

# Recent results on Vector-Like Quarks and Excited Fermions at CMS

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on behalf of the CMS collaboration

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BROWN



## ► Vector-Like Quarks

- ▷ Motivation and theory
- ▷ [CMS-PAS-B2G-23-009](#):  $T \rightarrow t\phi(H)$  in single lepton final state
- ▷ [CMS-PAS-B2G-22-001](#):  $T \rightarrow t\phi(H)$  in hadronic final state **Newest!**
- ▷ [CMS-PAS-B2G-22-004](#):  $Y/T \rightarrow Wb$  in single-lepton final state

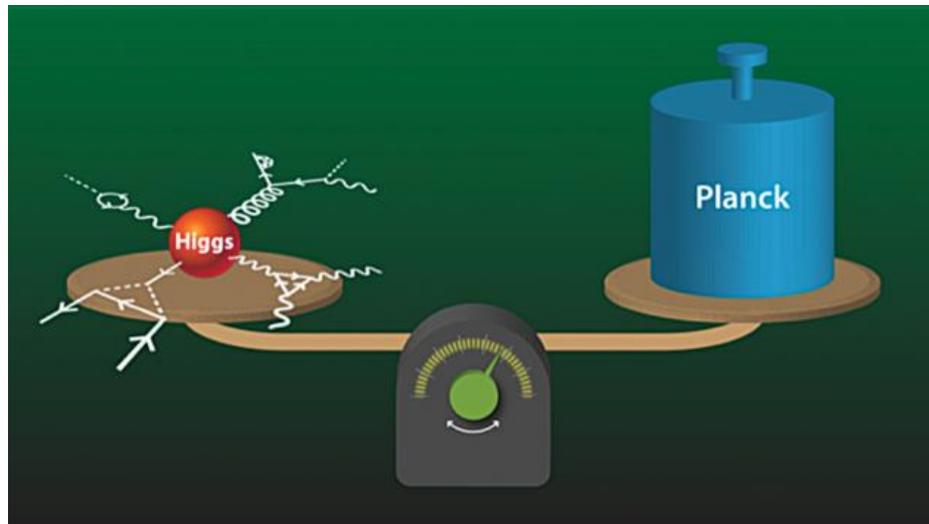
## ► Excited Fermions

- ▷ Motivation and theory
- ▷ [EPJC 85 \(2025\) 342](#):  $t^*\bar{t}^* \rightarrow t\bar{t}g$  in lepton + jets final state
- ▷ [CMS-PAS-B2G-24-006](#):  $t^*\bar{t}^* \rightarrow t\bar{t}\gamma$  in photon + jets final state

## ► Summary

## Naturalness Problem

- ▶ Higgs vacuum expectation value (VEV) is expected at Planck scale ( $> 10^{19}$  GeV)
  - Suggests new physics at TeV scale
- ▶ Models attempting to address the problem:
  - Composite Higgs, two-Higgs boson doublets (2HDMs), extra dimensions



## Vector-Like Quarks (VLQs)

- ▶ Colored spin-1/2 fermions
- ▶ Chiral symmetry under the electroweak symmetry group
- ▶ Mass at  $\mathcal{O}(1 \text{ TeV})$
- ▶ Can appear as singlets, doublets or triplets

### Singlets

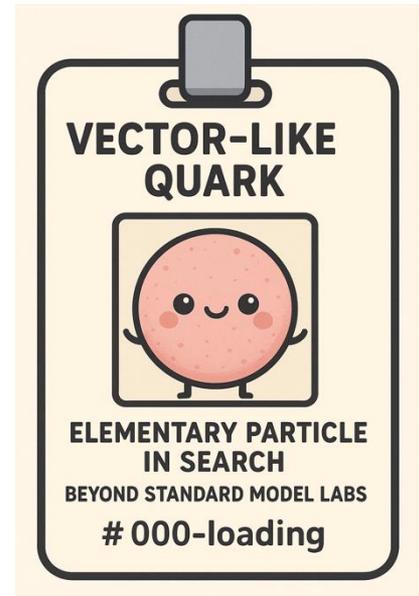
$$1_{2/3} = T$$
$$1_{-1/3} = B$$

### Doublets

$$2_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$$
$$2_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$$
$$2_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$$

### Triplets

$$3_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$$
$$3_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$



### Charge

- ▶ T: +3/2
- ▶ B: -1/3
- ▶ X: +5/3
- ▶ Y: -4/3

## VLQ decays

- ▶ **Minimal scenario:** couples exclusively to third-generation **SM** quarks and W, Z, H bosons
  - ▷ Singlet:  $T \rightarrow bW, T \rightarrow tZ, T \rightarrow tH$
  - ▷ Doublet:  $Y \rightarrow bW$
  
- ▶ **Non-minimal scenario:** can decay to **non-SM** particles such as
  - ▷  $T \rightarrow t\phi, \phi$  is a new scalar boson

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Search in single lepton final state [CMS-PAS-B2G-22-004](#)

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Search in single lepton final state [CMS-PAS-B2G-22-004](#)

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Search in single lepton final state [CMS-PAS-B2G-22-001](#)

Search in hadronic final state [CMS-PAS-B2G-22-004](#)

★ Newest!

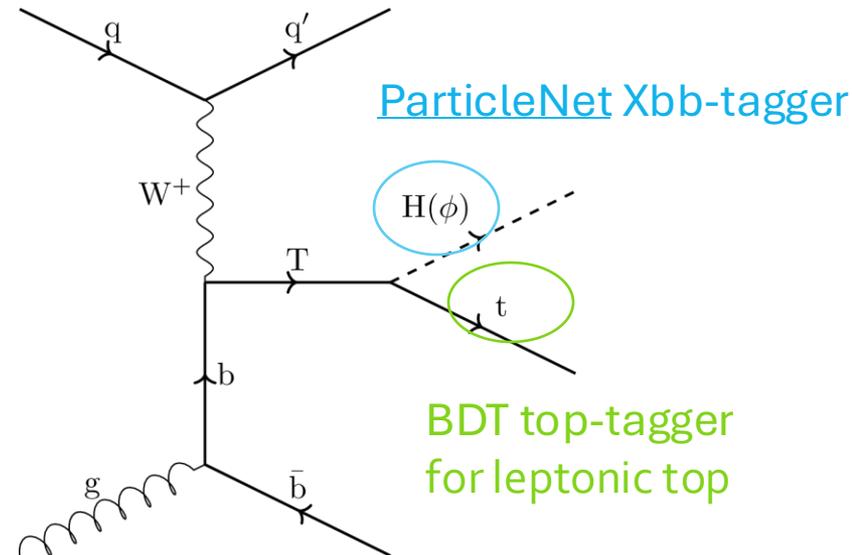
★ Combined results to release soon!

## Analysis Target

- ▶ Single production of vector-like T quark
  - ▷  $\text{Br}(T \rightarrow tH)$ : 25%
  - ▷  $\text{Br}(T \rightarrow t\phi)$ : 100%
- ▶ Search range:
  - ▷ T mass: 1 – 3 TeV
  - ▷  $\phi$  mass: 25 – 250 GeV
- ▶ Single lepton final state

## Event signature

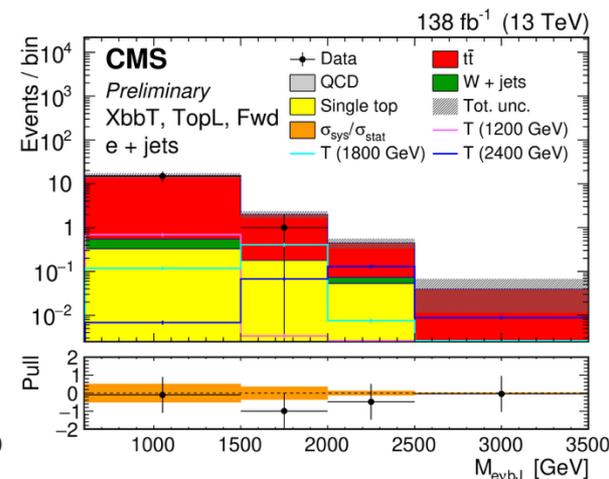
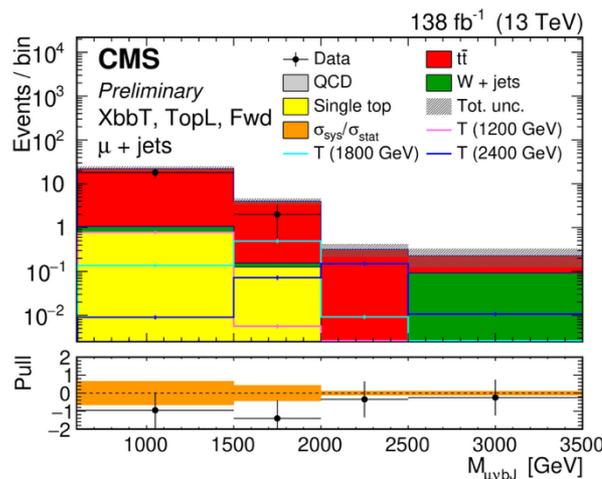
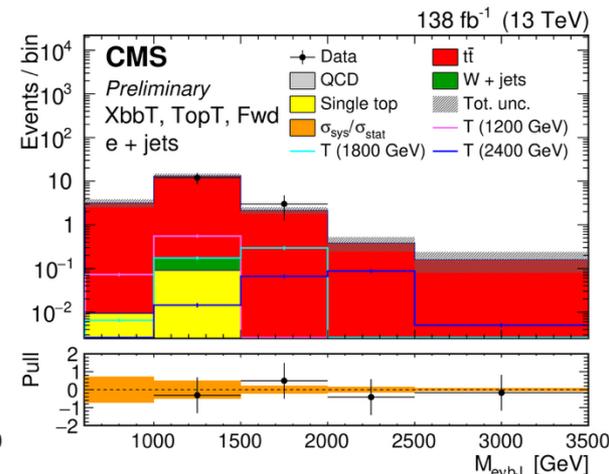
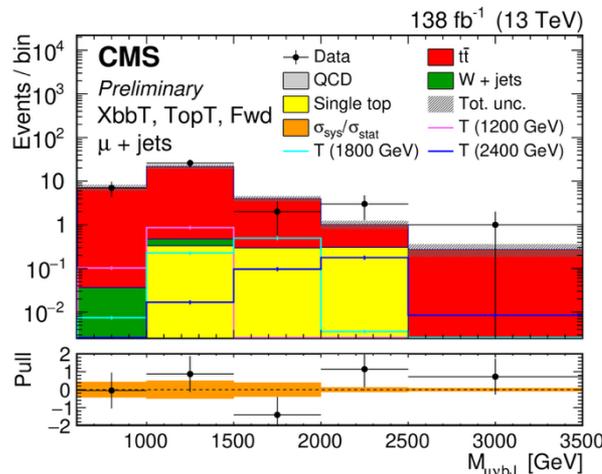
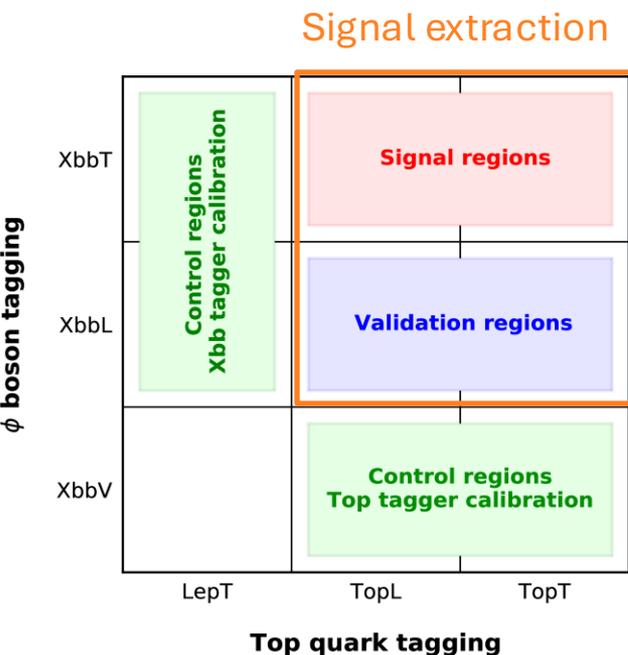
- ▶  $\phi(H) \rightarrow b\bar{b}$ : large-radius jet
- ▶  $t \rightarrow Wb \rightarrow l\nu b$ : lepton + MET + small-radius jet



# Vector-Like Quark: $T \rightarrow t\phi(H)$ in single lepton final state

## Analysis Highlights

- ▶ BDT top-tagger improves top identification efficiency by 30%
- ▶ Region definition with the top-tagger and Xbb-tagger



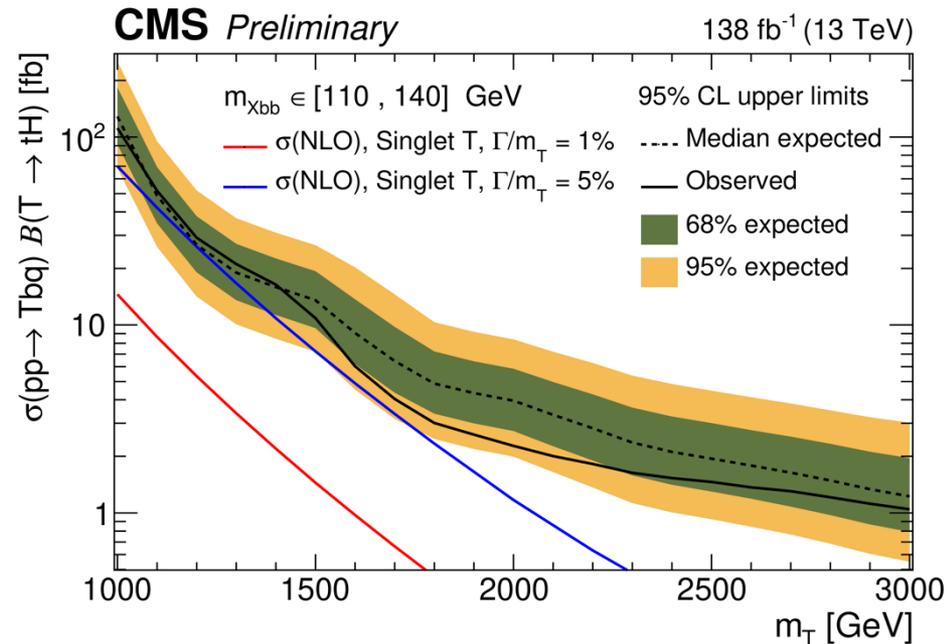
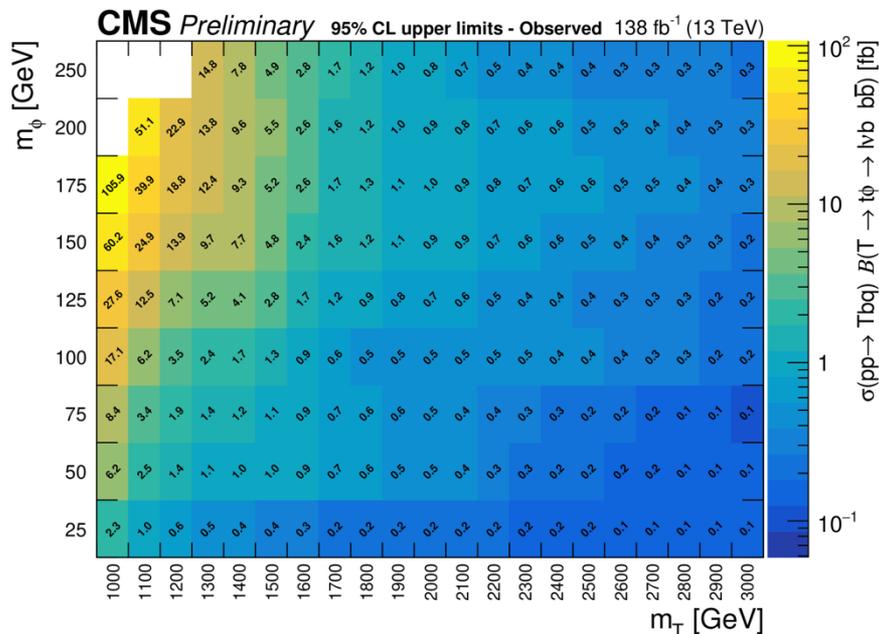
# Vector-Like Quark: $T \rightarrow t\phi(H)$ in single lepton final state



CMS-PAS-B2G-23-009

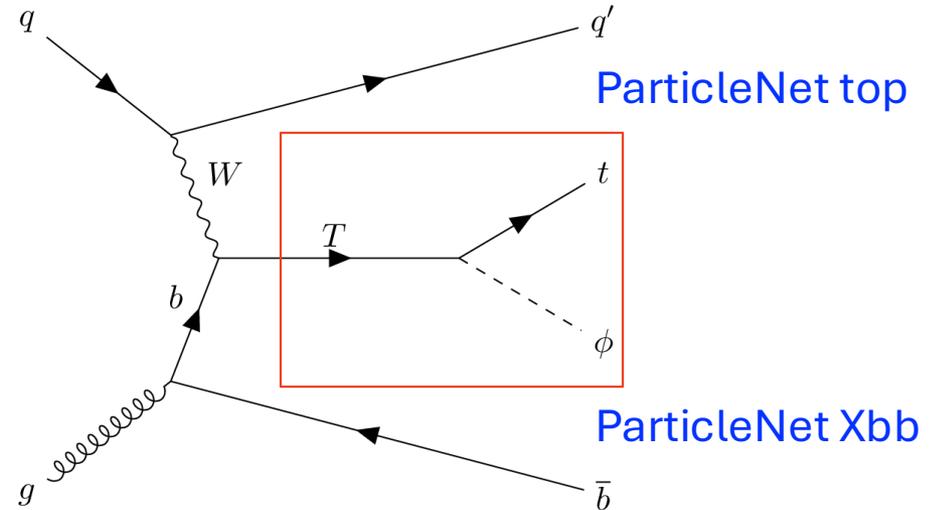
## Results

- ▶ No significant excess
- ▶  $T \rightarrow tH$ : Excludes values greater than 100 – 1.0 fb
  - ▷ Close to  $T$  mass exclusion around 1.2 TeV
  - ▷ Improves sensitivity for  $m_T \geq 1.3$  TeV compared to previous searches



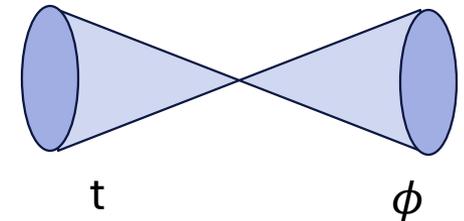
## Analysis Target

- ▶ Single production of vector-like T quark
  - ▷  $T \rightarrow t\phi(H), \phi(H) \rightarrow b\bar{b}$
- ▶ Search range:
  - ▷ T mass: 0.8 – 3 TeV
  - ▷  $\phi$  mass: 75 – 500 GeV
- ▶ Hadronic final state



## Event Signature

- ▶ Two highly Lorentz-boosted large-radius jets that are roughly opposite to each other in the transverse plane

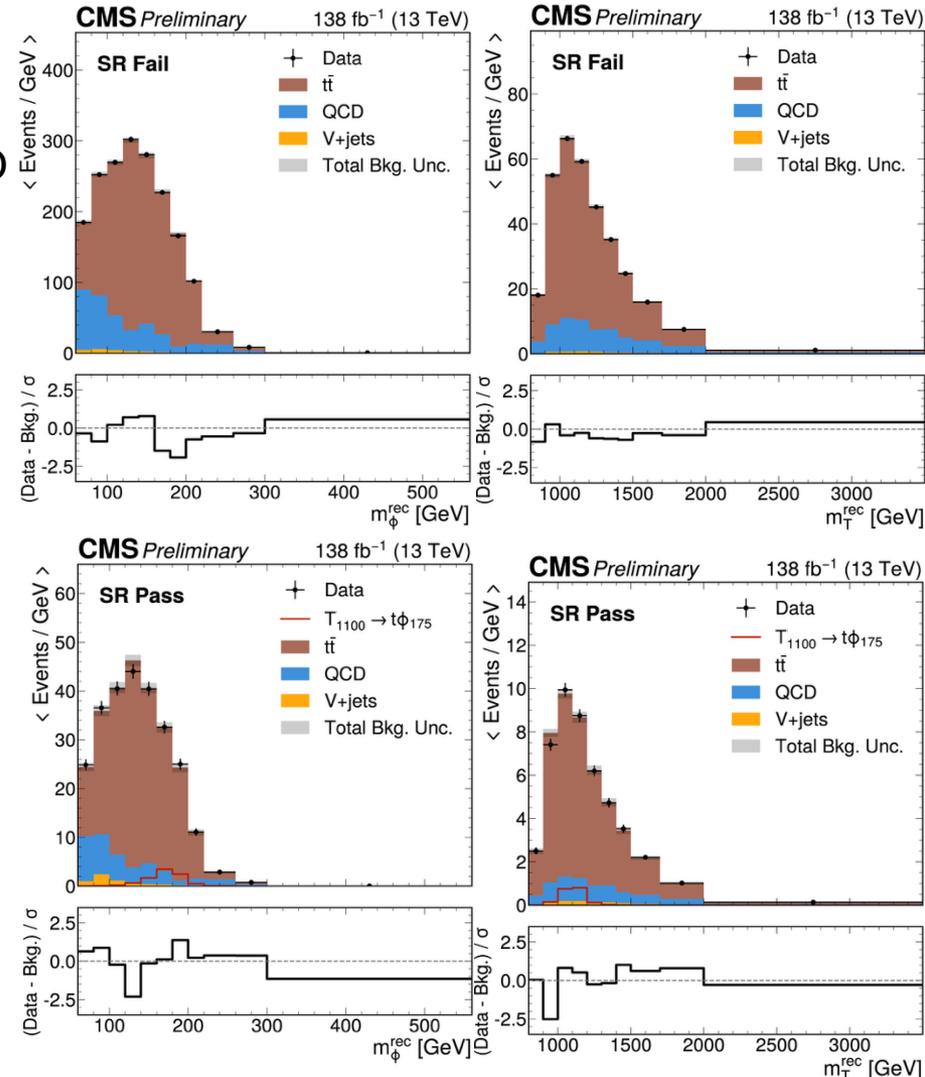
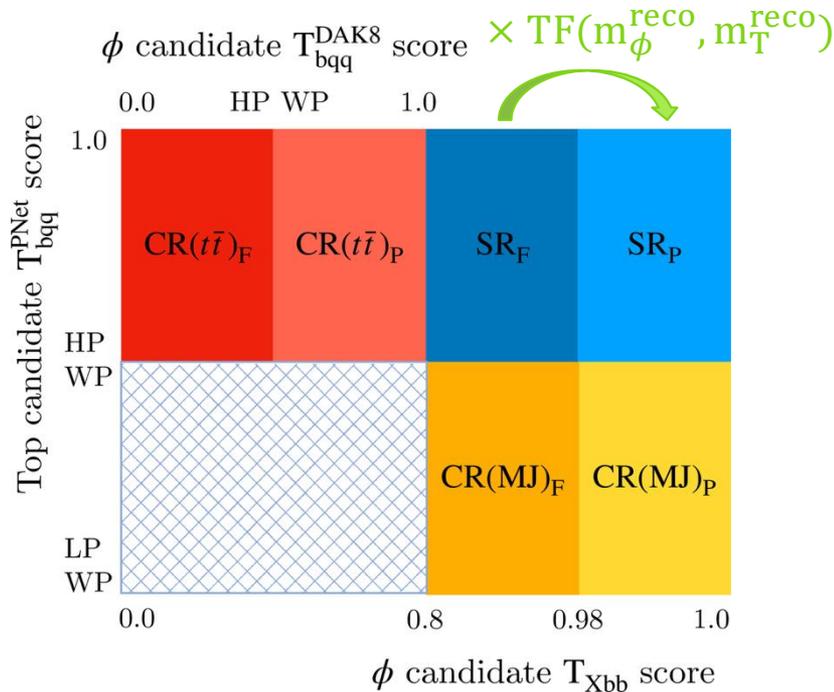


# Vector-Like Quark: $T \rightarrow t\phi(H)$ in hadronic final state

Newest! [CMS-PAS-B2G-22-001](#)

## Analysis Highlight

- ▶ Definition of  $t\bar{t}$  and QCD enriched CRs
- ▶ Data-driven background estimation for QCD
- ▶ Signal extraction in 2D plane:  $(m_T^{\text{reco}}, m_\phi^{\text{reco}})$

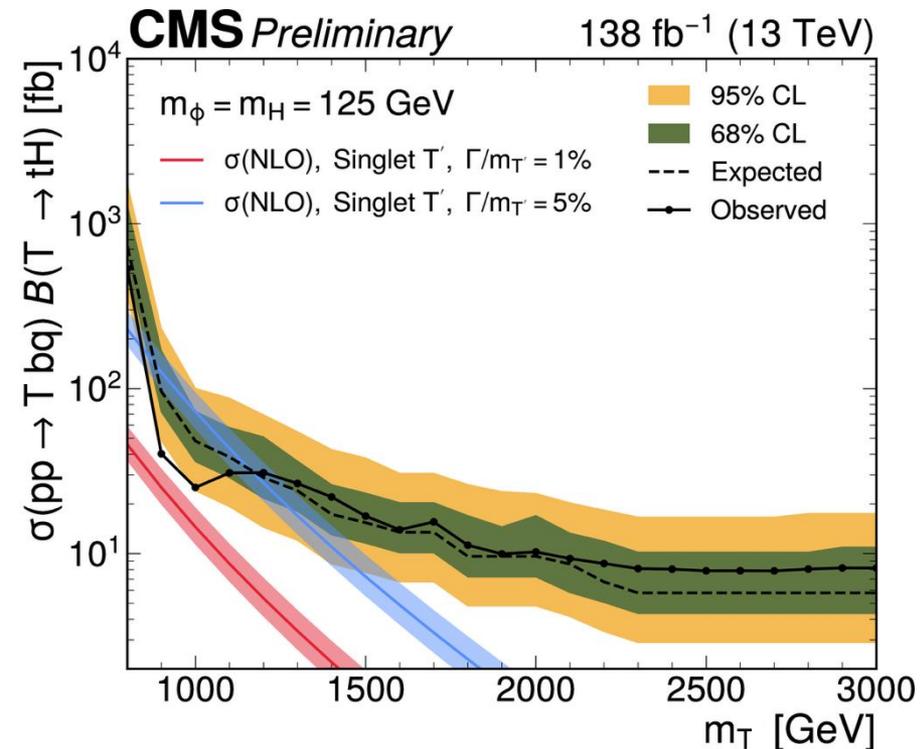
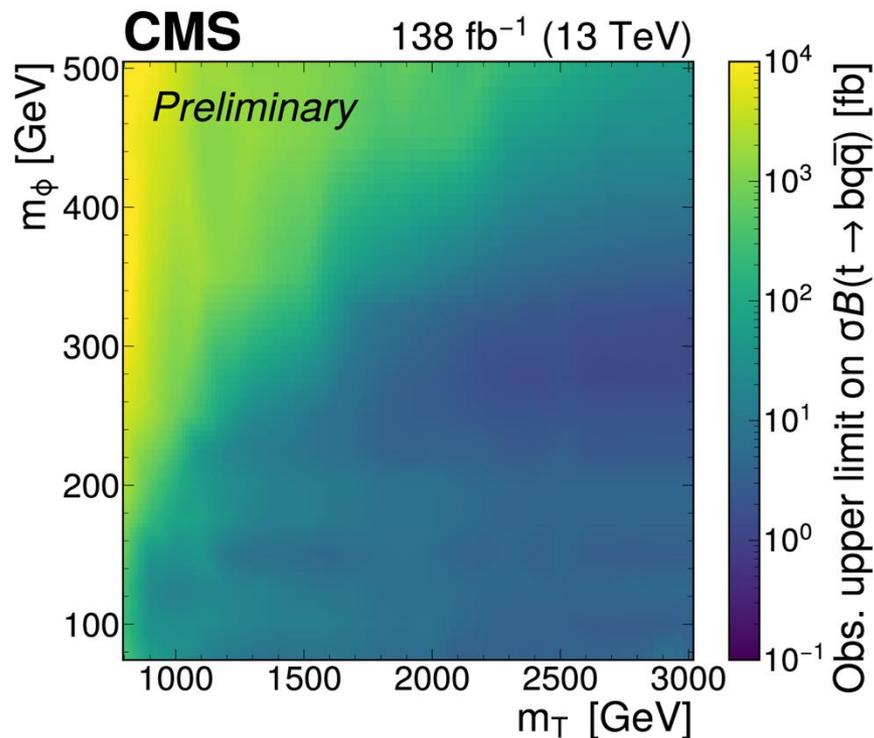


# Vector-Like Quark: $T \rightarrow t\phi(H)$ in hadronic final state

## Results

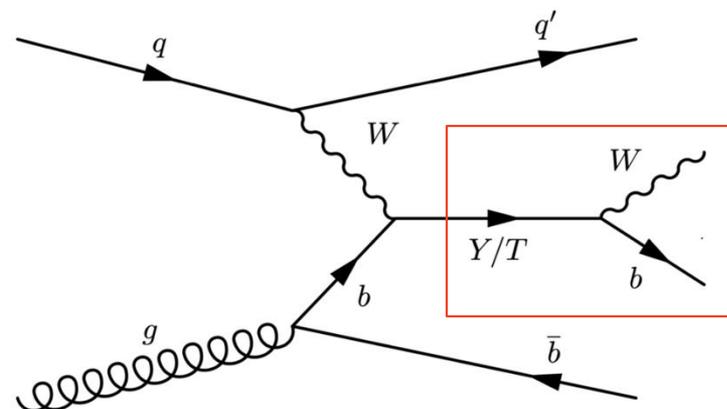
- ▶ No significant excess
- ▶ VLQ  $T$  mass exclusion at 1.2 TeV at 95% CL for singlet  $T \rightarrow tH$  with 5% decay width

Observed upper limit



## Analysis Target

- ▶ Single production of vector-like  $Y/T$  quark
  - ▶  $\text{Br}(\text{doublet } Y \rightarrow Wb) = 100\%$
  - ▶  $\text{Br}(\text{singlet } T \rightarrow Wb) = 50\%$
- ▶ VLQ  $Y/T$  mass: 0.7 – 2.4 TeV
- ▶ Single lepton final state with  $W \rightarrow l\nu$



## Event Signature

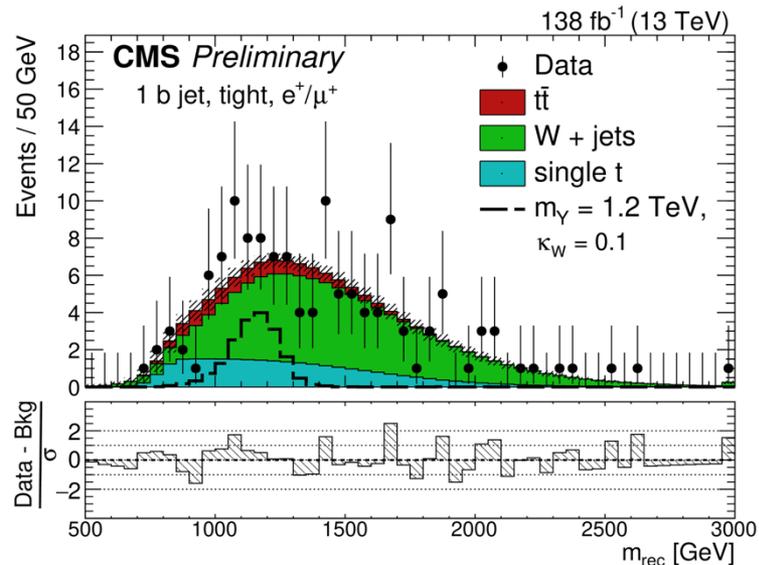
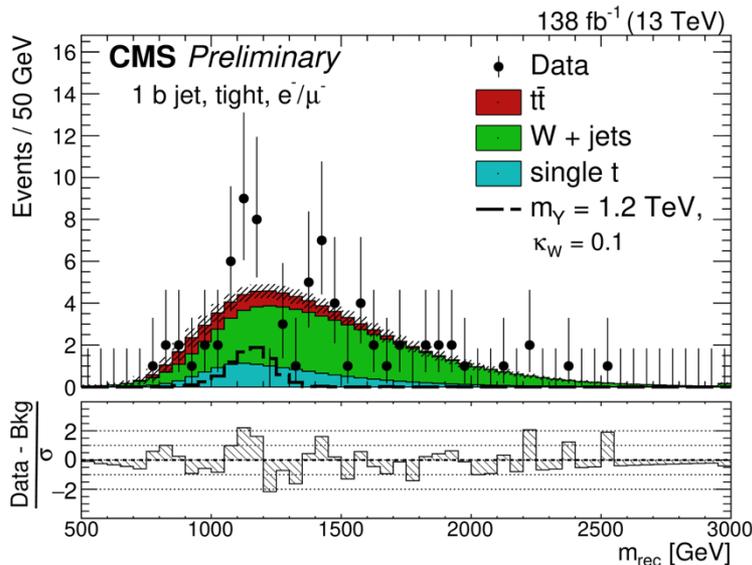
- ▶ Decay products highly boosted because of large VLQ mass
- ▶ lepton + large  $p_T^{\text{miss}}$  + high  $p_T$  b-jet + forward jets

## Analysis Highlight

- ▶ **Neural network discriminator** for background rejection and signal sensitivity
- ▶ Accurate reconstruction of  $m_{Y/T}$  with **recursive jigsaw algorithm** → **improves sensitivity**

$$m_{\text{rec}} = \sqrt{m_{\text{vis}}^2 + 2 \left( p_{\text{T}}^{\text{miss}} \sqrt{m_{\text{vis}}^2 + |\vec{p}_{\text{T}}^{\text{vis}}|^2} - \vec{p}_{\text{T}}^{\text{miss}} \cdot \vec{p}_{\text{T}}^{\text{vis}} \right)} \quad \text{PhysRevD.96.112007}$$

- ▶ **Smooth background distribution** in  $m_{Y/T}$  obtained from fitting Crystal Ball function to each dominant background process
- ▶ Split events based on the **sign of the lepton charge** → **improves sensitivity**

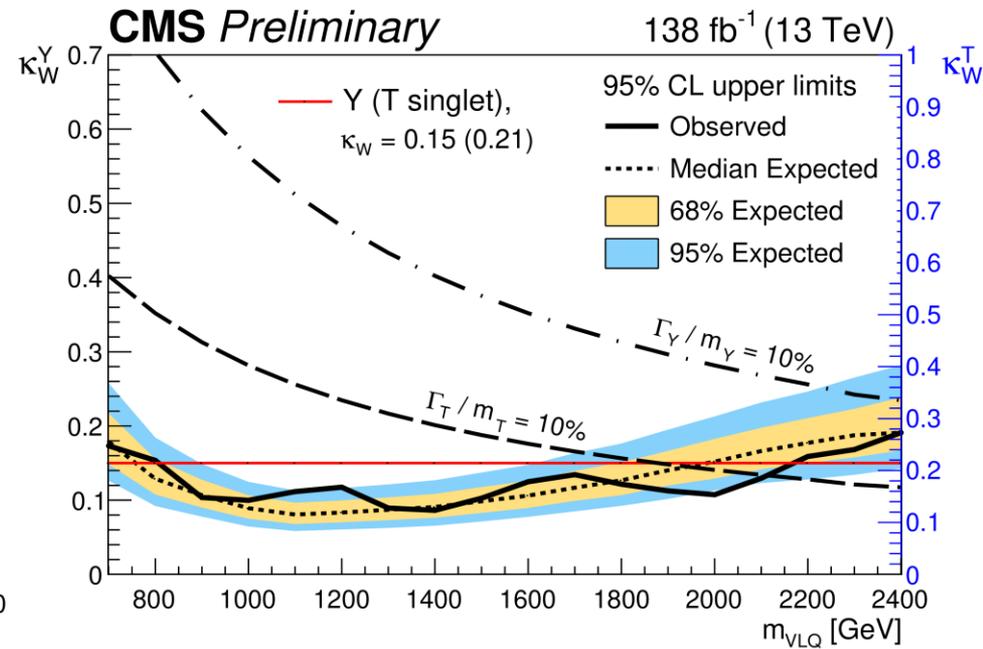
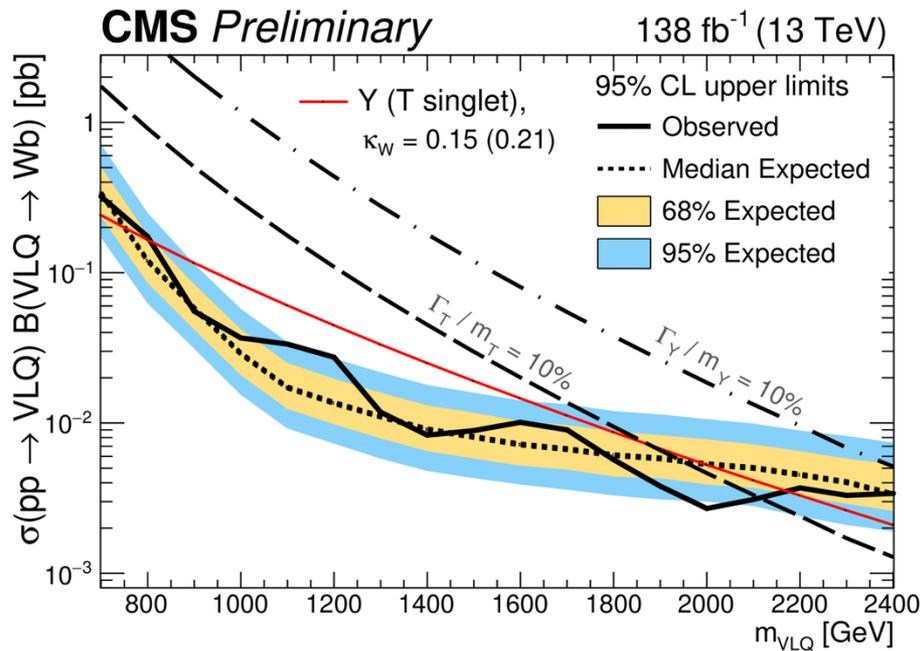


# Vector-Like Quark: $Y/T \rightarrow Wb$ single lepton final state

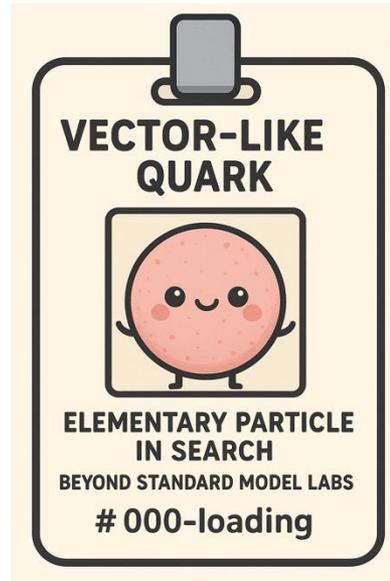
## Results

- ▶ No significant excess
- ▶ Exclude VLQ Y mass in the range of **0.7-2.4 TeV** for  $\kappa_W^Y = 0.2$
- ▶ Exclude singlet VLQ T mass up to **2 TeV** at 95% CL for  $\kappa_W^T > 0.2$

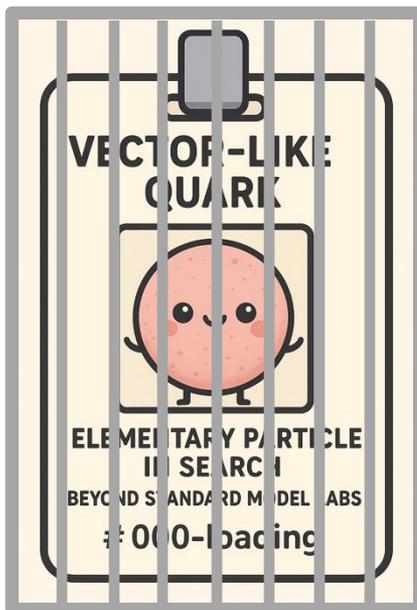
★ Most stringent limits on  $Y/T \rightarrow Wb$

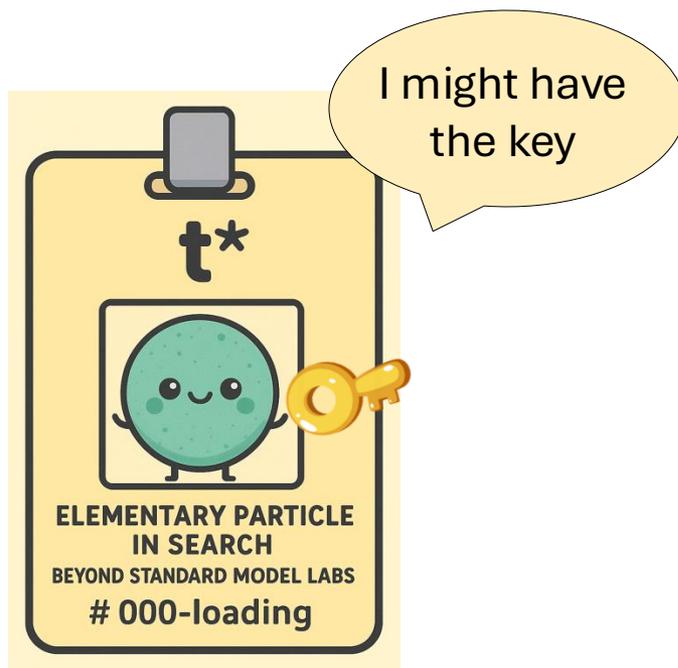


Search for standard decay  
channels



When mixing angle is small,  
 $T \rightarrow bW, tZ, tH$  are suppressed.





- ▶ Excited top  $t^*$
- ▶ Composite or partial composite top models
- ▶ Spin-1/2 or spin-3/2
- ▶  $\text{Br}(t^* \rightarrow t\bar{g}) = 97\%$     Search for  $t^*\bar{t}^* \rightarrow t\bar{g}t\bar{g}$     [EPJC 85 \(2025\) 342](#)
- ▶  $\text{Br}(t^* \rightarrow t\bar{\gamma}) = 3\%$     Search for  $t^*\bar{t}^* \rightarrow t\bar{g}t\bar{\gamma}$     [CMS-PAS-B2G-24-006](#)

## Analysis Target

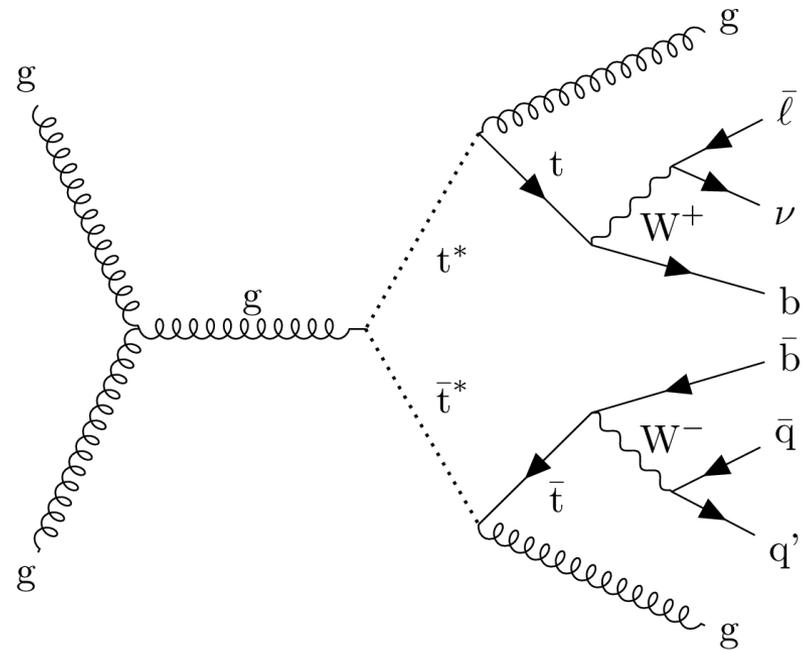
- ▶ Pair production of heavy excited top quarks  $t^*\bar{t}^* \rightarrow tg\bar{t}g$ 
  - ▷ Spin-1/2 and spin-3/2
  - ▷  $\text{Br}(t^* \rightarrow tg) = 97\%$  → motivates a search with  $tg\bar{t}g$  final states
- ▶  $t^*$  mass: 0.7– 3.0 TeV
- ▶ Lepton + jets final state

## Event Signature

- ▶ Final states:  $l + \nu + 4$  light jets + 2 b jets

## Background

- ▶  $t\bar{t}$ , single top,  $W$ +jets, diboson, QCD multijet



## Analysis Target

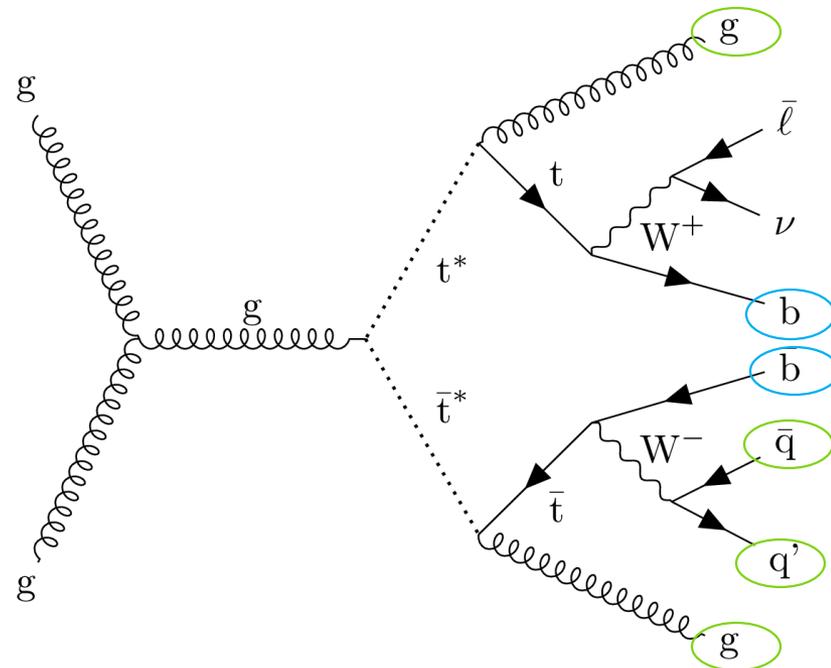
- ▶ Pair production of heavy excited top quarks  $t^* \bar{t}^* \rightarrow t g \bar{t} g$ 
  - ▷ Spin-1/2 and spin-3/2
  - ▷  $\text{Br}(t^* \rightarrow t g) = 97\%$  → motivates a search with  $t g \bar{t} g$  final states
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- ▶  $t \bar{t}$ , single top, W+jets, diboson, QCD multijet



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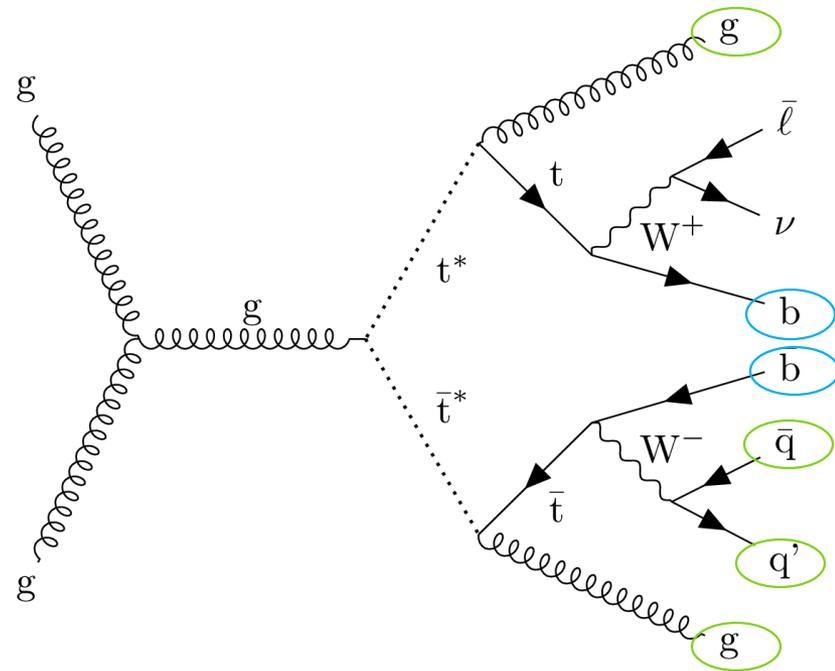
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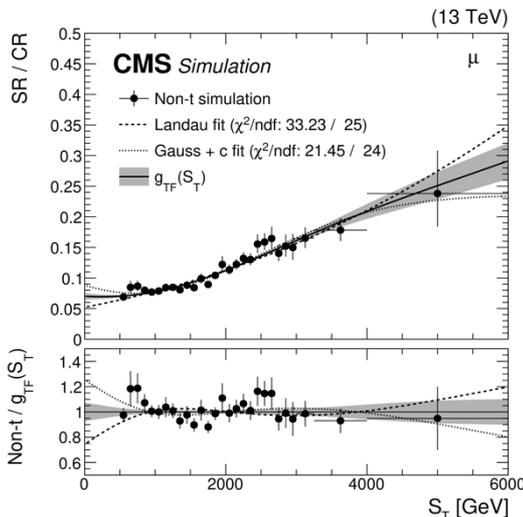
## Background

- ▶  $t\bar{t}$ , single top,  $W$ +jets, diboson, QCD multijet
- |                                 |   |
|---------------------------------|---|
| <p>Top</p> <p>MC simulation</p> | <p>Non-top</p> <p>Data-driven</p> <p><math>\rightarrow</math> more accurate</p> |
|---------------------------------|---|

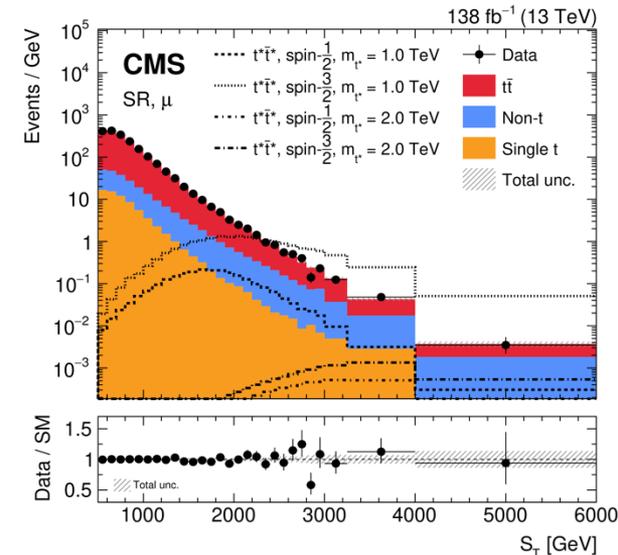
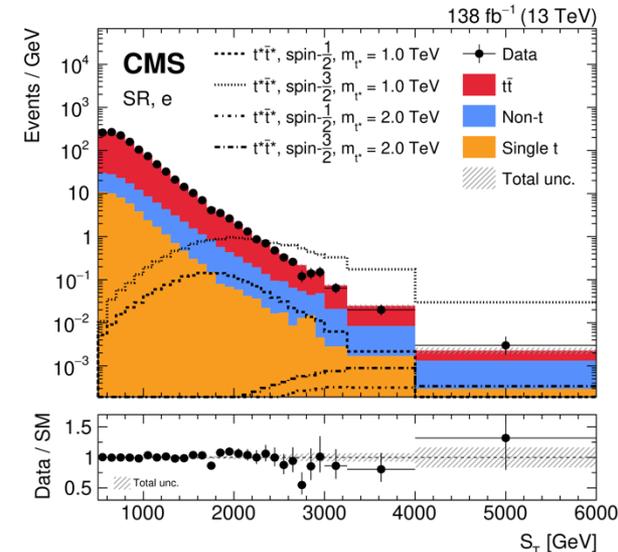


## Analysis Highlights

- ▶ Use **variable-radius jets**
  - ▶ Binned maximum likelihood fit on  $S_T$
- $$S_T = p_T^l + p_T^{\text{miss}} + \sum_i p_{T,i}^{\text{jet}}$$
- Large  $p_T$  variable-size jets
- ▶ DNN signal/background discriminator, with its score decorrelated with  $S_T$  by the **designing decorrelated taggers (DDT) technique** *JHEP 05 (2016) 156*



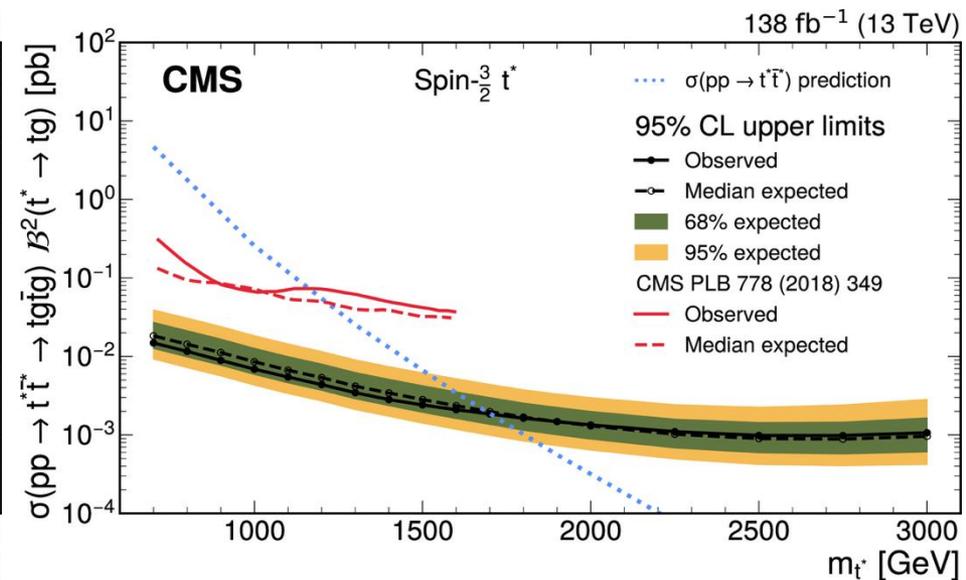
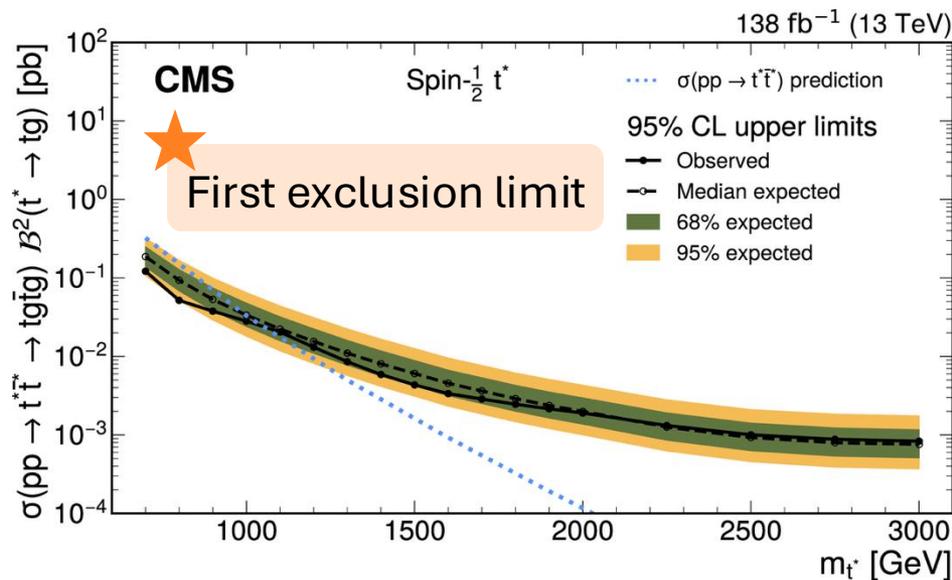
Simulation-based ratio between SR and CR  
→ transfer function



# Excited Fermion: $t^* \bar{t}^* \rightarrow t g \bar{t} g$ in the lepton+jets final state

## Results

- ▶ No significant excess
- ▶ Mass exclusion of spin-1/2 (spin-3/2)  $t^*$  up to **1050 (1700) GeV**

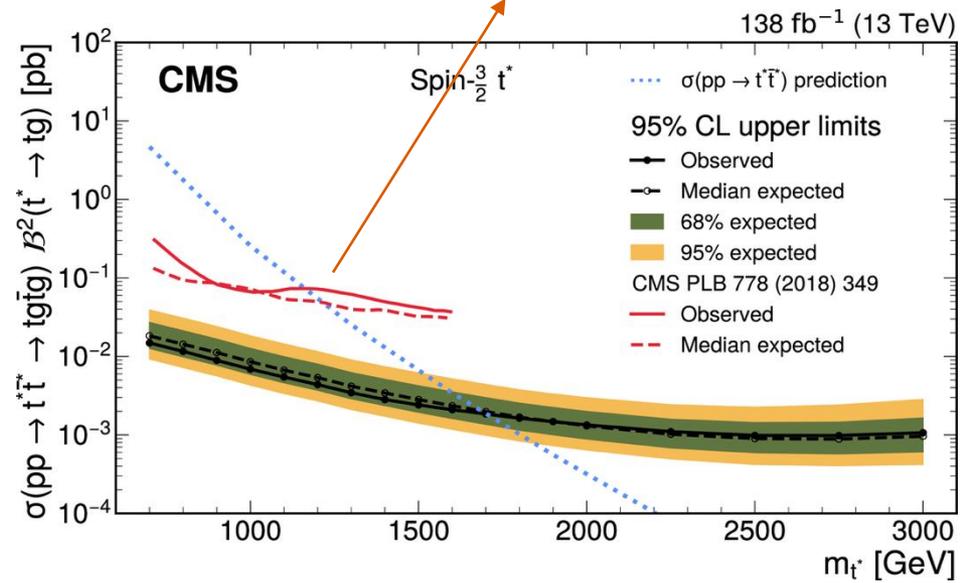
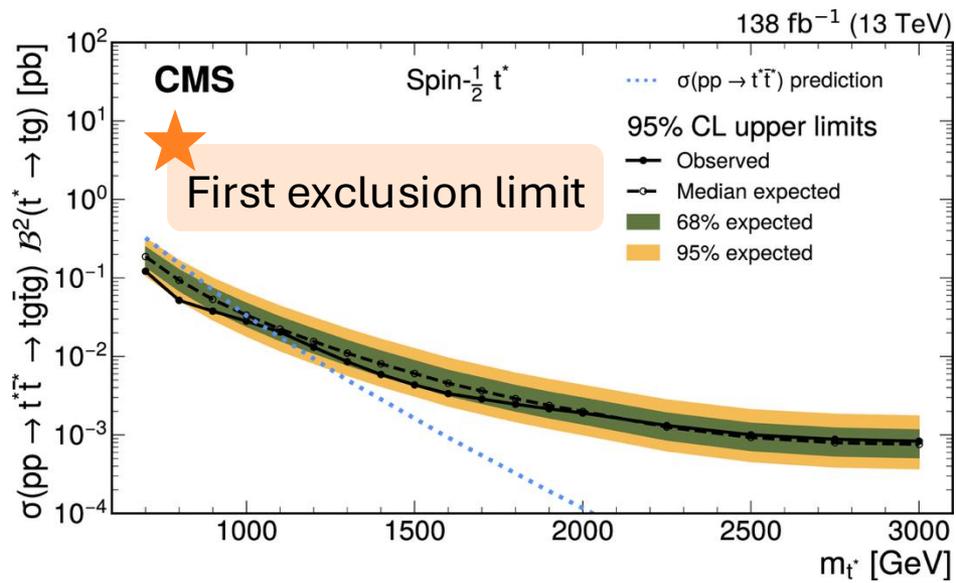


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Substantially improved the search at 35.9 fb<sup>-1</sup>

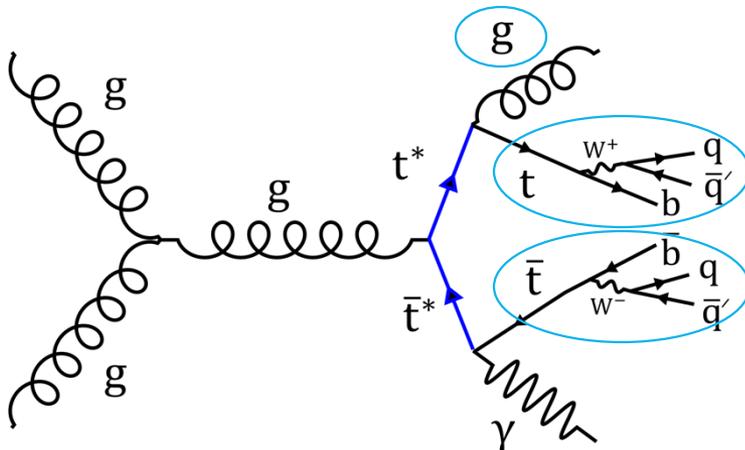


## Analysis Target

- ▶ Pair production of heavy excited top quarks  $t^*t^* \rightarrow tg\bar{t}\gamma$ 
  - ▷  $\text{Br}(t^* \rightarrow tg) = 97\%$ ,  $\text{Br}(t^* \rightarrow t\gamma) = 3\%$  → suppressed by weak coupling
- ▶ Search between 0.7 TeV to 3.0 TeV
- ▶ In hadronic final states
- ▶ Clean signature from high-momentum photon
- ▶ Comparable sensitivity with  $tg\bar{t}g$  final states

## Event signature

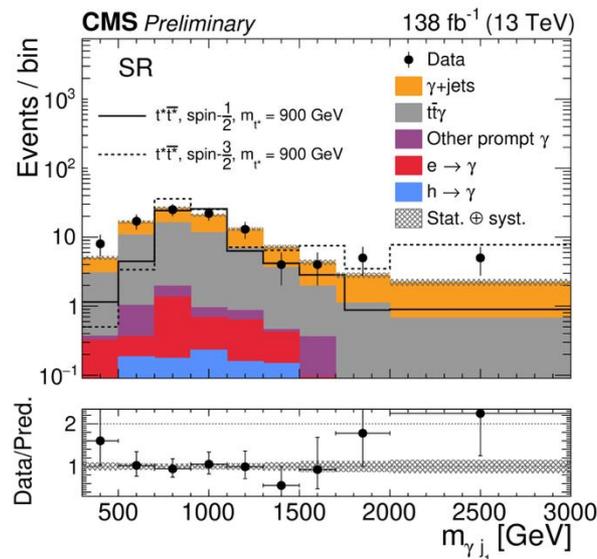
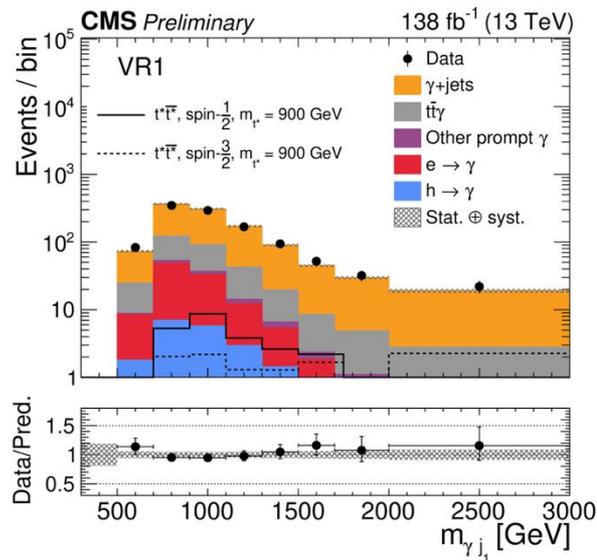
- ▶ High  $p_T$  isolated photon + multiple jets





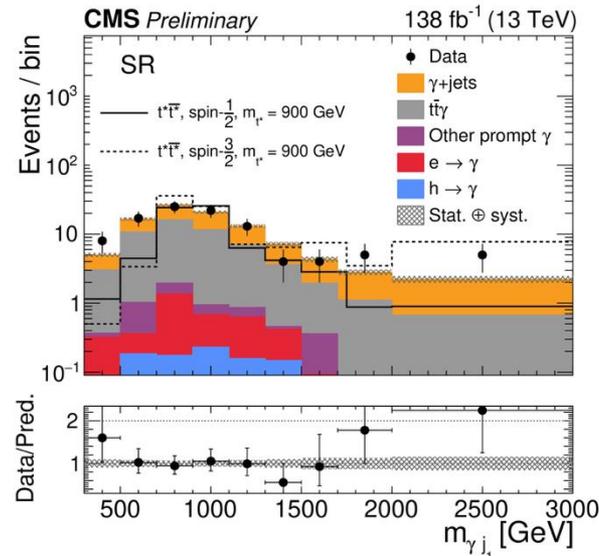
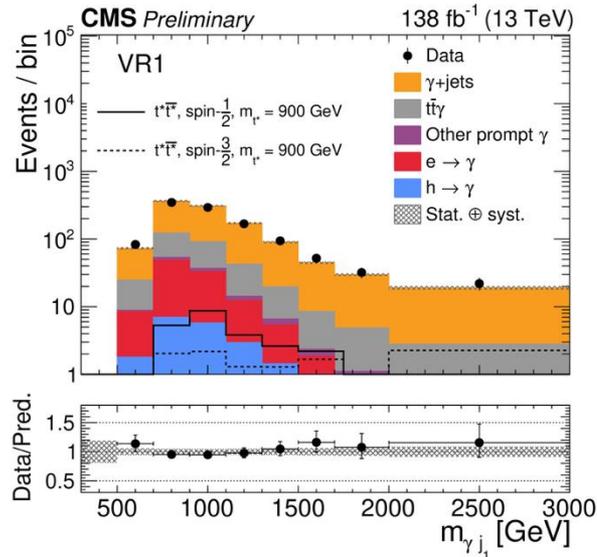
## Analysis Highlights

- ▶ Reduce background by exploiting the **high-energy photon**
- ▶ Reconstruct  $t^*$  mass from  **$t\bar{t}$**
- ▶ Background categorization based on **photon origin**
  - ▷ **Prompt photon:**  $\gamma$ +jets and  $t\bar{t}\gamma$
  - ▷ **Hadron misidentified as photon:** hadronic  $t\bar{t}$
  - ▷ **Electron misidentified as photon:** semi-leptonic  $t\bar{t}$



## Analysis Highlights

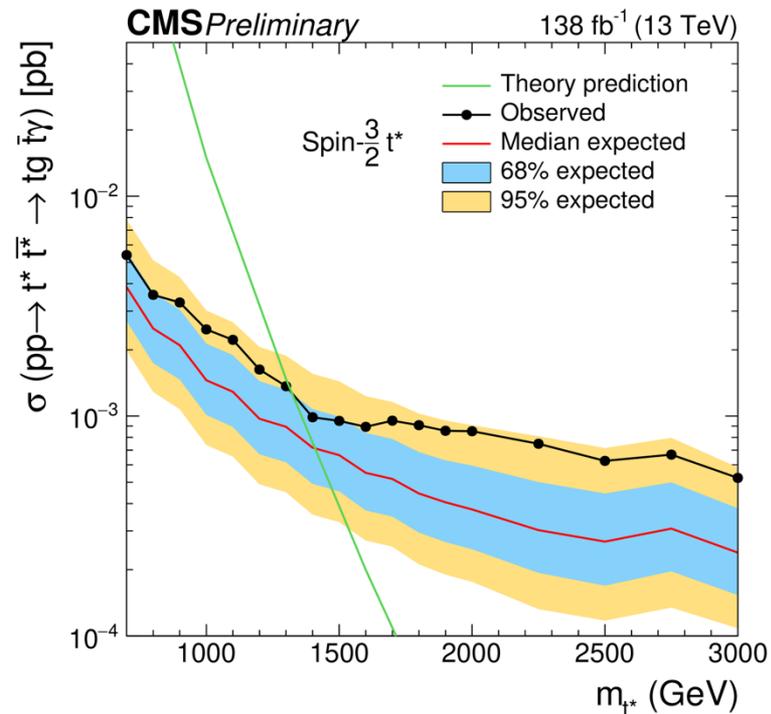
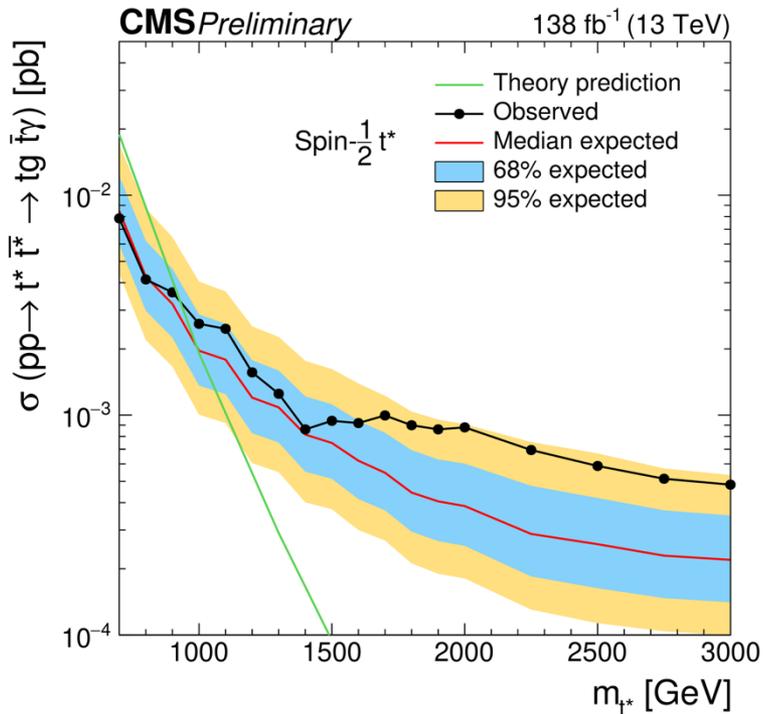
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    - ▷ **Hadron misidentified as photon:** hadronic  $t\bar{t}$
    - ▷ **Electron misidentified as photon:** semi-leptonic  $t\bar{t}$
- Data-driven



## Results

- ▶ No significant excess
- ▶ Exclude  $t^*$  mass below **940 GeV** for spin-1/2
- ▶ Exclude  $t^*$  mass below **1330 GeV** for spin-3/2
- ▶ Sensitivity **comparable with  $t^* \bar{t}^* \rightarrow tg \bar{t} g$**  search

Channel	Expected [GeV]		Observed [GeV]	
	spin- $\frac{1}{2}$	spin- $\frac{3}{2}$	spin- $\frac{1}{2}$	spin- $\frac{3}{2}$
$pp \rightarrow t^* \bar{t}^* \rightarrow tg \bar{t} g$	990	1690	1050	1700
$pp \rightarrow t^* \bar{t}^* \rightarrow tg \bar{t} \gamma$	1000	1410	940	1330



# Excited Fermion: $t^* \bar{t}^* \rightarrow tg \bar{t} \gamma$ in the photon+jets final state

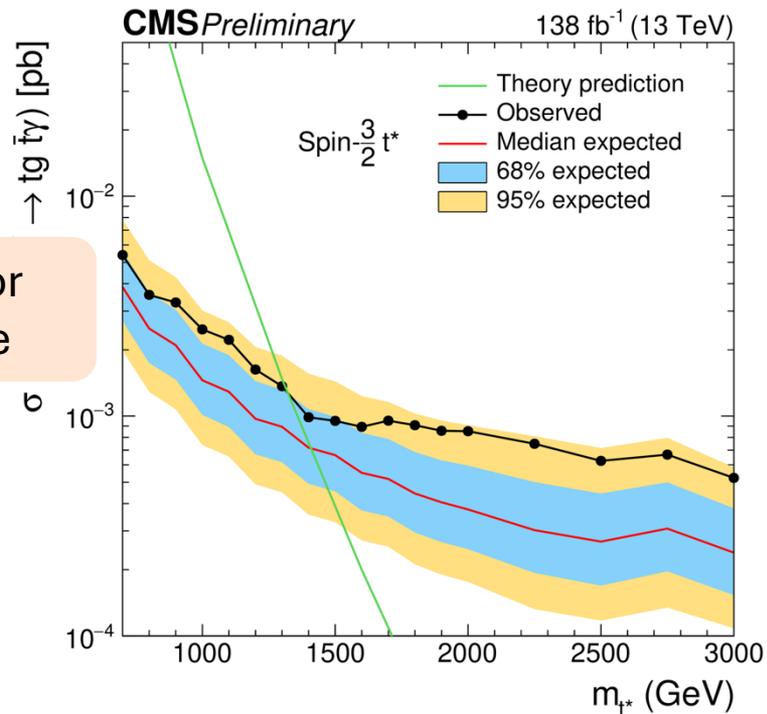
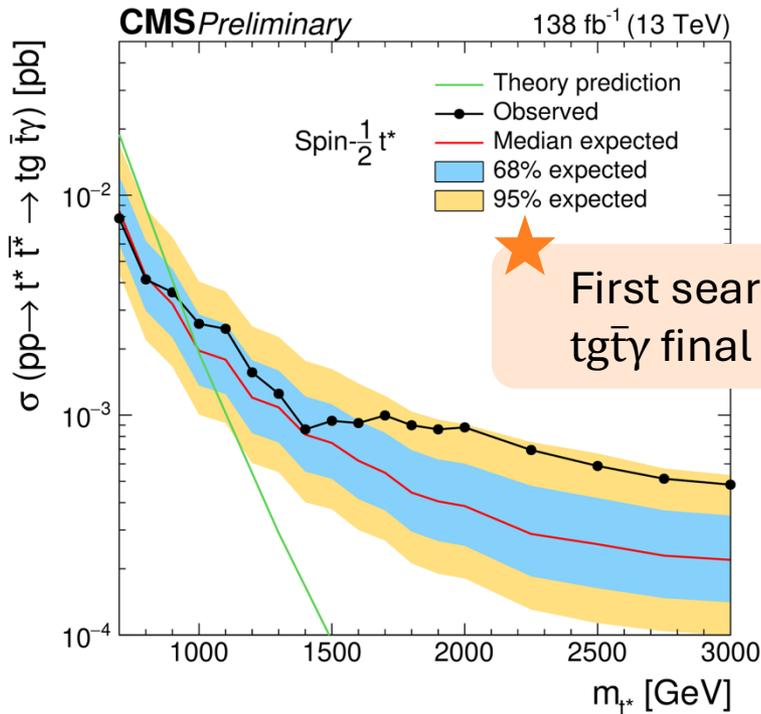


CMS-PAS-B2G-24-006

## Results

- ▶ No significant excess
- ▶ Exclude  $t^*$  mass below **940 GeV** for spin-1/2
- ▶ Exclude  $t^*$  mass below **1330 GeV** for spin-3/2
- ▶ Sensitivity **comparable with  $t^* \bar{t}^* \rightarrow tg \bar{t} g$**  search

Channel	Expected [GeV]		Observed [GeV]	
	spin- $\frac{1}{2}$	spin- $\frac{3}{2}$	spin- $\frac{1}{2}$	spin- $\frac{3}{2}$
$pp \rightarrow t^* \bar{t}^* \rightarrow tg \bar{t} g$	990	1690	1050	1700
$pp \rightarrow t^* \bar{t}^* \rightarrow tg \bar{t} \gamma$	1000	1410	940	1330



- ▶ VLQs and excited fermions with **various decay modes and final states** have been searched at the CMS using the full Run 2 data
- ▶ Novel techniques and analysis strategies have been explored for improved sensitivity:
  - ▶ **machine learning** methods for signal/background separation
  - ▶ **data-driven methods** for background estimation
  - ▶ dedicated **reconstruction techniques**
- ▶ Results highlight:
  - ▶ [CMS-PAS-B2G-23-009](#): Improved sensitivity for T mass above 1.3 TeV
  - ▶ [CMS-PAS-B2G-22-001](#): T mass exclusion up to 1.2 TeV for 5% decay width
  - ▶ [CMS-PAS-B2G-22-004](#): Most stringent limit on  $Y/T \rightarrow tW$
  - ▶ [EPJC 85 \(2025\) 342](#): First mass exclusion for spin-1/2  $t^*$
  - ▶ [CMS-PAS-B2G-24-006](#): First  $t^* \bar{t}^*$  search in  $tg\bar{t}y$  final states

- ▶ More VLQ and excited-fermion searches using **full Run 2** data expected to release soon
- ▶ **Combinations** of Run 2 searches on the way
- ▶ Effort on searches in **Run 3** has been on-going

More results coming soon!

## Analysis strategy

- ▶ Top tagger: multiclass BDT discriminator
  - ▶ Input: kinematic and jet shape variables from the small-radius jet and lepton
  - ▶ Output:  $P(t_{\text{true}})$ ,  $P(t_{\text{QCD}})$ ,  $P(t_{\text{other}})$
  - ▶ Improves the efficiency of true-top identification by 30% for a background fake rate of 6%.

## Top Tagger

- ▶ Compute two scores from the BDT outputs

$$\text{TopVsQCD} = \frac{p(t_{\text{true}})}{p(t_{\text{true}}) + p(t_{\text{QCD}})}$$

$$\text{TopVsOther} = \frac{p(t_{\text{true}})}{p(t_{\text{true}}) + p(t_{\text{Oth}})}$$

## Xbb Tagger

- ▶ Compute XbbVsQCD score from ParticleNet-MD

$$\text{XbbVsQCD} = \frac{p(X_{\text{bb}})}{p(X_{\text{bb}}) + p(\text{QCD})}$$

### ParticleNet-MD:

A mass-decorrelated algorithm based on a dynamic graph convolutional neural network for identifying two-prong hadronic decays of highly Lorentz-boosted particles

## Region definition with Xbb and Top taggers

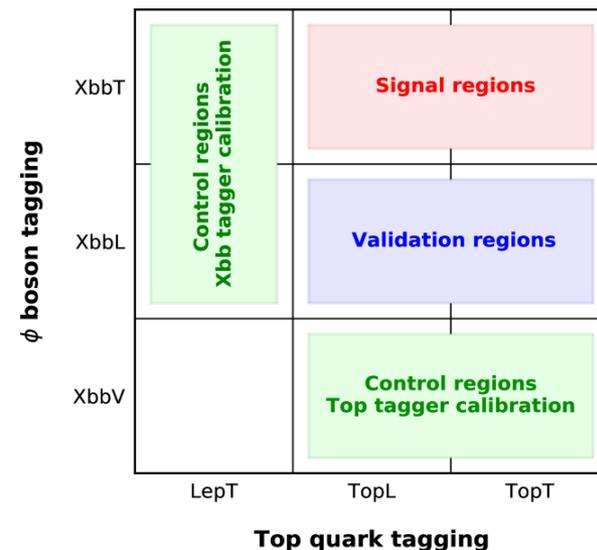
- ▶ TopTight (TopT):  $\text{TopVsQCD} > \text{tight WP}$ ,  $\text{TvsQCD} > 0.06$
- ▶ TopLoose (TopL):  $\text{loose WP} < \text{TopVsQCD} < \text{tight WP}$ ,  $\text{TvsQCD} > 0.06$
- ▶ LeptonTight (LepT):  $\text{TopVsQCD} < \text{loose WP}$  but event has a well-reconstructed lepton

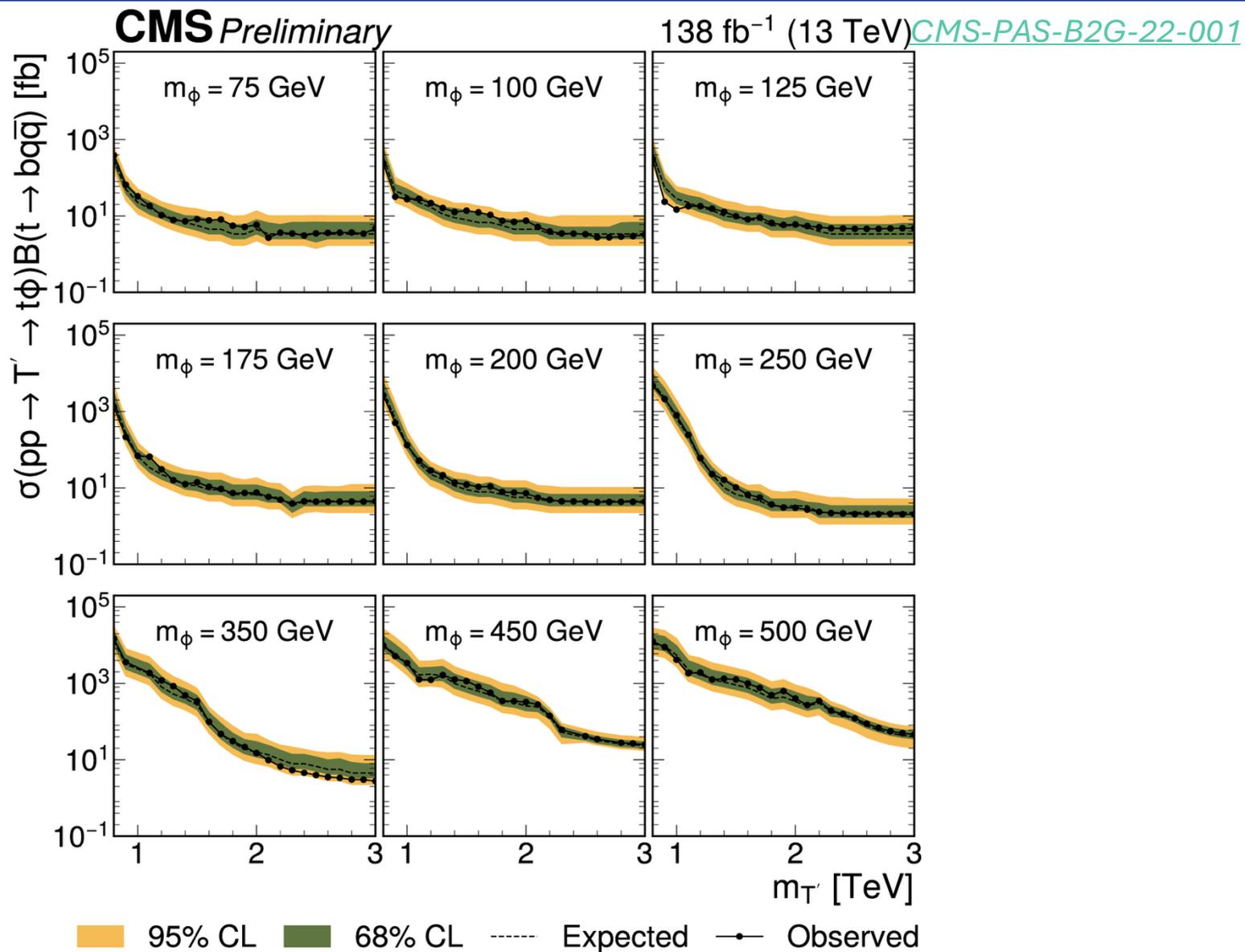
## Top tagger WP

- ▶ TvsQCD WP **signal efficiency**: 99%
- ▶ TvsOther loose (tight) WP **background rejection**: 90% and 99%

## Xbb tagger WP

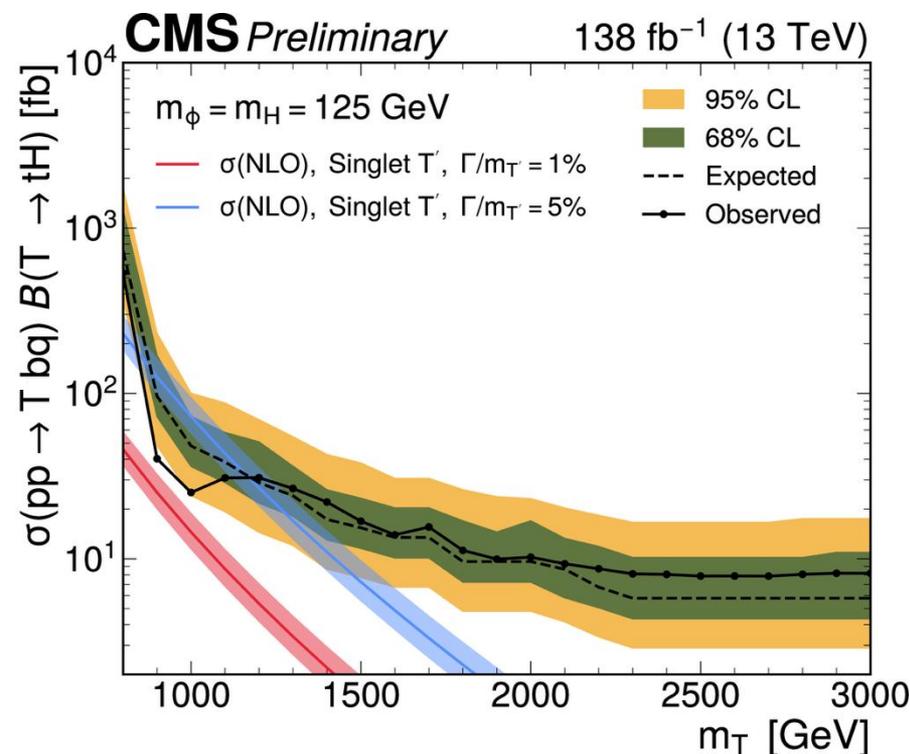
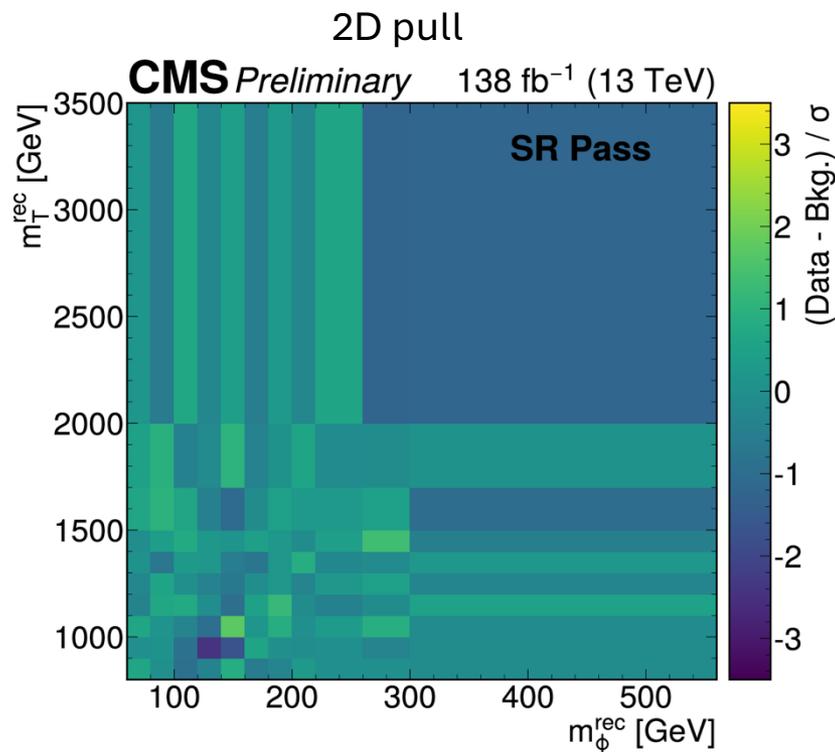
- ▶ Loose WP **background rejection**: 90%





## Results

- ▶ Sets upper limits on  $\sigma(pp \rightarrow T b q) \times \text{Br}(T \rightarrow t \phi(H))$
- ▶ No significant excess
- ▶ VLQ T mass exclusion at 1.2 TeV at 95% CL for singlet T  $\rightarrow tH$  with 5% decay width



## 6 event categories in SR based on b-tagging and lepton charge

- “2 b jet, medium”:  $e^+/\mu^+$ ,  $e^-/\mu^-$
- “1 b jet, medium”:  $e^+/\mu^+$ ,  $e^-/\mu^-$
- “1 b jet, tight”:  $e^+/\mu^+$ ,  $e^-/\mu^-$

