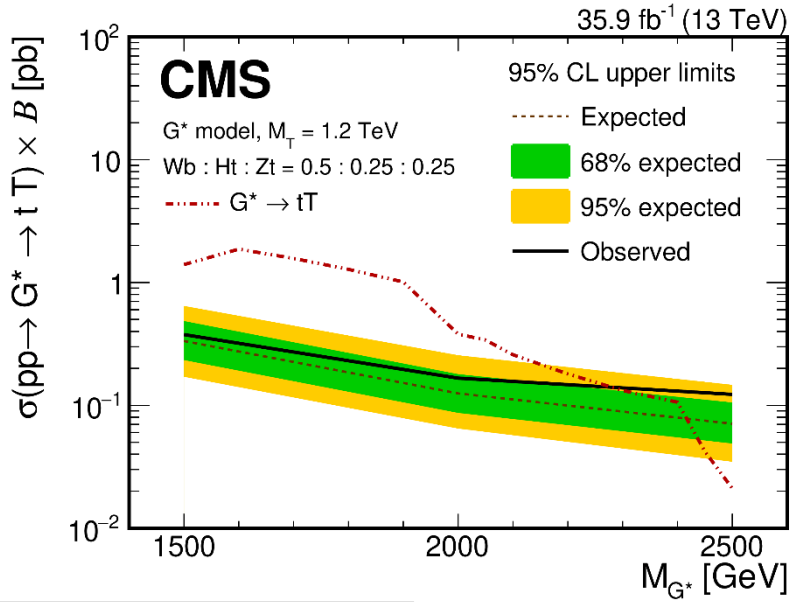


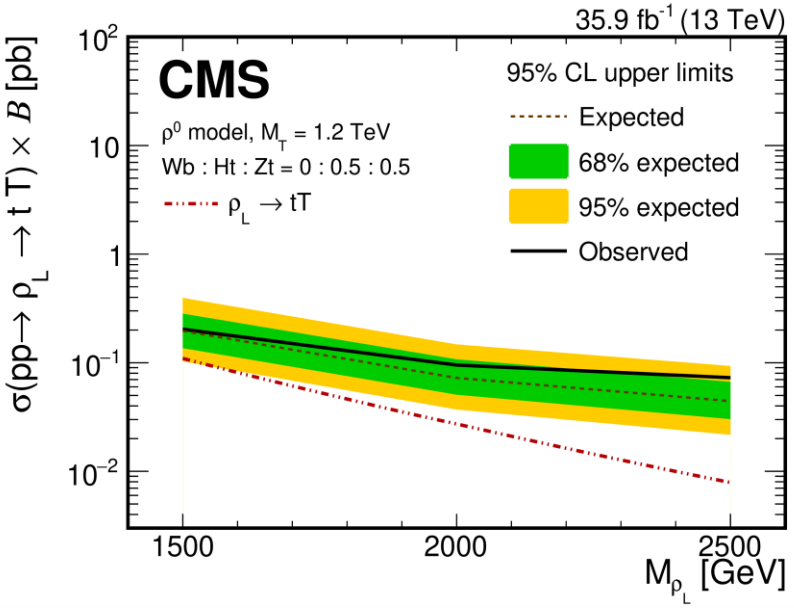




B2G-17-015: Z' → Tt

- Analysis optimised for **Z' → tT** with T decaying to **T → Zt and T → Ht**, in the 1 lepton (from top) and boosted jets final state
- **12 categories** considering electron/muon channels plus Z/H jet tagging and top jet tagging for the additional top
- Main background given by ttbar events
- **Background estimated** correcting simulation with mistag/tagging efficiencies for Z/H/top algorithms plus overall normalization correction





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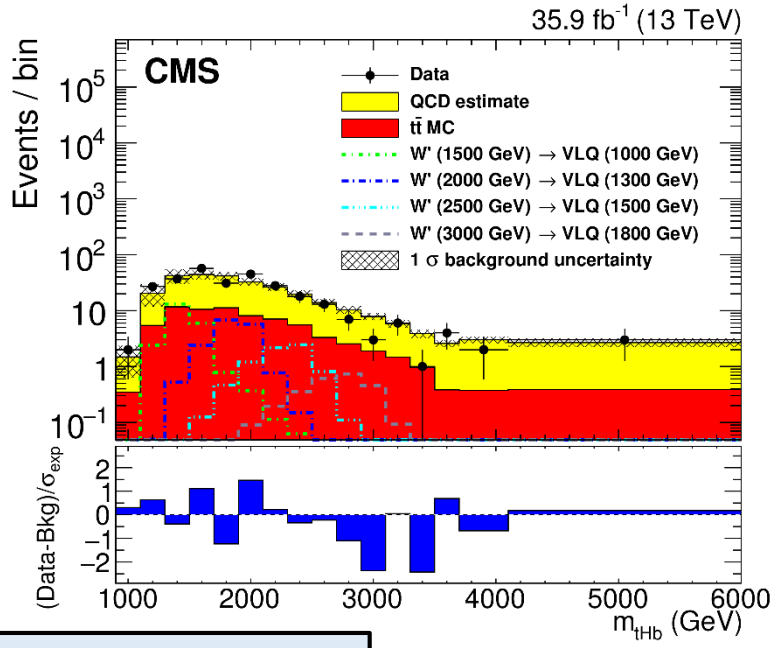
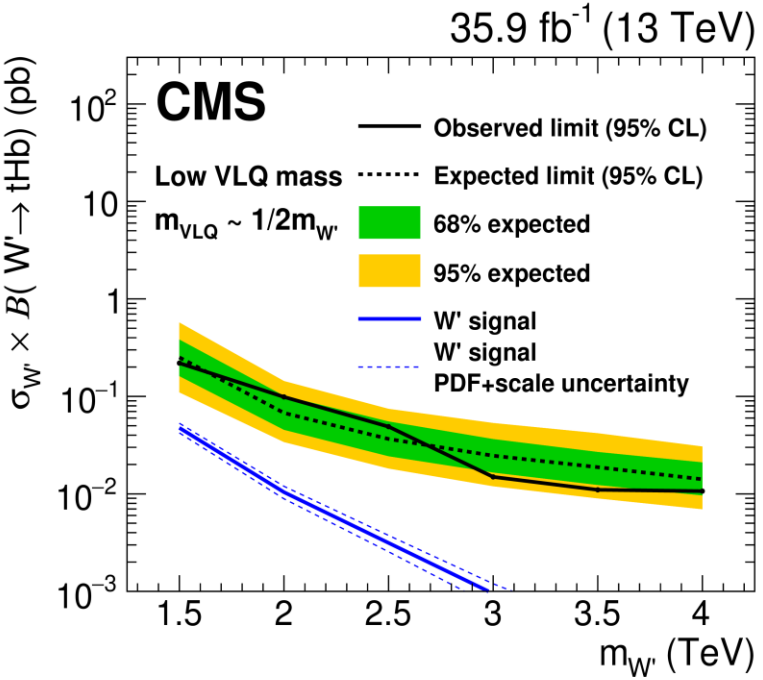
B2G-18-001: W' → Bt/Tb

- Analysis looking for **W' → Bt → bHt** and **W' → Tb → tHb**
- **Three jets final state**: b jet, top jet, H jet
- Main background is multijets from QCD, estimated from data by inverting top and H tagging requirements
- These are the **first limits for W' boson production in VLQ**, and cover a range of **0.01 to 0.43 pb** in the W' mass range of [1.5, 4.0] TeV





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Conclusion

- The CMS experiment has an extensive physics program devoted to the search for vector-like fermions
- A selection of searches has been presented
  - **single production of VLQs**
  - **pair production of VLQs**
  - **VLQ produced by the decay of BSM heavy resonances**
- Unfortunately no hint of new physics has been found
- But Run 3 is starting soon: new energy frontiers to explore!

Thank you for your attention

BACKUP