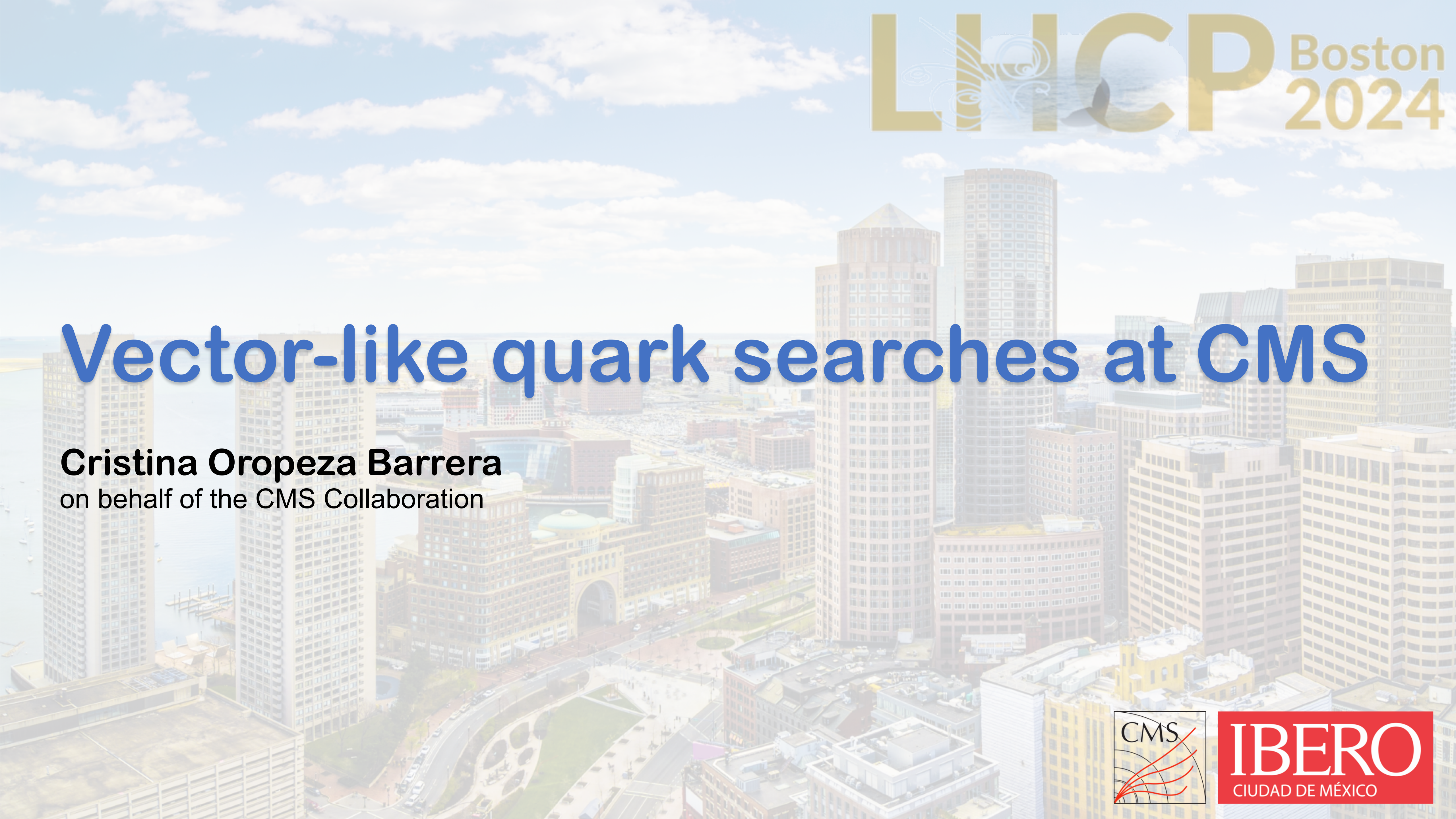


LHCP Boston 2024

Vector-like quark searches at CMS

Cristina Oropeza Barrera
on behalf of the CMS Collaboration

Outline

I Theoretical motivation and phenomenology of VLQ

II Overview of the CMS search program

III New results

Single production:

- T ⟶ tH/tZ in the all-hadronic final state (arXiv:2405.05071, submitted to PRD) 138 fb^{-1}
- Combination of single T searches (arXiv:2405.17605, submitted to Phys. Repts.) New

Pair production:

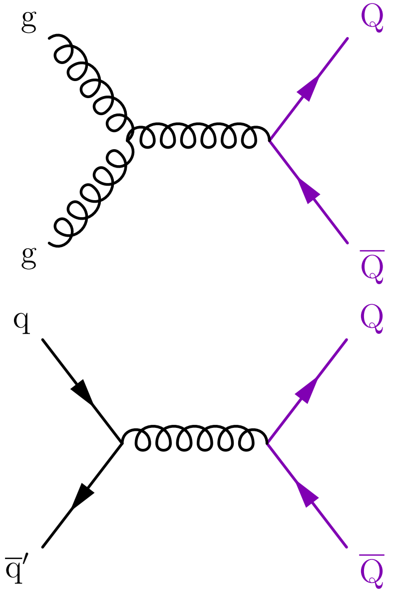
- BB in the dileptonic and all-hadronic final states (arXiv:2402.13808, submitted to PRD) 138 fb^{-1}
- Combination of BB searches (arXiv:2405.17605, submitted to Phys. Repts.) New

IV Summary

Theoretical motivation and phenomenology of VLQ

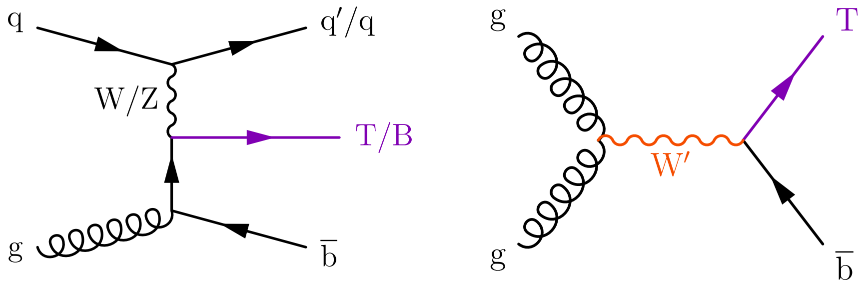
arXiv:2405.17605

- Introduced by several extensions to the SM to address the hierarchy and naturalness problems.
- Left- and right-handed components transform in the same way under EW symmetry group.
- VLQ masses do not arise from Yukawa couplings ⇒ not constrained by current measurements.
- VLQ flavours: **T** (+2/3), **B** (-1/3), **X**$_{5/3}$ (+5/3) and **Y**$_{4/3}$ (-4/3).
- Decay into a third-generation SM quark plus either a W, Z or Higgs boson.



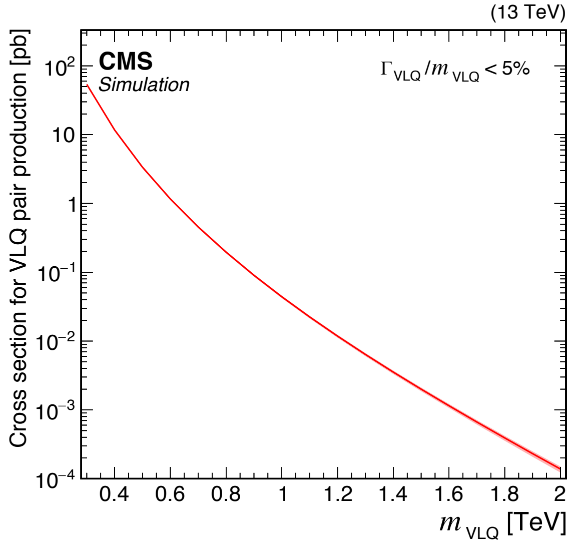
Pair production

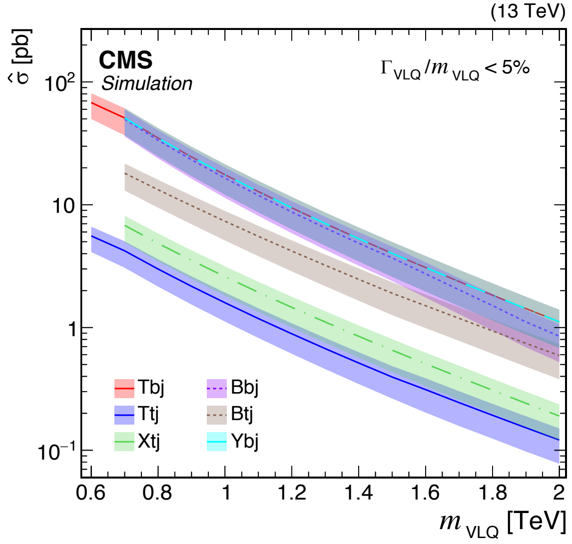
Dominant at low masses.



Single production

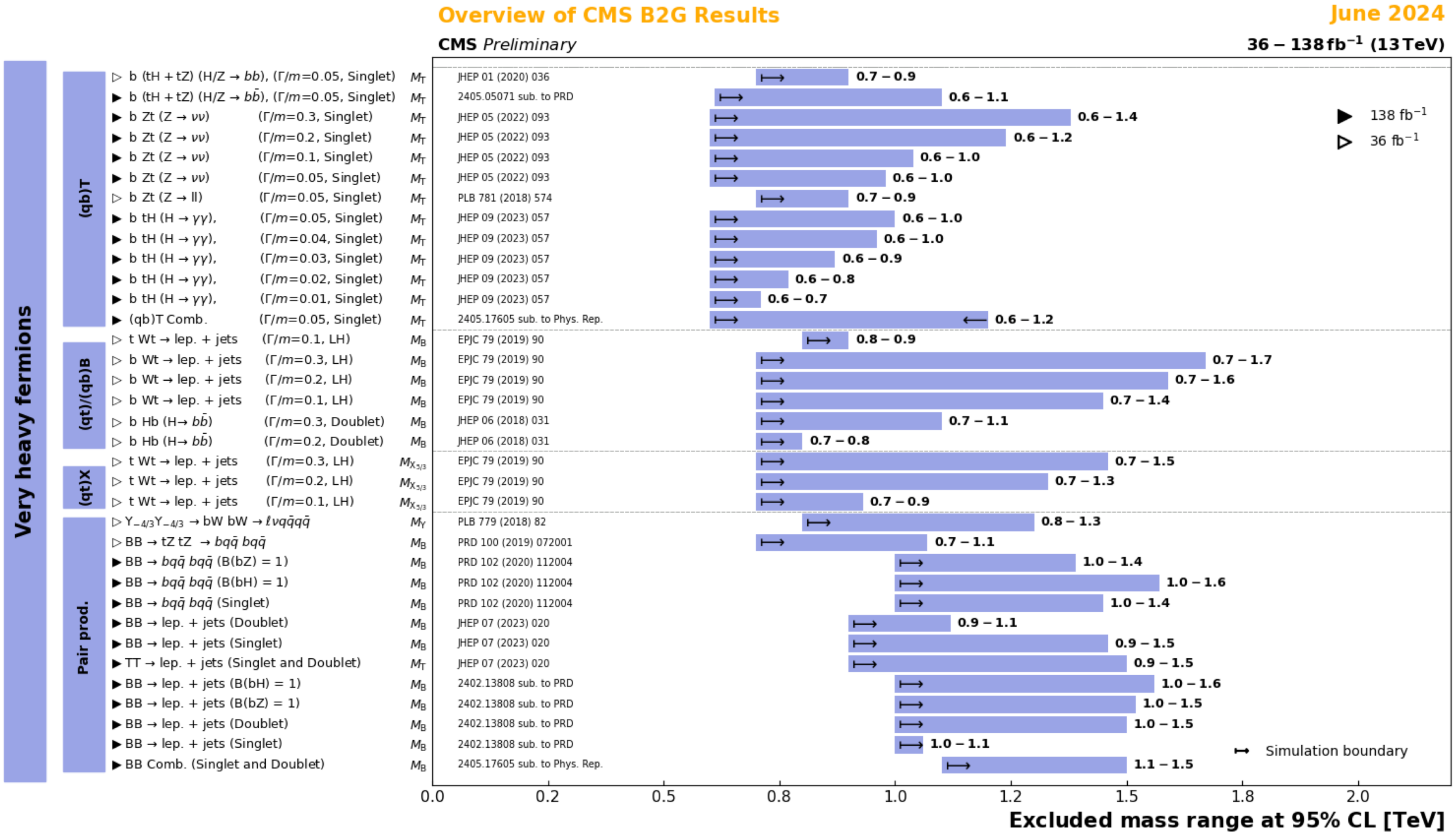
Model dependent (couplings, width).
Via EW processes or new interactions.





Overview of the CMS search program

CMS Results



New

- With Run 2 data, CMS has carried out searches for both pair and single production (all VLQ flavors), as well as for production through heavy resonance decays. For single production, different widths and couplings have also been explored.

Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

- T singlet with narrow width ($\Gamma/M < 1\%$) in the mass range [600,1200] GeV.
- Signal signature is a resonant peak in the reconstructed five-jet mass distribution (t_{had}+bb).
- Baseline event selection:

  ≥ 6 jets out of which **≥ 3 are b-tagged jets**

- T quark candidates are reconstructed using a multistep χ^2 minimization:

① Identify best H/Z candidates from b-tagged jet collection by minimizing:

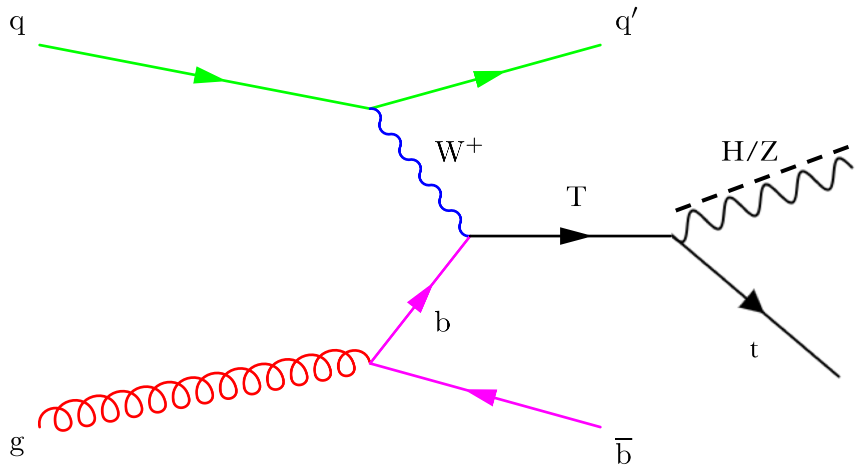
$$\chi^2_{\mathrm{H/Z}} = \left(\frac{m^{\mathrm{meas}}_{\mathrm{H/Z}} - \mu^{\mathrm{MC}}_{\mathrm{H/Z}}}{\sigma^{\mathrm{MC}}_{\mathrm{H/Z}}} \right)^2$$

② Identify best W and top candidates from the remaining jets:

$$\chi^2_{\mathrm{W}} = \left(\frac{m^{\mathrm{meas}}_{\mathrm{W}} - \mu^{\mathrm{MC}}_{\mathrm{W}}}{\sigma^{\mathrm{MC}}_{\mathrm{W}}} \right)^2 \qquad \chi^2_{\mathrm{t}} = \left(\frac{m^{\mathrm{meas}}_{\mathrm{t}} - \mu^{\mathrm{MC}}_{\mathrm{t}}}{\sigma^{\mathrm{MC}}_{\mathrm{t}}} \right)^2$$

by minimizing:

$$\chi^2 = \chi^2_{\mathrm{H/Z}} + \chi^2_{\mathrm{W}} + \chi^2_{\mathrm{t}}$$



Additional requirements:

Total $\chi^2 < 15$

$m_H > 100$ GeV and $m_Z < 100$ GeV (orthogonal channels)

$m_{\mathrm{H/Z\ +\ non\text{-}top\ hardest\ jet}} > 250$ GeV

Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

- Different selection criteria are used for low-mass (< 800 GeV) and high-mass T candidates.

Event categorization

High-mass selection

Takes into account the moderate Lorentz boost of the decay products:

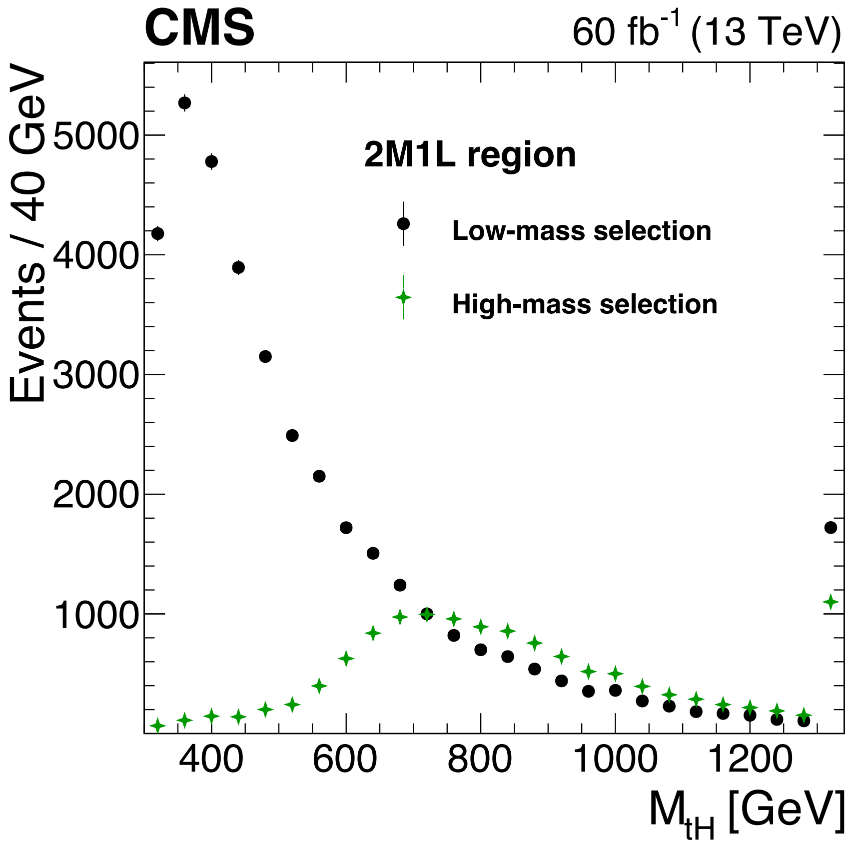
relative $H_T > 0.4$

$\Delta R(b,b) < 1.1$; $\Delta R(j1_W,j2_W) < 1.75$; $\Delta R(b_t,W) < 1.2$

Distorts the invariant mass distribution at low masses.

Low-mass selection

Mass-dependent cut on each of the variables that modify the shape of the invariant mass distribution.

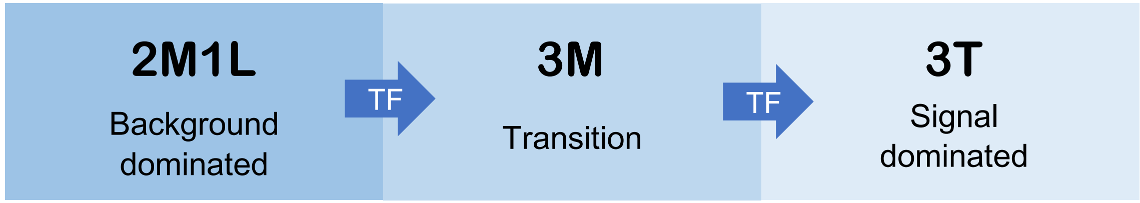


Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

- The background contribution is estimated directly from the data, from regions with relaxed b-tagging requirements.
- Constructed bin by bin using a simultaneous binned maximum likelihood fit.

$$\lambda_{3T}(b) = \lambda^{B}_{3T}(b) + \mu\lambda^{S}_{3T}(b)$$
$$\lambda_{3M}(b) = \lambda^{B}_{3M}(b) + \mu\lambda^{S}_{3M}(b)$$
$$\lambda_{2M1L}(b) = \lambda^{B}_{2M1L}(b) + \mu\lambda^{S}_{2M1L}(b).$$



2M1L

Background dominated

TF

3M

Transition

TF

3T

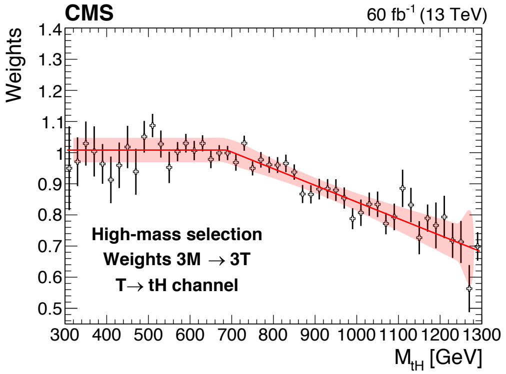
Signal dominated

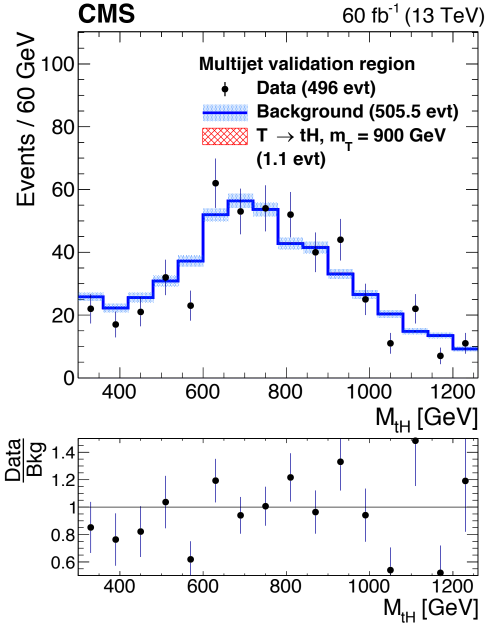
L – loose
M – medium
T – tight

transfer functions

$$\lambda^{B}_{3T}(b) = N_{3M\to 3T}\, f_{3M\to 3T}(b)\, \lambda^{B}_{3M}(b)$$
$$\lambda^{B}_{3M}(b) = N_{2M1L\to 3M}\, f_{2M1L\to 3M}(b)\, \lambda^{B}_{2M1L}(b)$$

normalization factors
(selection efficiency ratio)





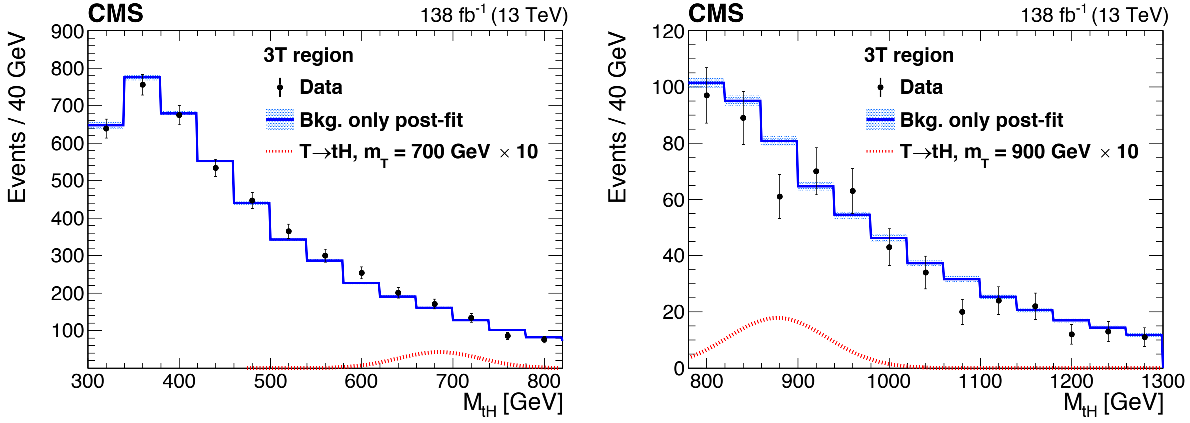
The background estimation method is validated in 45 control regions, enriched in multijet or ttbar events.

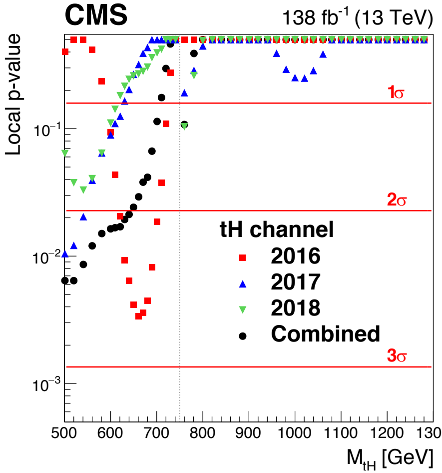
Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

- No evidence for single T production is observed.

  An upward fluctuation observed with 2016 data at 680 GeV vanishes when all years are combined.

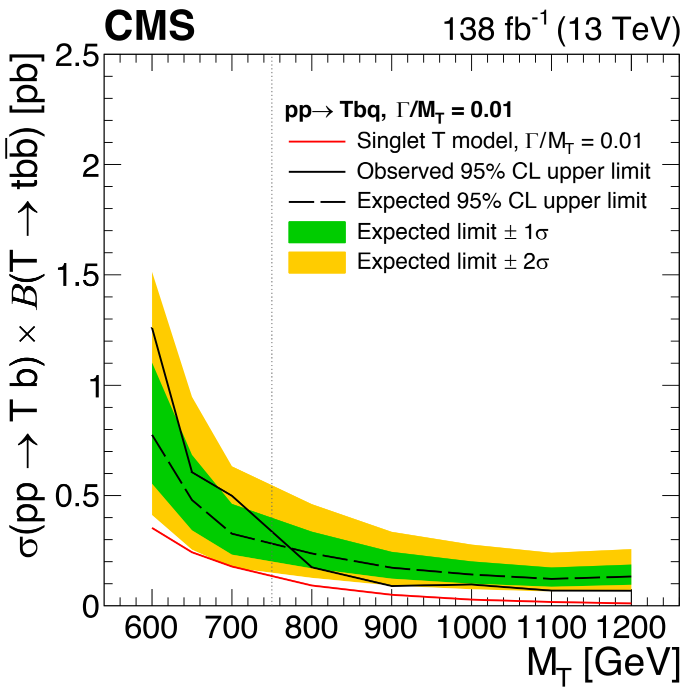




- 95% CL upper limits are set on the **σ**xBR to tH and tZ:

  1260 fb to 68 fb in the mass range 600-1200 GeV

- These limits are stronger by a factor of three than B2G-18-003.



Combination of single T searches

New

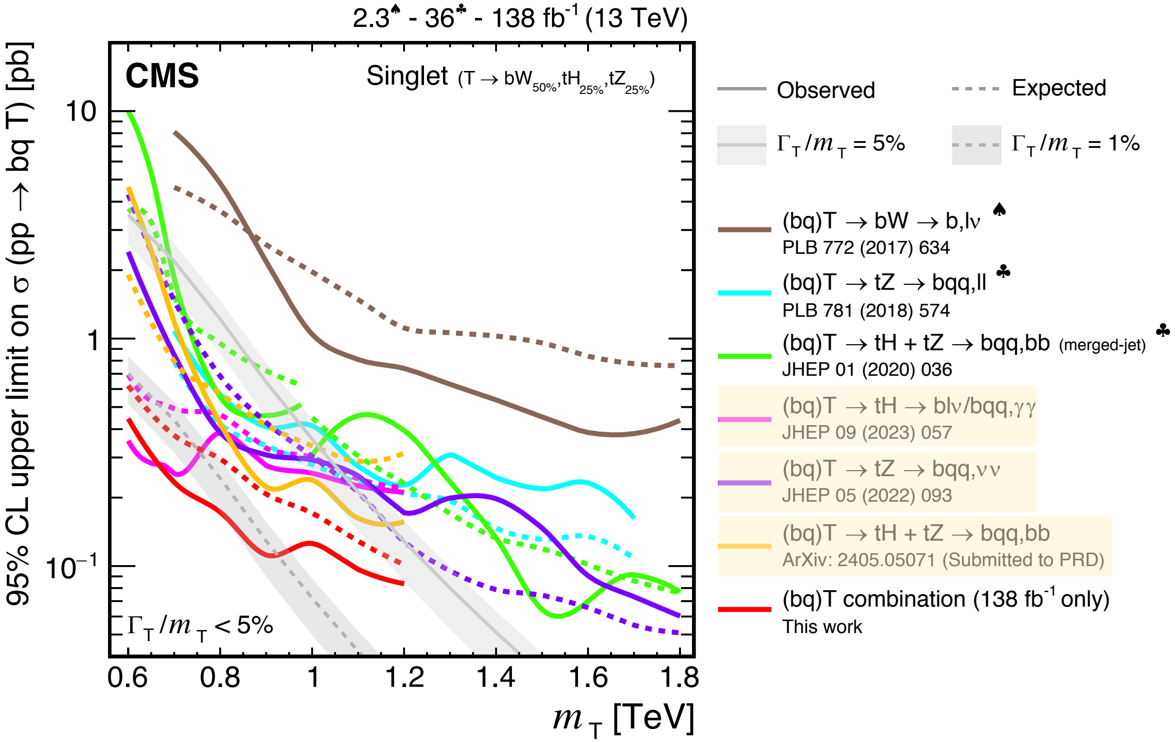
arXiv:2405.17605

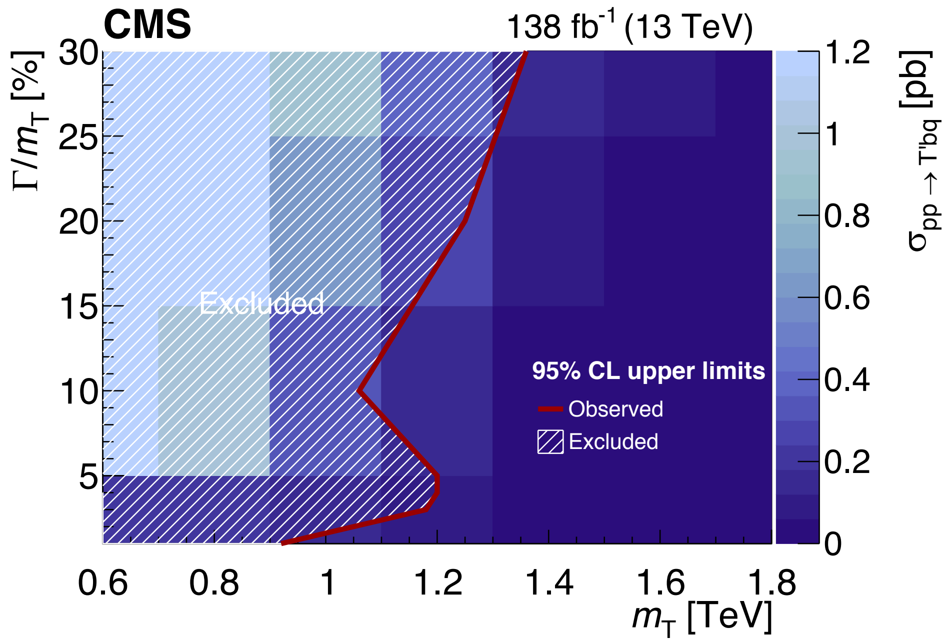
- Decay modes considered:

tH
$H \longrightarrow \gamma\gamma$
$H \longrightarrow bb$

tZ
$Z \longrightarrow \nu\nu$
$Z \longrightarrow bb$

- Mutually exclusive final states ⇒ statistically independent observations.
- Only NWA scenarios included in the combination.



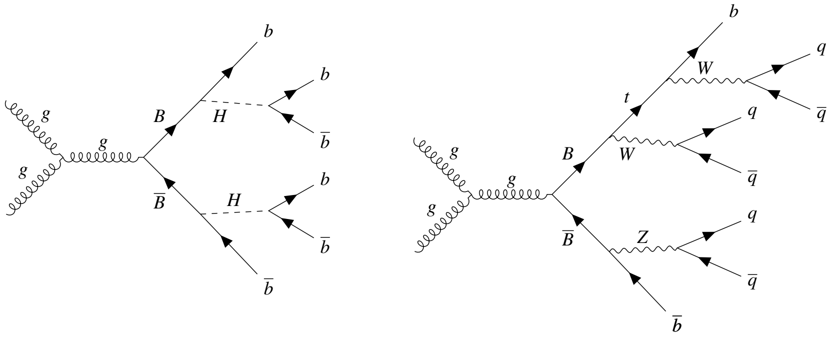


The upper limits on the cross section as a function of m_T in a singlet scenario show that the combination significantly improves the sensitivity.

BB production (dileptonic & all-had)

arXiv:2402.13808

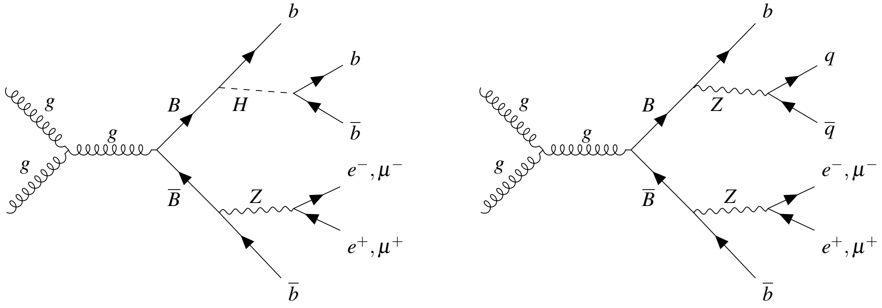
- Pair production search optimized for B masses greater than 1000 GeV.
- The three possible decay modes of the B are considered (bH, bZ and tW) in two categories: fully hadronic and dileptonic.



Fully hadronic
(representative diagrams)

Jet multiplicity	Leptonic category	Fully hadronic category
3	bHbZ, bZbZ	—
4	bHbZ, bZbZ	bHbH, bHbZ, bZbZ
5	—	bHbH, bHbZ, bZbZ, bHtW, bZtW
6	—	bHbH, bHbZ, bZbZ, bHtW, bZtW

Event classification takes into consideration possible merging of jets due to Lorentz boosts and ISR/FSR jets in dileptonic channel.



Dileptonic

Offline selection

Fully hadronic

- Between 4 and 6 ak4 jets.
- $H_T > 1350$ GeV.
- No isolated leptons nor pairs of leptons satisfying dileptonic criteria.

Dileptonic

- Between 3 and 5 ak4 jets.
- Pair of same-flavor opposite-sign leptons (e/μ) with mass between 80 and 102 GeV.

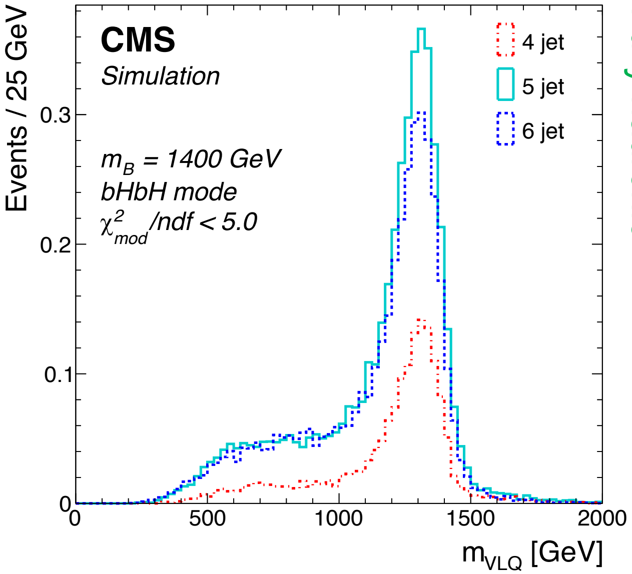
BB production (dileptonic & all-had)

arXiv:2402.13808

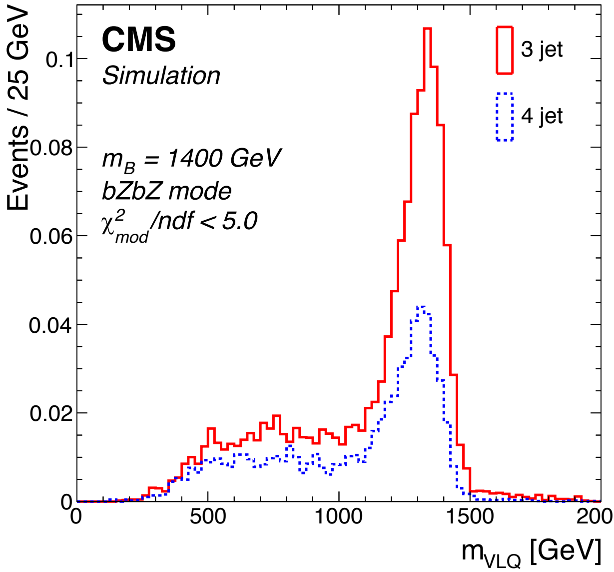
- A modified χ^2 metric is used to associate an event to a given decay mode and assign jets to a parent particle. All possible combinations are tested. The mode with the lowest value is selected as the reconstructed mode.

$$\chi^2_{\text{mod}} = \underbrace{\underbrace{\frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m_{\text{VLQ}}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}} + \frac{(m_1 - \overline{m_1})^2}{\sigma^2_{m_1}}}_{\text{Dileptonic}} + \frac{(m_2 - \overline{m_2})^2}{\sigma^2_{m_2}}}_{\text{Fully hadronic}}$$

Cut on χ^2/ndof is optimized for each jet multiplicity and decay mode.



Fully hadronic



Dileptonic

BB production (dileptonic & all-had)

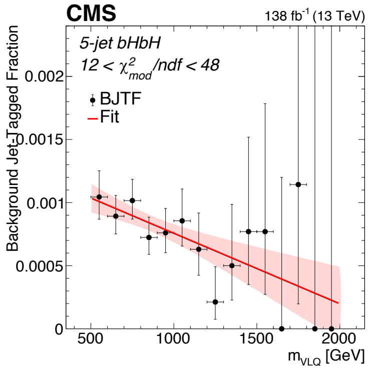
arXiv:2402.13808

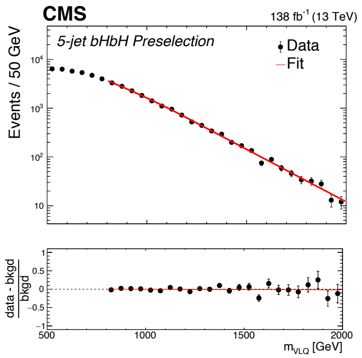
- The background estimation for both categories is based exclusively on control samples in data.

Fully hadronic:

$$n_{\mathrm{bkg}}(m_{\mathrm{VLQ}}) = n(m_{\mathrm{VLQ}})\varepsilon_0 \frac{\varepsilon(m_{\mathrm{VLQ}})}{\left(\int_{500\,\mathrm{GeV}}^{800\,\mathrm{GeV}} \varepsilon(m')\,\mathrm{d}m'\right)/(300\,\mathrm{GeV})}$$

BJTF dependence on m_{VLQ}
(control region with $12 < \chi^2/\mathrm{ndof} < 48$)



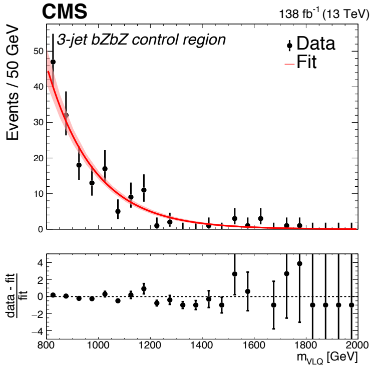


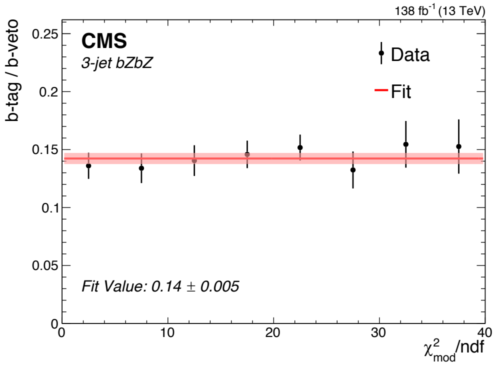
Background jet-tagged fraction (BJTF)
(sideband region $500 < m_{\mathrm{VLQ}} < 800$)

Dileptonic:

$$n_{\mathrm{bkg}}(m_{\mathrm{VLQ}}) = f(m_{\mathrm{VLQ}}) \frac{\int_{450\,\mathrm{GeV}}^{900\,\mathrm{GeV}} n_{\mathrm{signal}}(m')\,\mathrm{d}m'}{\int_{450\,\mathrm{GeV}}^{900\,\mathrm{GeV}} n_{\mathrm{control}}(m')\,\mathrm{d}m'}$$

Normalization factor
(independent of m_{VLQ}; derived in CR with $450 < m_{\mathrm{VLQ}} < 900$ GeV)



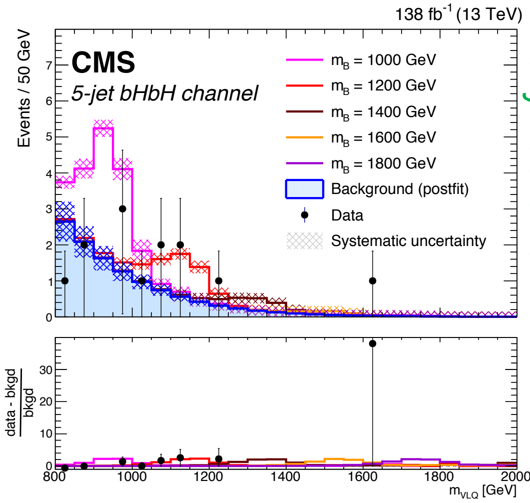


Control region (CR) defined as no b-tagged jet.

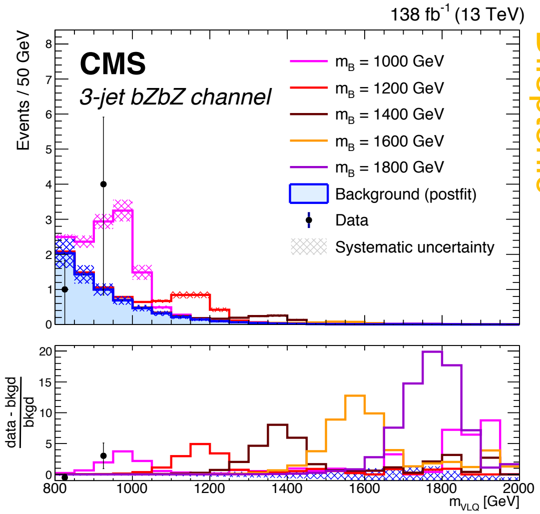
BB production (dileptonic & all-had)

arXiv:2402.13808

- Reconstructed m_{VLQ} distributions show no statistically significant excess over the background expectations.

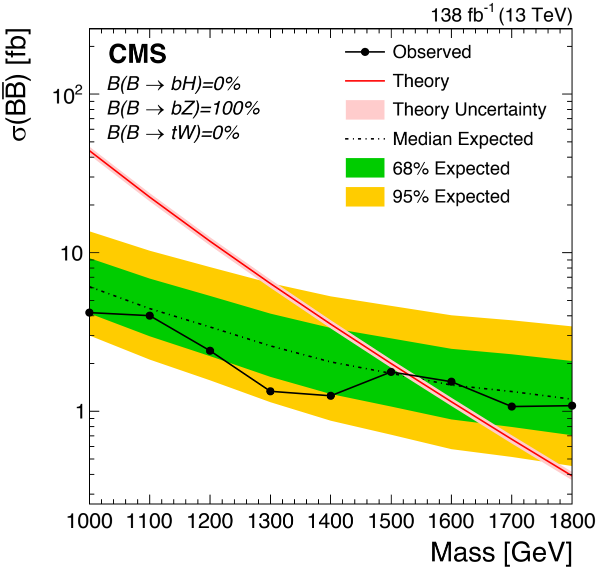


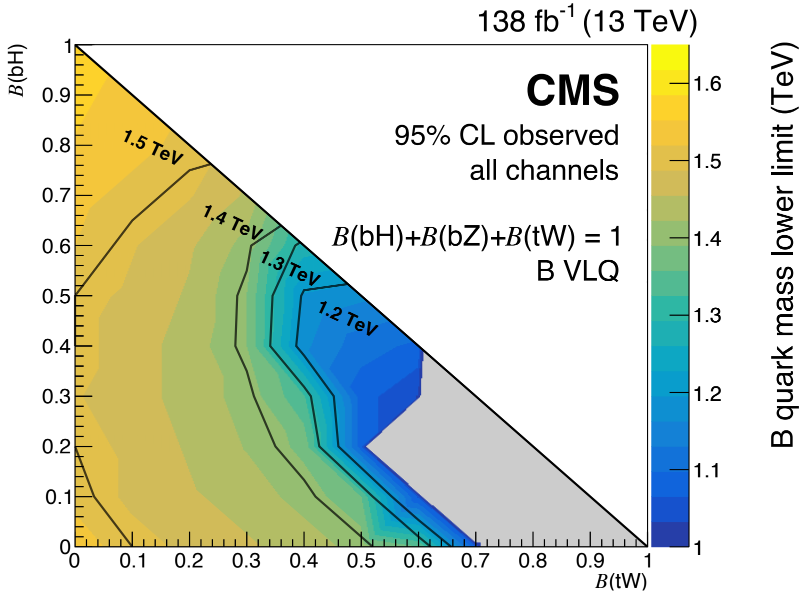
Fully hadronic



Dileptonic

- Exclusion limits on the VLQ mass are derived as a function of the branching fractions to the different decay modes.
- In models in which the branching fraction to bZ is larger, the increased sensitivity is more evident.
- The limits on B are the most stringent to date.





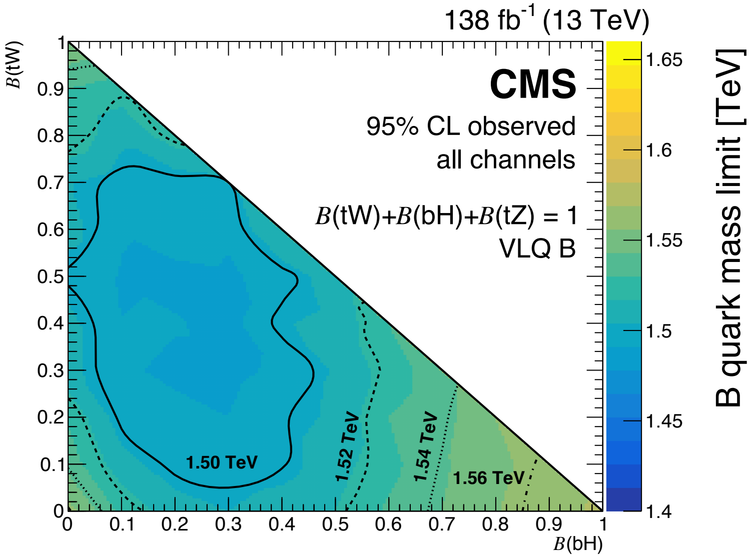
Combination of BB searches **New**

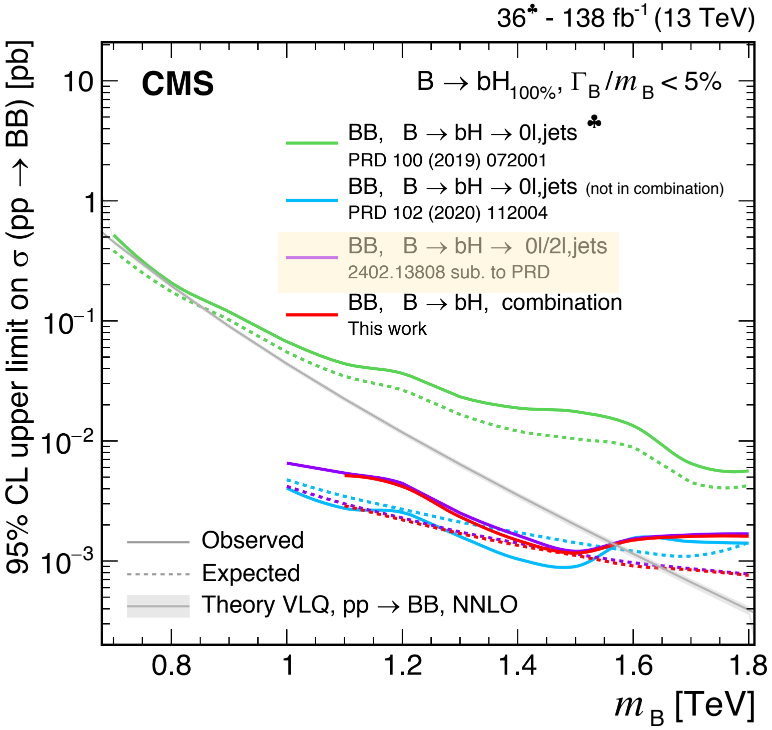
arXiv:2405.17605

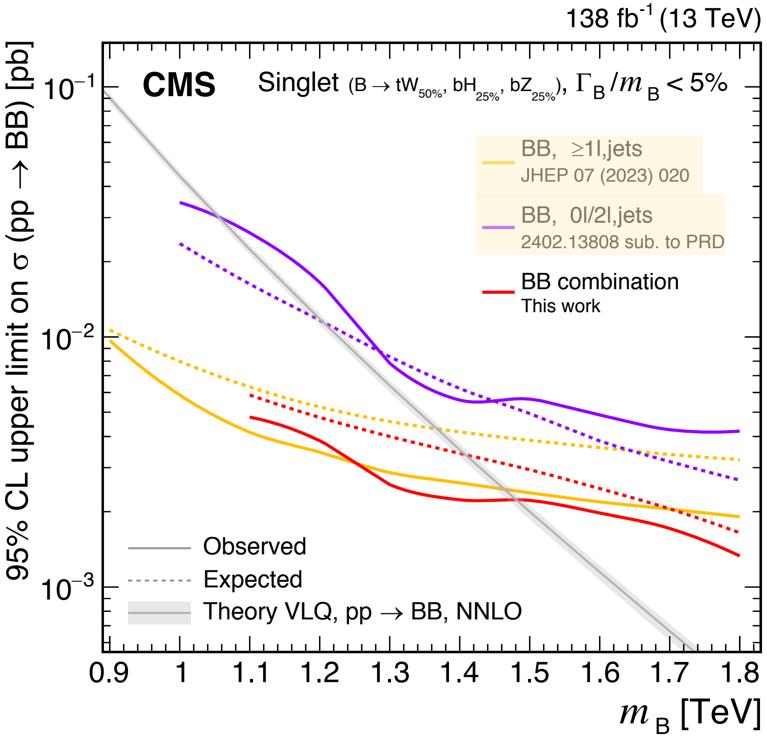
- Mutually exclusive lepton selection criteria. Final states:

hadronic	**same-sign dilepton**	**multilepton**
single-lepton	**opposite-sign dilepton**	

- Simultaneous fit to all template distributions to determine common signal strength.
- BB production is excluded for masses below 1.49 TeV ⇒ significant increase w.r.t. any of the individual searches.







> Depending on the assumed branching fraction is the gain in sensitivity from the combination.

Summary

- At CMS, an extensive search program for VLQs is underway.

- Two new individual analyses presented today. Alas, no new particles but…

  Sophisticated analysis techniques to deal with complex final states are pushing the limits for the production of these particles.

- A review of Run 2 results has just been released, including the combination of various analyses increasing the sensitivity of the searches. Only a handful of results shown today. Please go and have a look!

- With Run 3 data we can expect an increase in the VLQ production cross section (from the slight increase in c.o.m. energy), improvements in object reconstruction and analysis techniques, as well as the possibility of exploring exotic decays of VLQs.

Backup

Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

Low-mass selection

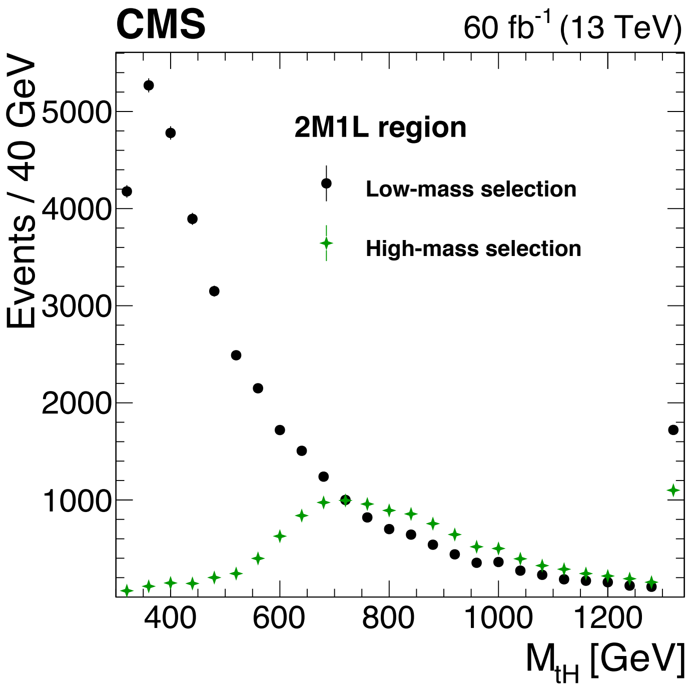
Mass-dependent cut on each of the variables that modify the shape of the invariant mass distribution.

Consider the distributions of the relative H_T and **Δ**R variables in bins of the five-jet invariant mass distribution.

For each bin, extract the quantile value associated to the fraction of events that are to be kept (defined so as to match the selection efficiency of the high-mass selection).

Fit the resulting threshold values as a function of the five-jet invariant mass. These functions represent the mass-dependent criteria for each variable.

The cut is extracted from the fit function, based on the reconstructed tbb mass.



Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

2M1L Background dominated → TF → **3M** Transition → TF → **3T** Signal dominated

L – loose
M – medium
T – tight

$$\lambda_{3T}(b) = \lambda^B_{3T}(b) + \mu\lambda^S_{3T}(b)$$
$$\lambda_{3M}(b) = \lambda^B_{3M}(b) + \mu\lambda^S_{3M}(b)$$
$$\lambda_{2M1L}(b) = \lambda^B_{2M1L}(b) + \mu\lambda^S_{2M1L}(b).$$

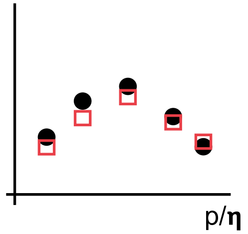
transfer functions

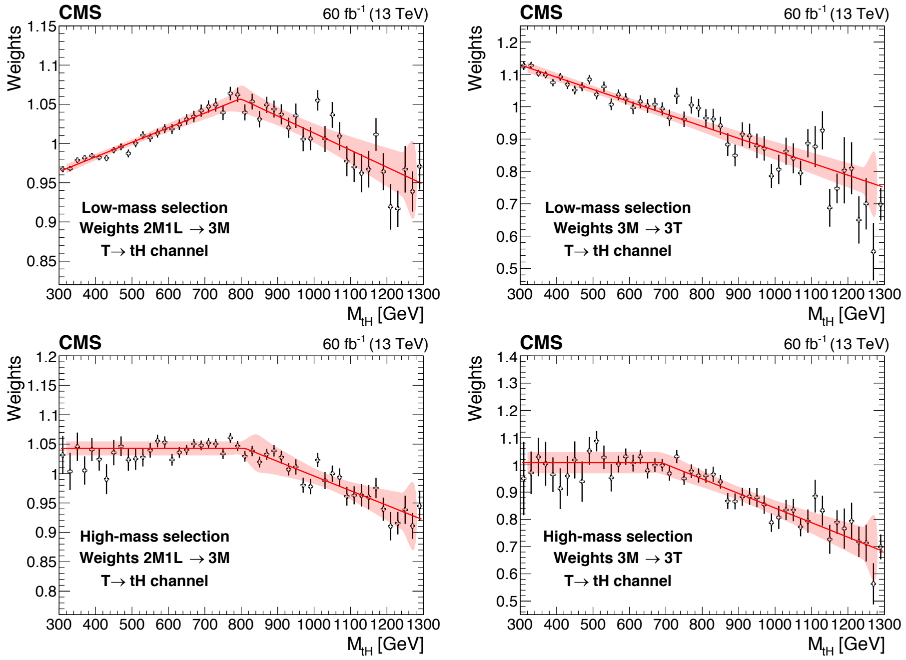
$$\lambda^B_{3T}(b) = N_{3M\to 3T}\, f_{3M\to 3T}(b)\, \lambda^B_{3M}(b)$$
$$\lambda^B_{3M}(b) = N_{2M1L\to 3M}\, f_{2M1L\to 3M}(b)\, \lambda^B_{2M1L}(b)$$

normalization factors
(selection efficiency ratio)

$$N_{3M\to 3T} = \varepsilon_{\mathrm{sel}\ 3T} / \varepsilon_{\mathrm{sel}\ 3M}$$
$$N_{2M1L\to 3M} = \varepsilon_{\mathrm{sel}\ 3M} / \varepsilon_{\mathrm{sel}\ 2M1L}$$

To correctly model the background shape in regions with different b-tagging criteria, events are reweighted based on the ratio of jets between categories (parameterized as functions of total momentum and **η**).





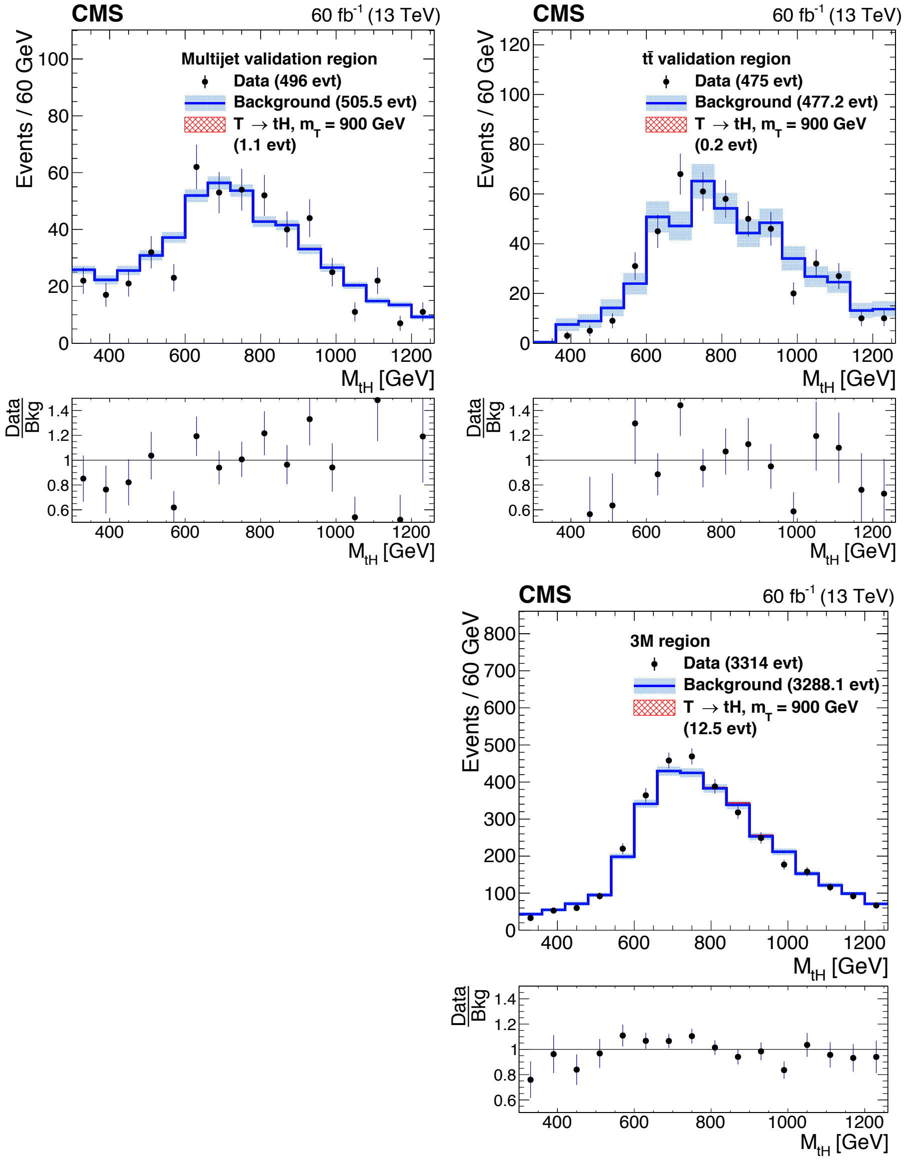
Ratio between categories is fitted, for each variable. The weight for a given jet is $w_p \bullet w_\eta$, and the total event weight is the product of all jet weights.

Transfer functions are derived by fitting two linear functions to the weight distributions as a function of mass.

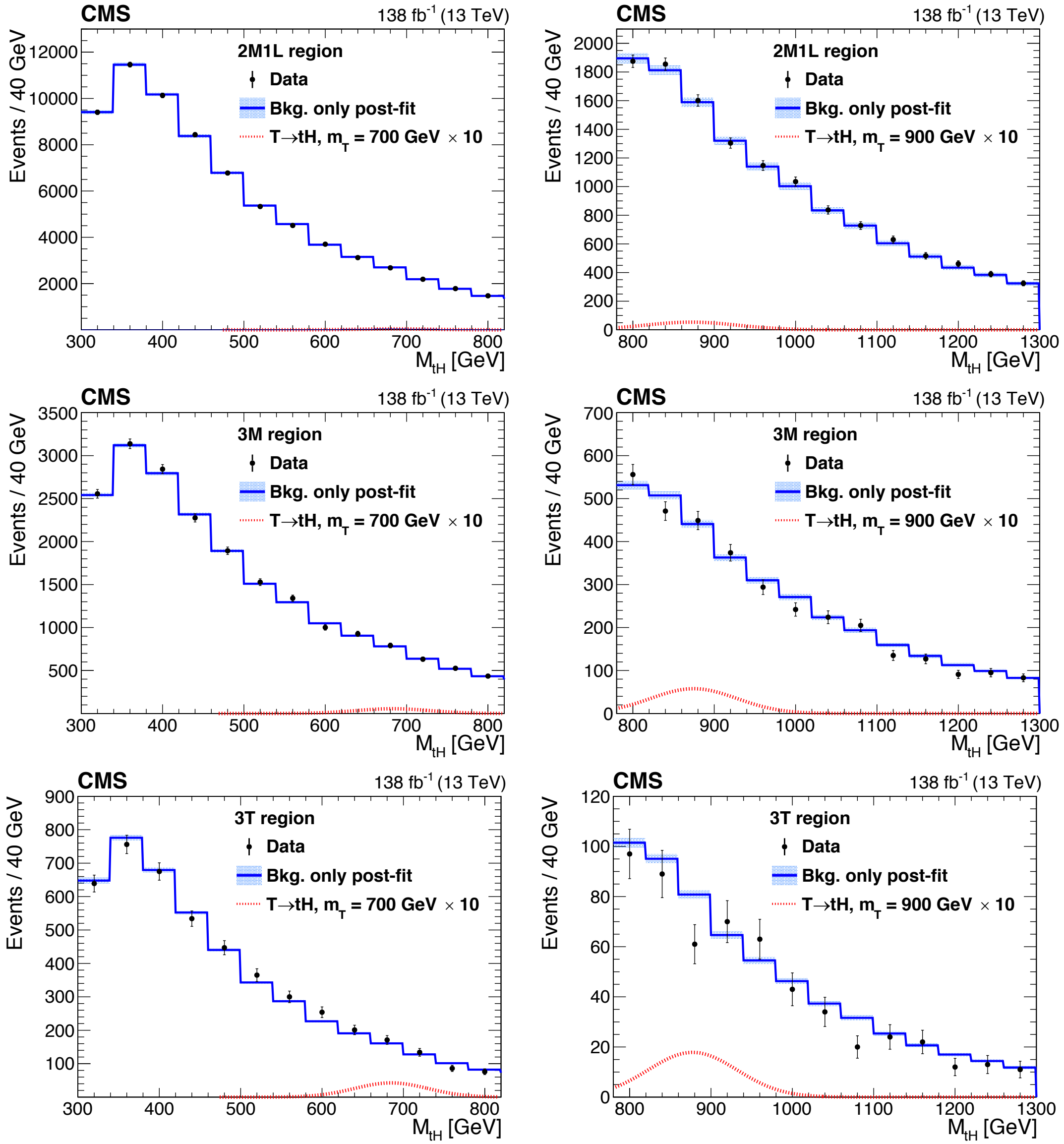
Single production of T to tH/tZ (all-hadronic)

arXiv:2405.05071

Validation of data-driven background method



5-jet invariant mass distributions after bkg-only fit



BB production (dileptonic & all-had)

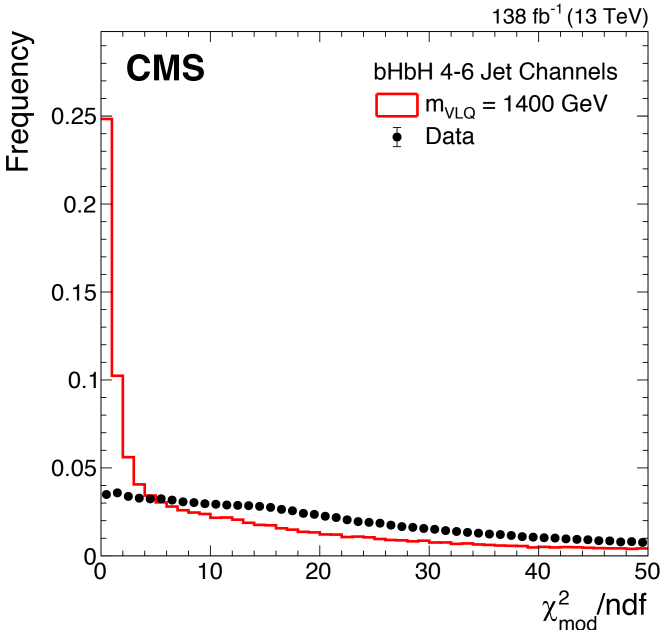
arXiv:2402.13808

Cut on χ^2/ndof is optimized for each jet multiplicity and decay mode.

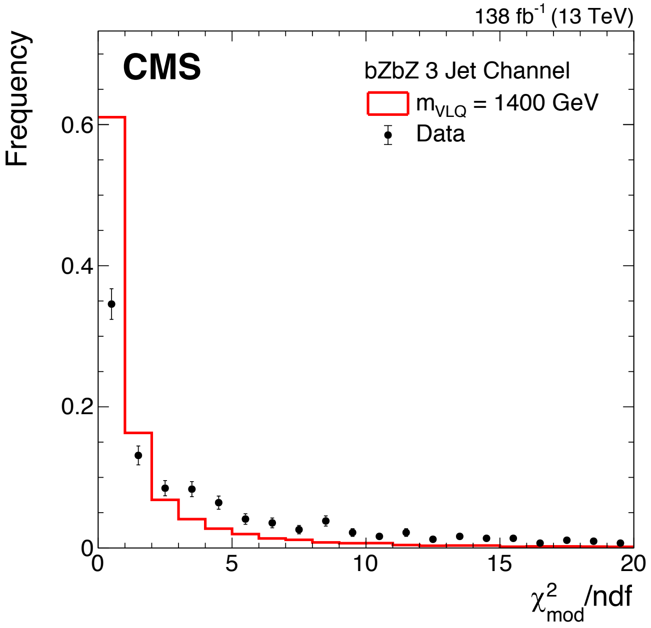
Decay mode	Jet multiplicity			
	3	4	5	6
Fully hadronic bHbH	—	1.5	2.75	1.0
Fully hadronic bHbZ	—	2.0	1.25	1.25
Fully hadronic bZbZ	—	0.75	1.25	1.75
Fully hadronic bHtW	—	—	2.5	5.0
Fully hadronic bZtW	—	—	1.5	6.0
Leptonic bHbZ	2.9	2.5	—	—
Leptonic bZbZ	2.0	2.6	—	—

Since the values for χ^2/ndof are lower for signal than for background events, an upper limit is set, optimized for signal sensitivity.

This is done separately for each category and channel.



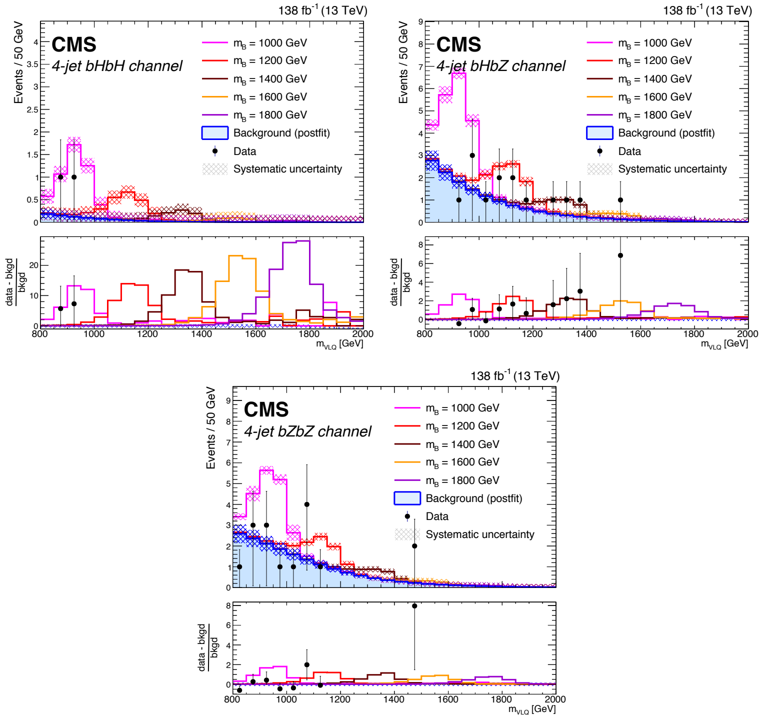
Fully hadronic



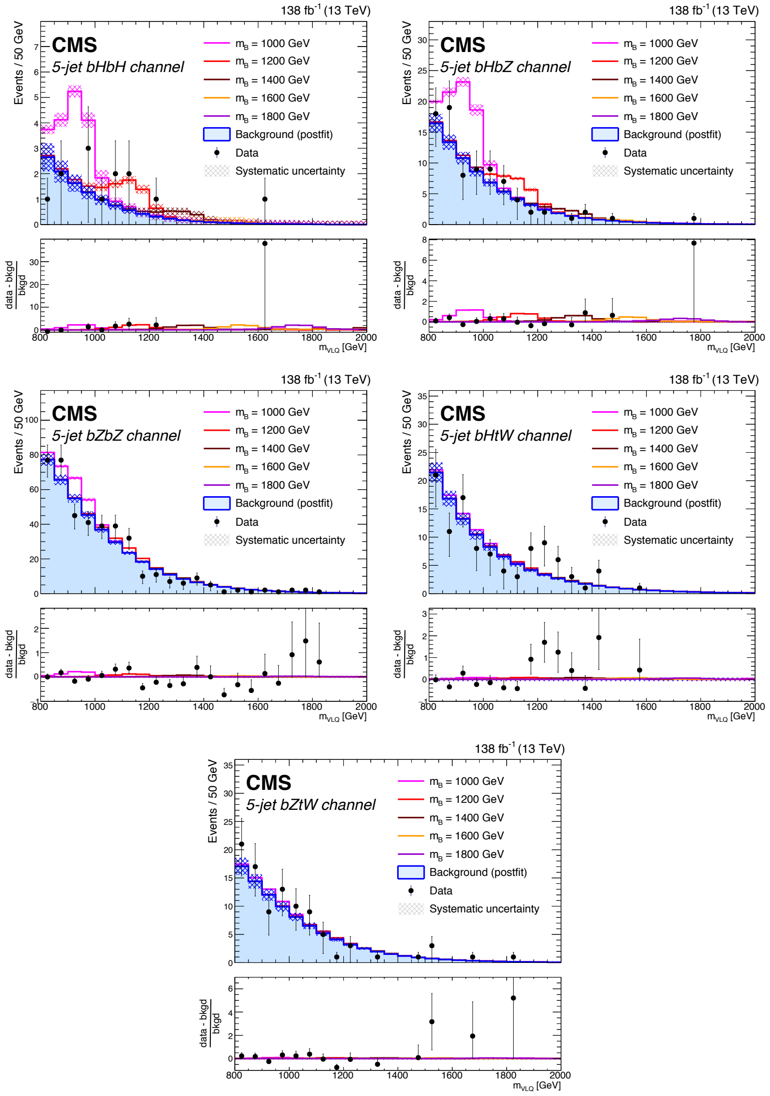
Dileptonic

BB production (dileptonic & all-had)

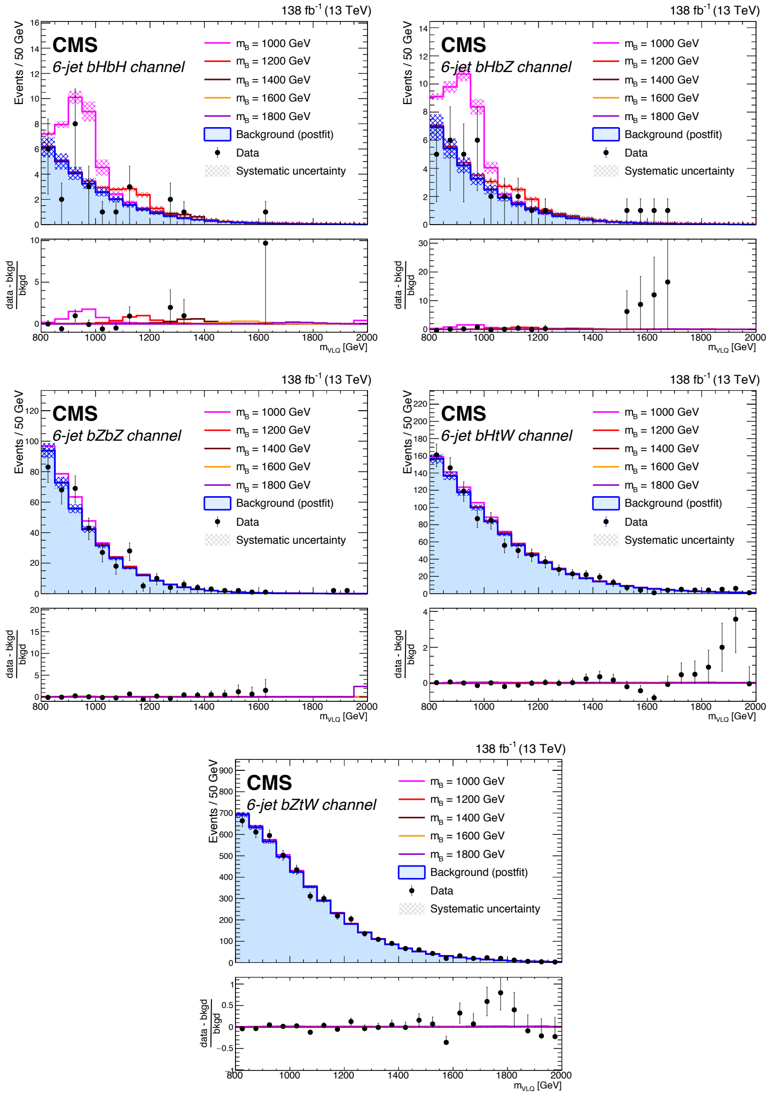
arXiv:2402.13808



4-jet fully hadronic



5-jet fully hadronic



6-jet fully hadronic