Searches for vector-like quarks and leptons at CMS

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EPS-HEP 2025
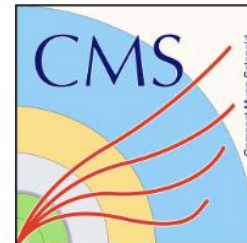
➢ **Vector-like fermions aim to solve multiple beyond standard model questions**

 ▪ Hierarchy problem, nonzero neutrino mass, dark matter...
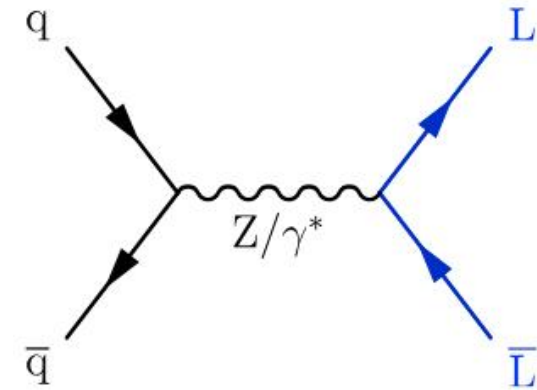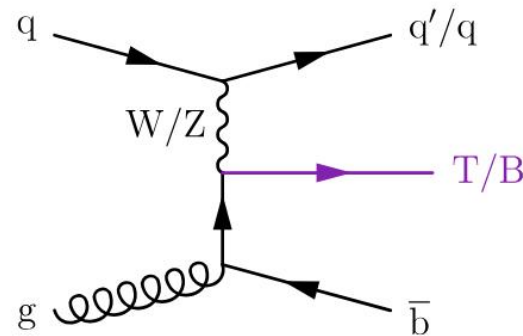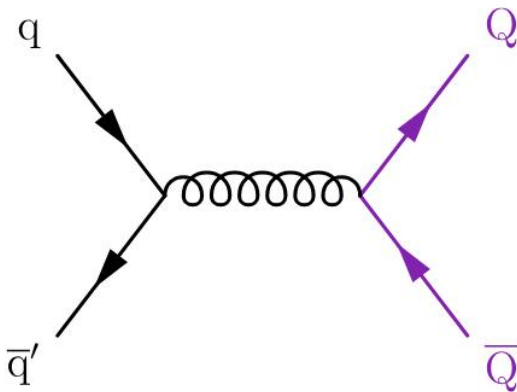
➢ **Vector-like quarks (VLQ)**

 ▪ Left-handed and right-handed components interact equally within the weak interaction

 ▪ **Singly produced** via electroweak interaction or **pair-produced** via strong interaction

 ▪ 4 types of VLQ (Widely searched in LHC experiments)

 ▪ Single production cross-section depends on coupling with SM particles

$$T \to bW^+, \quad T \to tZ, \quad T \to tH$$
$$B \to tW^-, \quad B \to bZ, \quad B \to bH$$
$$X_{5/3} \to tW^+$$
$$Y_{4/3} \to bW^-$$

➢ **Vector-like leptons (VLL)**

 ▪ Color-singlet counterparts of VLQ

$$E \to Zl, \quad E \to Hl$$
$$N \to Wl$$

Results covered in this talk

➢ **Vector-like Leptons**
  ▪ Search for τ' with long-lived particle decays in CMS Run 2 (CMS-EXO-23-015)

➢ **Vector-like Quarks**
  ▪ Search for single production of $Y/T \rightarrow b + W$ using the single-lepton final states in CMS Run 2 (CMS-PAS-B2G-22-004)
  ▪ Search for single production of $T \rightarrow t + H/\phi$ in lepton+jets final states in CMS Run 2 (CMS-PAS-B2G-23-009)
  ▪ Search for single production of $T \rightarrow t + H/Z$ in all hadronic final state in CMS Run 2 (Phys. Rev. D 110 (2024) 072012)
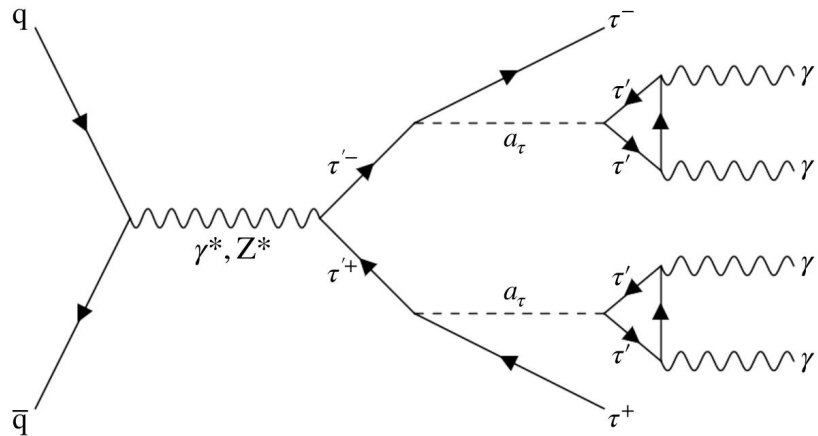
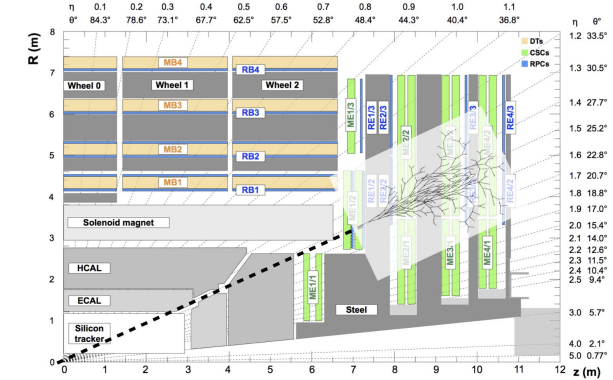➢ **Combined search**
 ▪ Combination of searches for VLQ and VLL in CMS Run 2 (Phys. Rept. 1115 (2025) 570-677)

VLL with long-lived particle decays

➢ Search for a heavy τ' decays into a prompt τ lepton and a light (boosted) long-lived pseudoscalar a_τ

- a_τ decay produces showers in muon detector system
  - Event categories: cathode strip chambers (**CSC**) & drift tubes (**DT**)
- Missing E_T trigger, ≥ 1 τ_h and ≥ 1 CSC/DT cluster with 50 reconstructed hits
- Signal extraction observable: the number reconstructed hits in the cluster N_{hits}
- Background model: Alphabet parametric fit
  - Control region: reverse τ_h selection
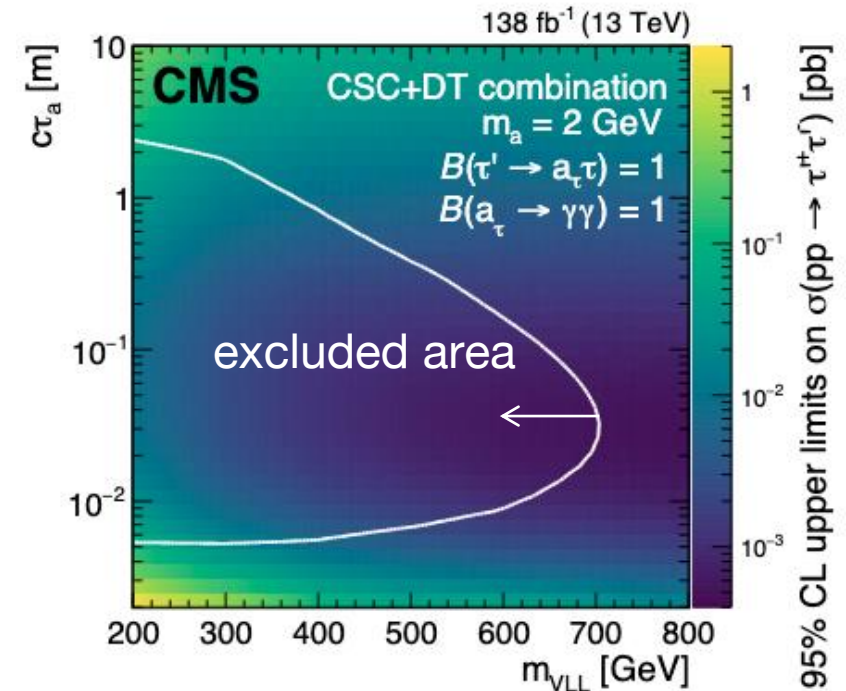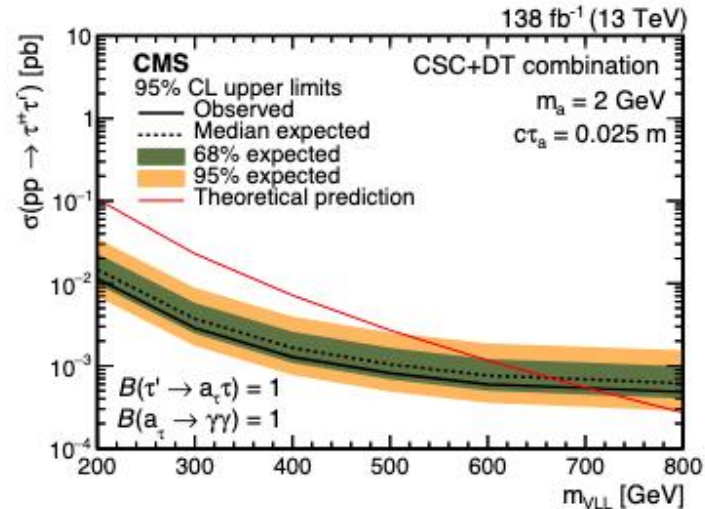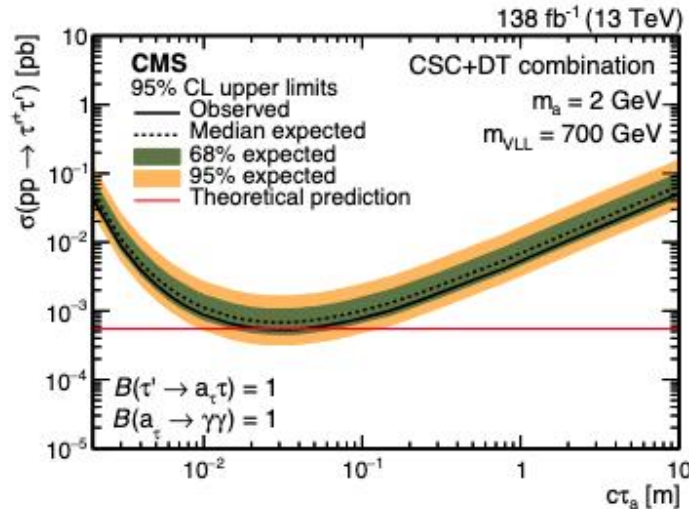 - Validation region: Out of Time data

([CMS-EXO-23-015](CMS-EXO-23-015))
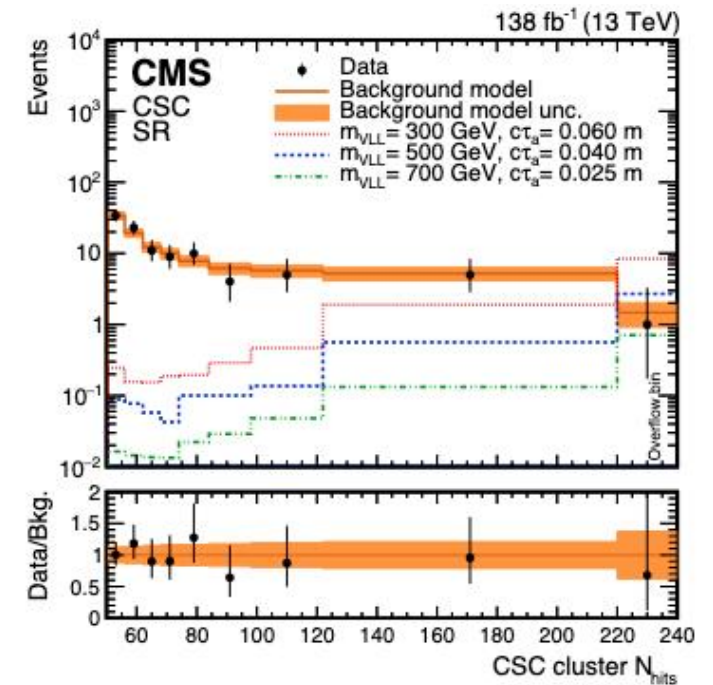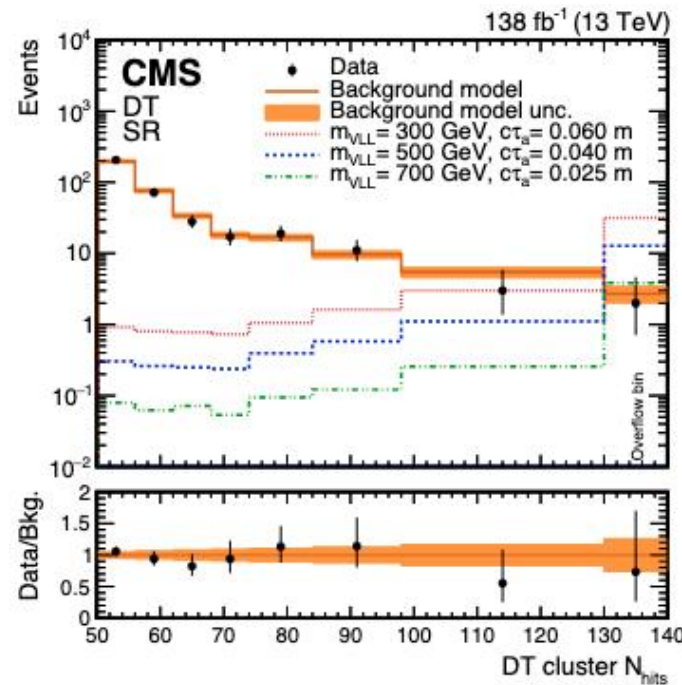
VLL with long-lived particle decays

➢ 95% CL upper limits on production cross section are set, assuming $Br(\tau' \to a\tau_h) = Br(a \to \gamma\gamma) = 1$

- First search for VLLs with long-lived decays at the LHC
- Combine the CSC and DT categories
- VLL mass are excluded up to around 690 GeV, depending on the $c\tau_a$ hypothesis
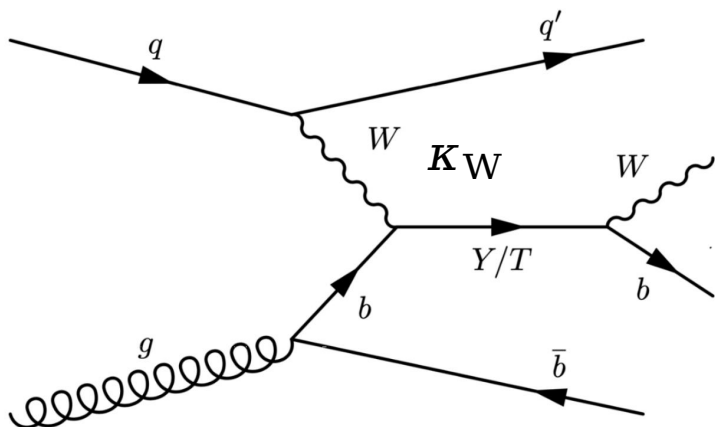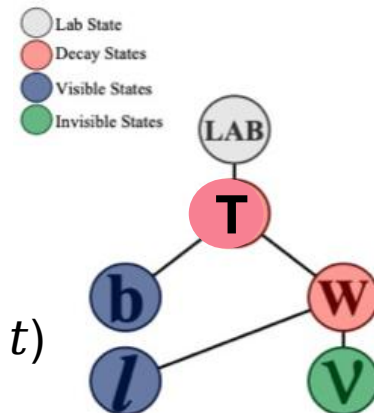
(CMS-EXO-23-015)

➤ Search for single production of $Y/T \to bW;\ W \to l\nu$ in semi-leptonic final state

- Signal extraction observable: m_{rec} from mass reconstruction

$$m_{rec} = \sqrt{m_{vis}^2 + 2(p_T^{miss}\sqrt{m_{vis}^2 + |\vec{p}_T^{\,vis}|^2} - \vec{p}_T^{\,miss} \cdot \vec{p}_T^{\,vis})}$$

- Neural network is trained for each category to remove background ($t\bar{t}$, $W + \mathrm{jets}$ & single t)
  - 6 categories are defined based on the b-tagged jets information and lepton charge
  - NN models are validated in 3 CRs and the region after pre-selection
- Background modeling: Analytical functions fitted for each main background in 6 categories
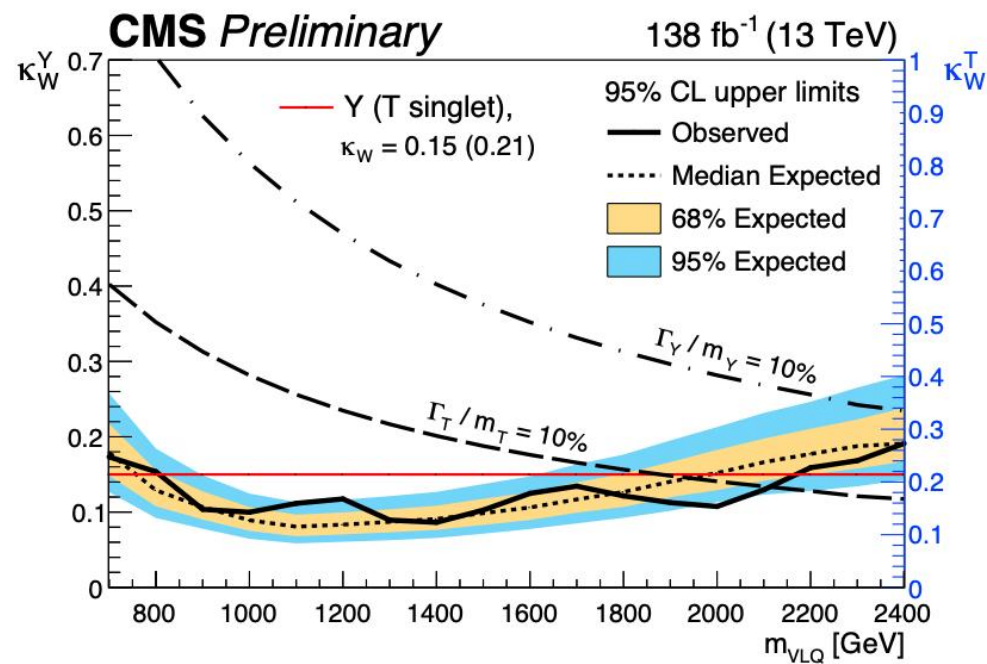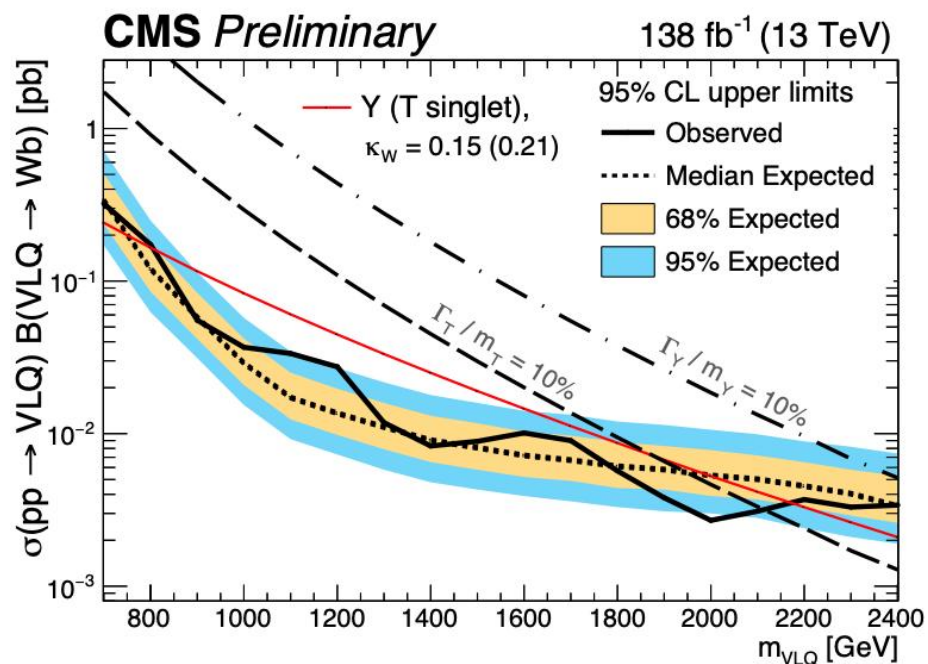
CMS-PAS-B2G-22-004
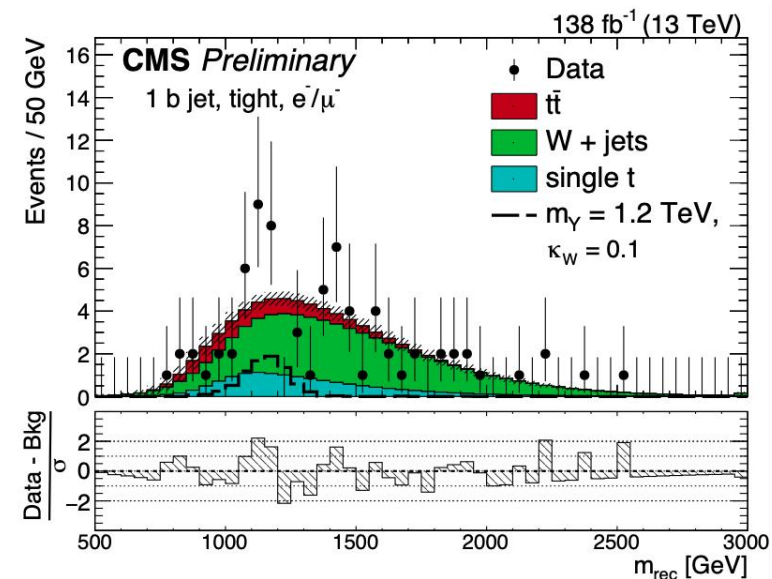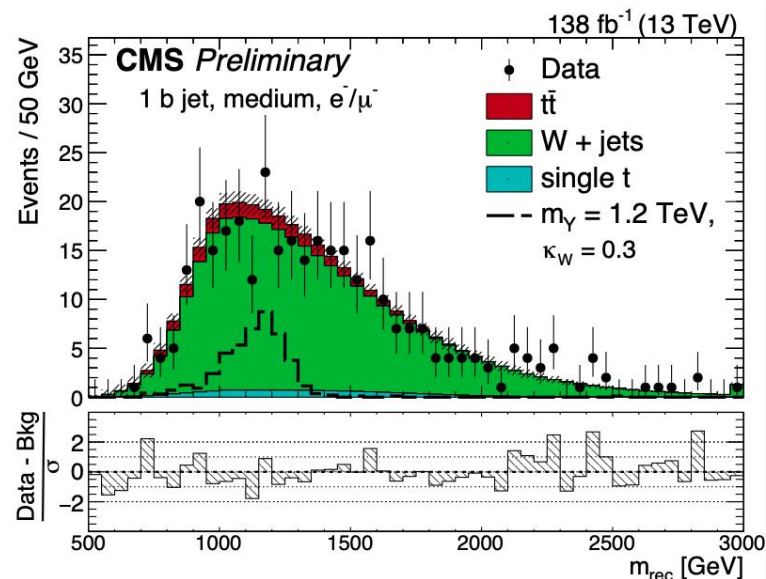
New results!

➤ 95% CL upper limits on VLQ single-production cross section and coupling parameter κ_W

- Most stringent limits on single production of $Y/T \to bW$

- The result excludes the preferred coupling in the (BY)-doublet hypothesis favored by the electroweak fit

 - VLQ mass ranges 0.7 to 2.4 and 0.82 to 2.15 TeV are excluded with κ_W^Y of 0.2 and 0.15

CMS-PAS-B2G-22-004

VLQ search: $T \to tH/\phi$

➢ Search for single production of $T \to tH/\phi$ in lepton+jets final state

- Signal extraction observable: reconstructed T mass $m_{l\nu bJ}$

- Multiclass BDT algorithm to discriminate the top quark from background ($t\bar{t}$, $W + jets$, single t, QCD multijets)

- 16 regions are defined based on number of forward jets and top/ϕ tagging categories

  - 8 signal categories: combination of tight ϕ, (loose top, tight top), (μ, e) and ($n_{fwdJ} = 0$, $n_{fwdJ} \geq 1$)
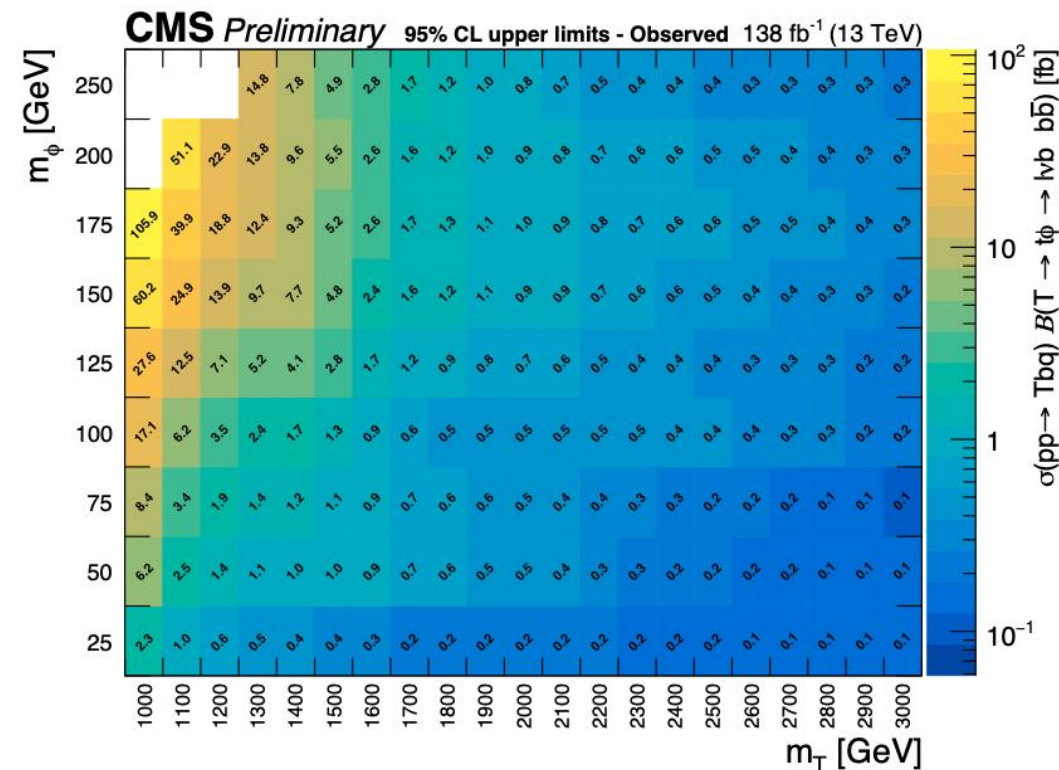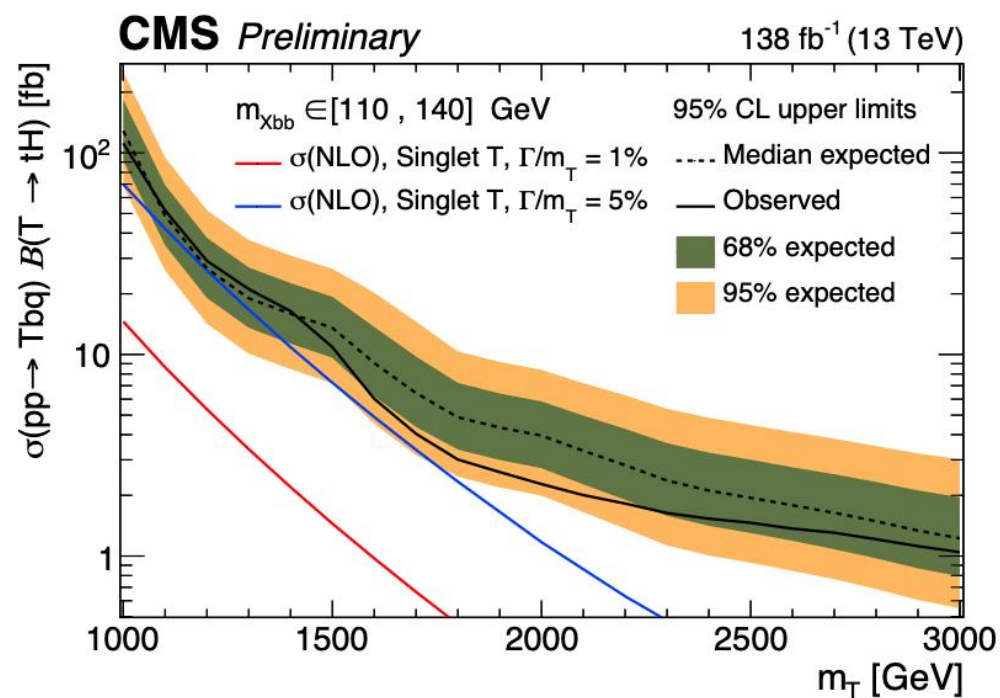
  - Background modeling: MC simulation
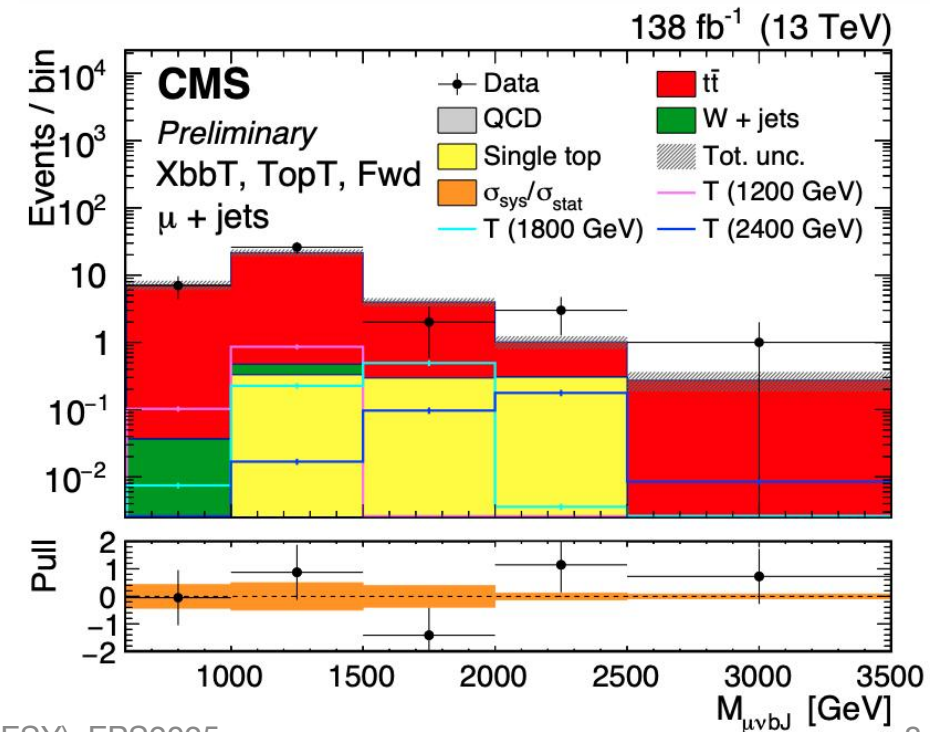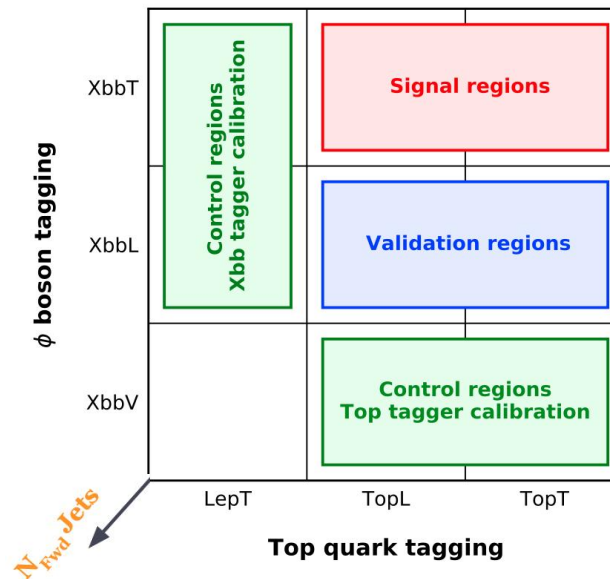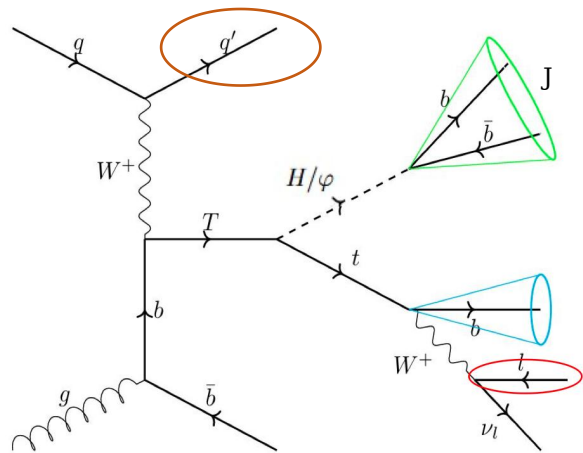
➢ 95% CL upper limits on T single-production cross section

- Significant improvement on previous CMS searches in $m_T > 1.3$ TeV region
- Left: Standard model Higgs boson hypothesis (T → tH): $110 < m_{Xbb} < 140$ GeV
- Right: Limit on $\sigma(pp \to Tbq) * Br(T \to t\phi \to bl\nu b\overline{b})$ as a function of m_T and m_ϕ

CMS-PAS-B2G-23-009

➢ Search for single production of T → tH/Z in all hadronic final state   [Phys. Rev. D 110 (2024) 072012](#)

- Signal extraction observable: reconstructed T mass with χ^2 minimization method
- Event selection criteria optimized for low-mass and high-mass regions
  - Main background: QCD multijets, $t\bar{t}$
  - Selection highly depends on b tagging: 3 tight b-tagged jets in signal region
  - For low-mass region: Apply sliding cuts instead of fixed cuts to avoid sculpting the background
- Background modeling: Derived from relaxed b-tagging region data
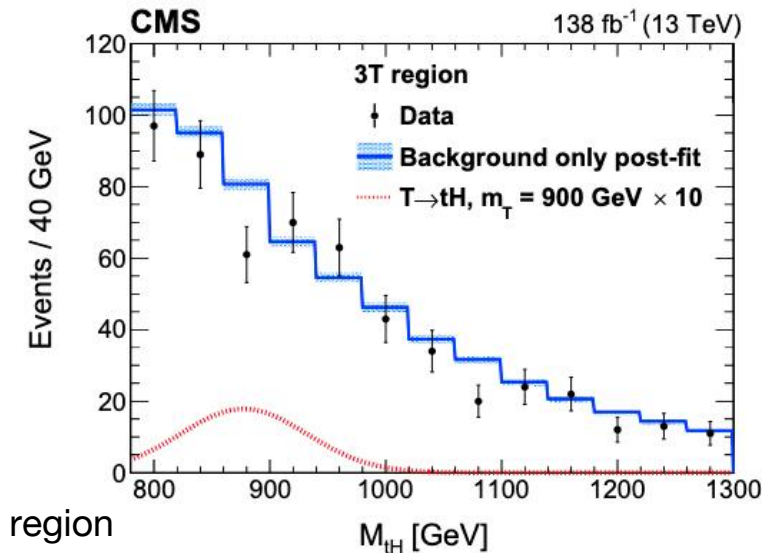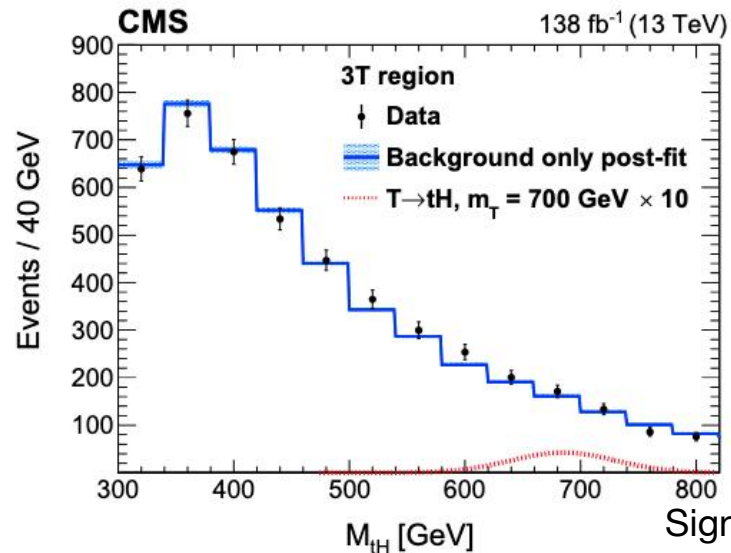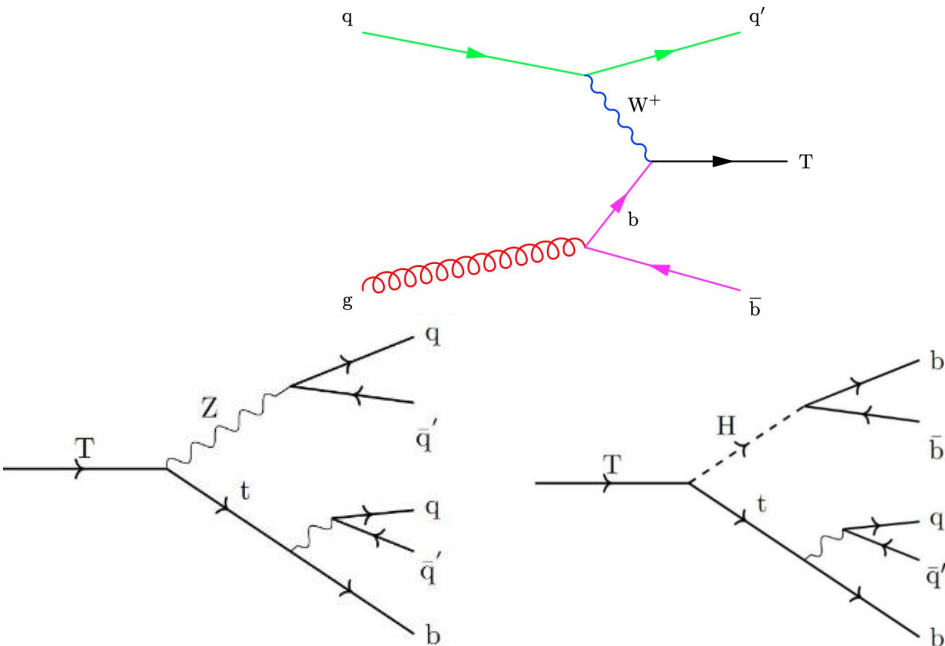

Signal region

VLQ search: T → tH/Z

➤ 95% CL upper limits on T single-production cross section
- Limits are stronger than in 2016-only search by a factor of 3
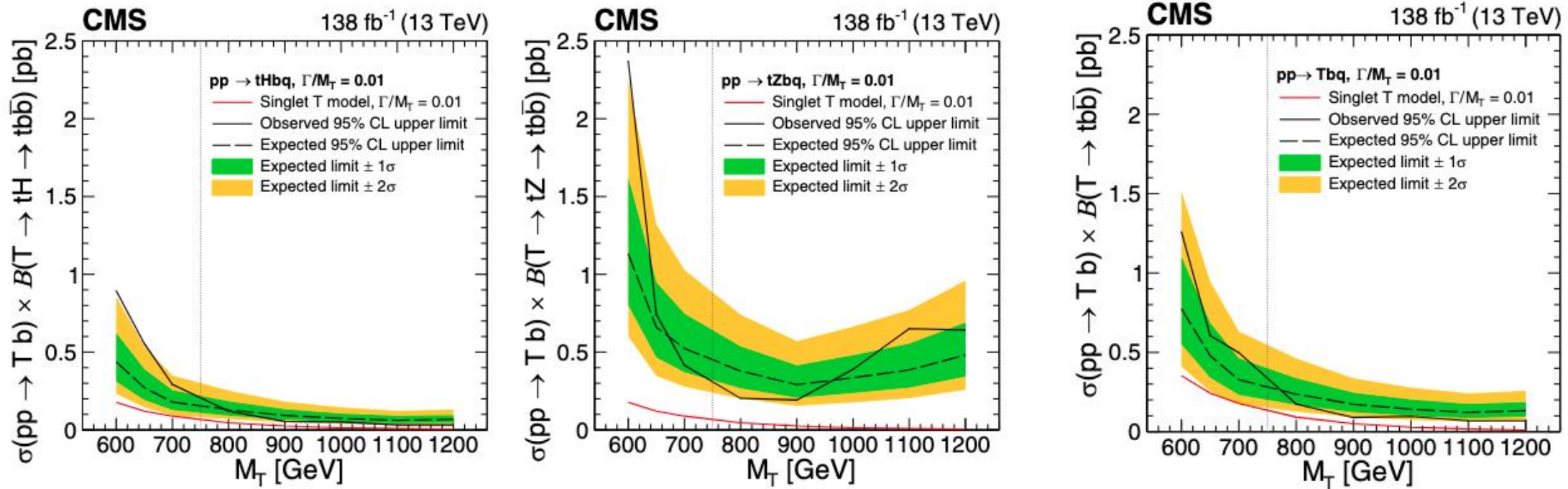
- Combine pair-produced VLQ searches in the 0, 1, SS & OS 2, and 3+ lepton channels
  - BB production with third-generation quark decays excluded for B quark masses below 1.49 TeV
- Combine single production $T \rightarrow tH/Z$ searches with bb, $\nu\nu$, $\gamma\gamma$ decays
  - T production is excluded up to a mass of 1.20, 1.06, 1.25 and 1.36 TeV for decay width of 5%, 10%, 20% and 30%
    - Under narrow-width approximation: 0.91 TeV for decay width of 1%

Phys. Rept. 1115 (2025) 570-677
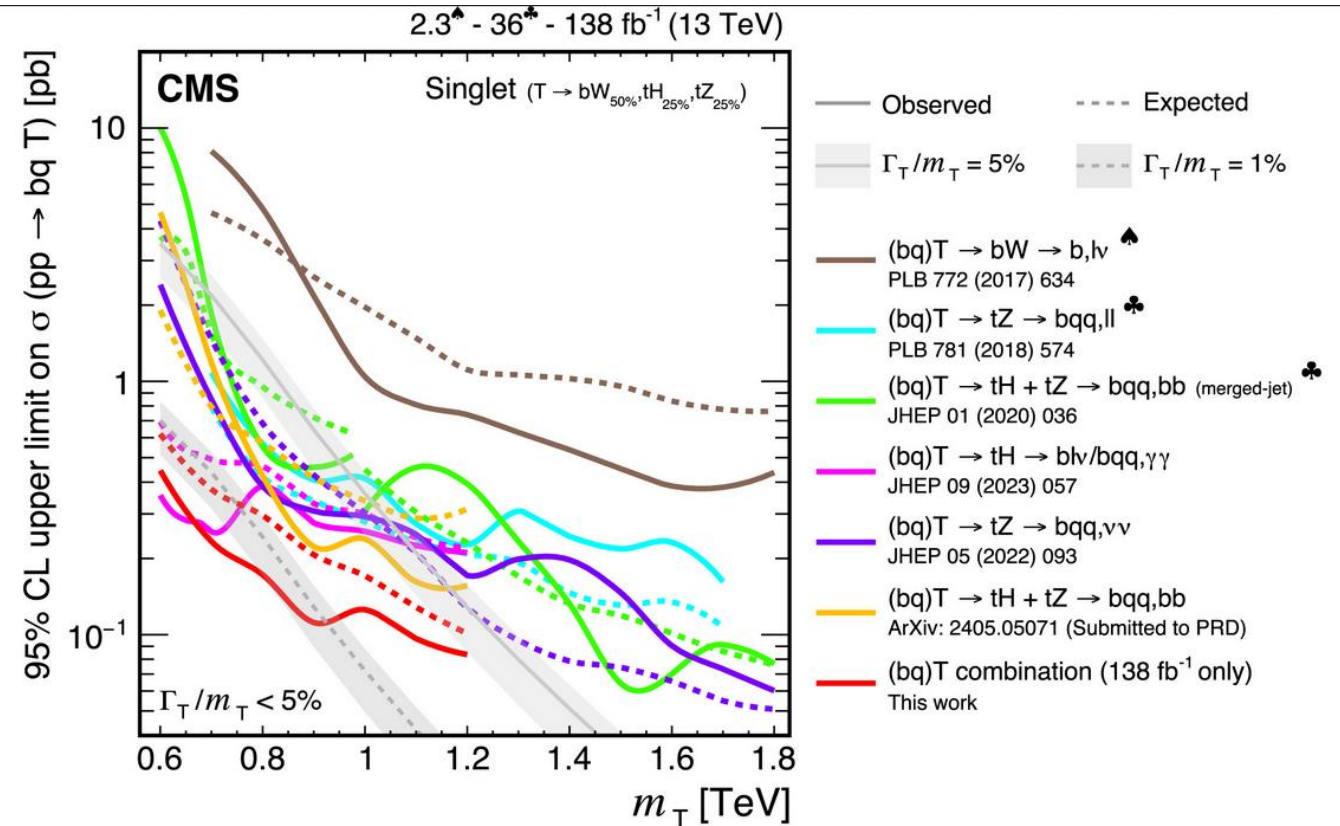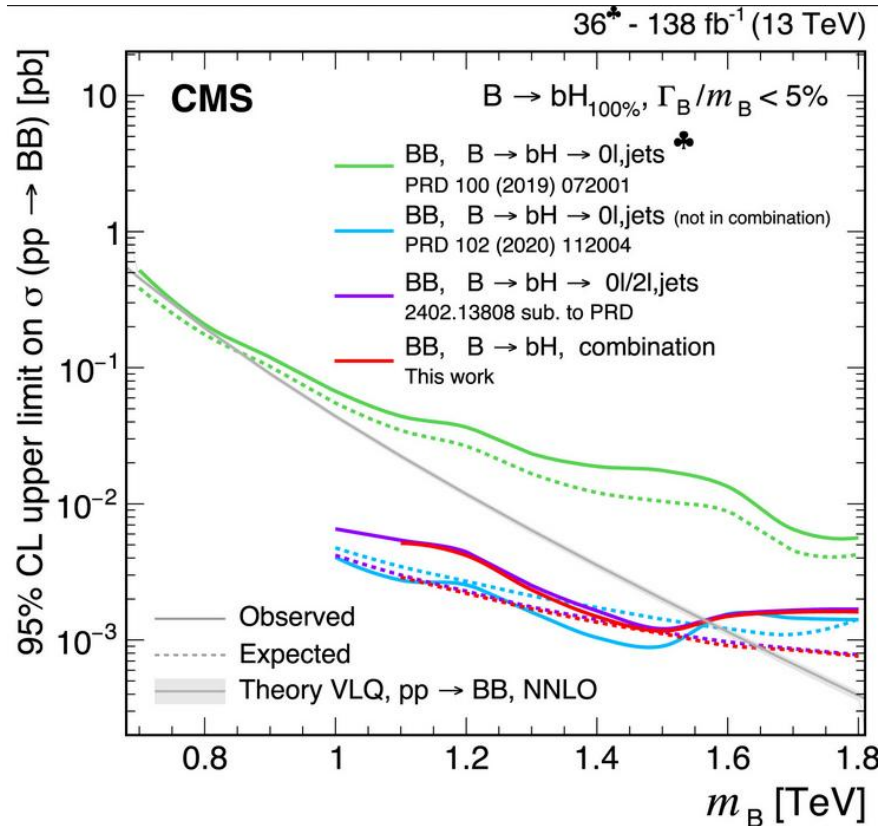
Summary

- ➢ **Many CMS analyses searching for VLQ and VLL across different production mode and final states are published**
  - Single production of VLQ in CMS Run 2
    - $Y/T \rightarrow b + W$ in single-lepton final state
    - $T \rightarrow t + H/\phi$ in lepton+jets final state
    - $T \rightarrow t + H/Z$ in all hadronic final state
  - Pair production of VLL in CMS Run 2
    - τ' with long-lived particle decays
  - Combination and review of VLQ & VLL
- ➢ **Look forward to many ongoing analyses coming out**
- ➢ **No beyond standard model excess of VLQ or VLL found**
  - **There are still unexplored regions of parameter space in VLQ& VLL models**
  - ***Let's stay tuned!***

Thanks!

Backup

- More luminosity: 450 fb^{-1} in total
- Many technical optimizations
  - e.g. online & offline b tagging in Run 3: 10 times reduction in background & 40% increase in signal efficiency
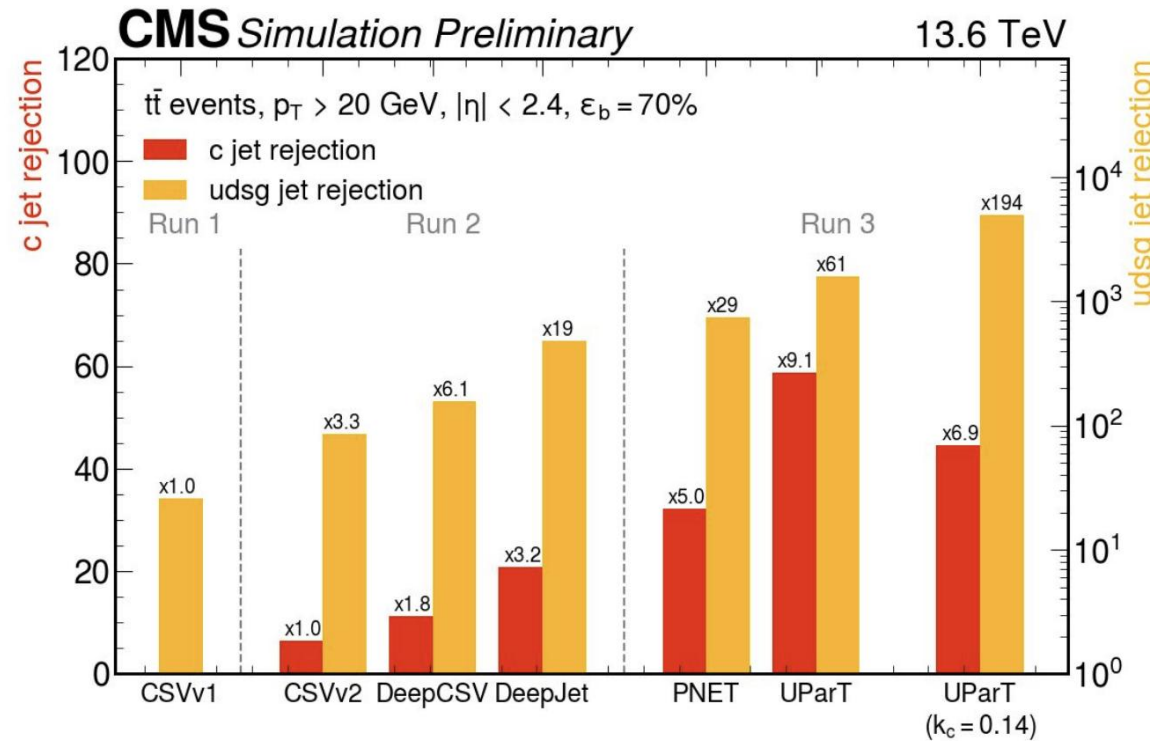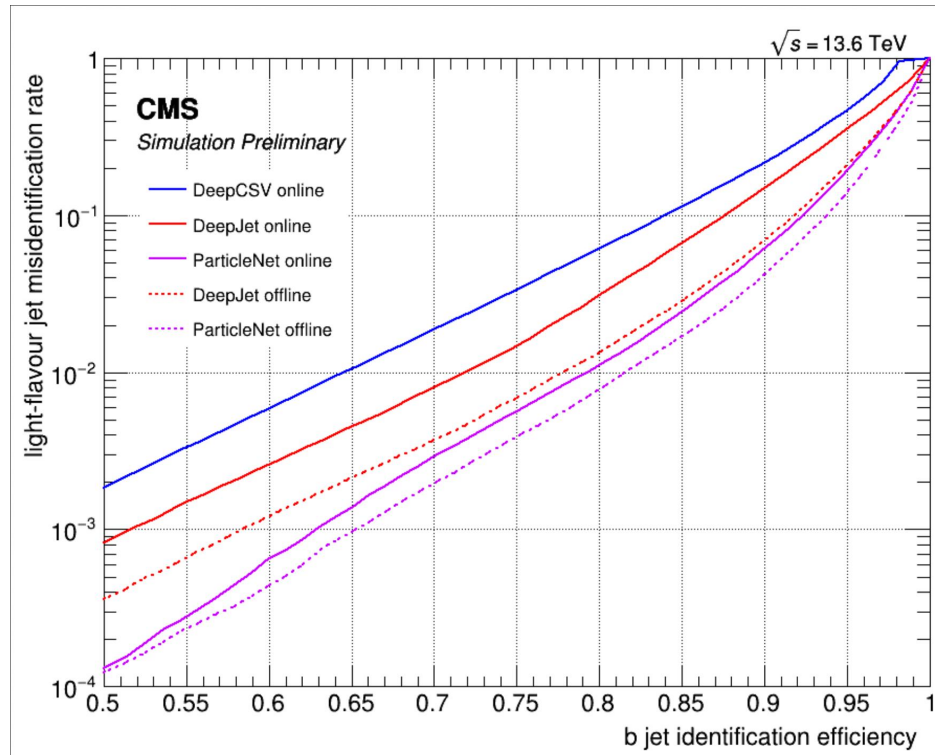
➢ HL-LHC: 3000 fb^{-1} of data expected
- e.g. T$\overline{\text{T}}$ search: HL-LHC study projects a 95% CL exclusion for T quarks with masses below 1750 GeV