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Erforschung von
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Bundesministerium
für Bildung
und Forschung

Searches for new resonances coupling to third generation quarks at CMS

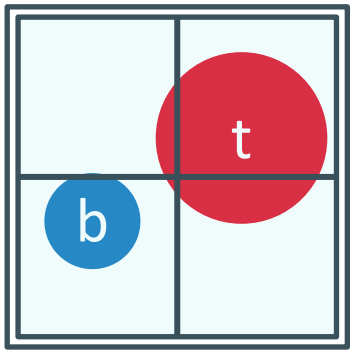
Finn Labe (Universität Hamburg)
on behalf of the CMS Collaboration

20.07.2024 | ICHEP 2024 Prague

Introduction

- **Third generation quarks** could be a window to new physics
- Many models predict new **heavy particles** at the **TeV scale**
  - Lorentz-boosted decay products
  - b quarks and boosted t quarks have **distinctive signatures**

→ Utilize **jet substructure** to search for new physics



This presentation: overview of results since ICHEP 2022 with 2016 – 2018 (run 2) CMS data!

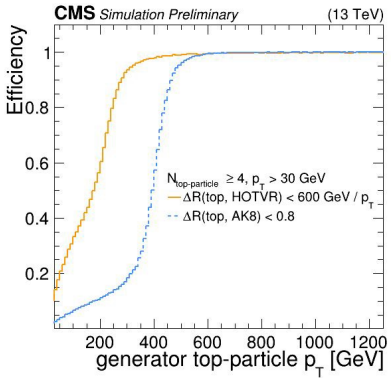
Other related presentations:
- Searches for VLQs
- Searches for LQs
- Res. to Z, W and H
- Res. to two Higgs

Jet classification

b-jet identification

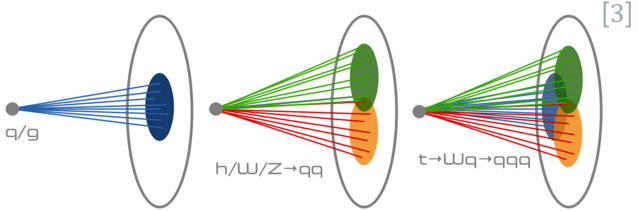
- Usually **small-radius** jets
- **DeepJet**[1]: Deep learning approach to classify jets by flavor

HOTVR top quark reconstruction efficiency



[6]

W- and t-jet identification

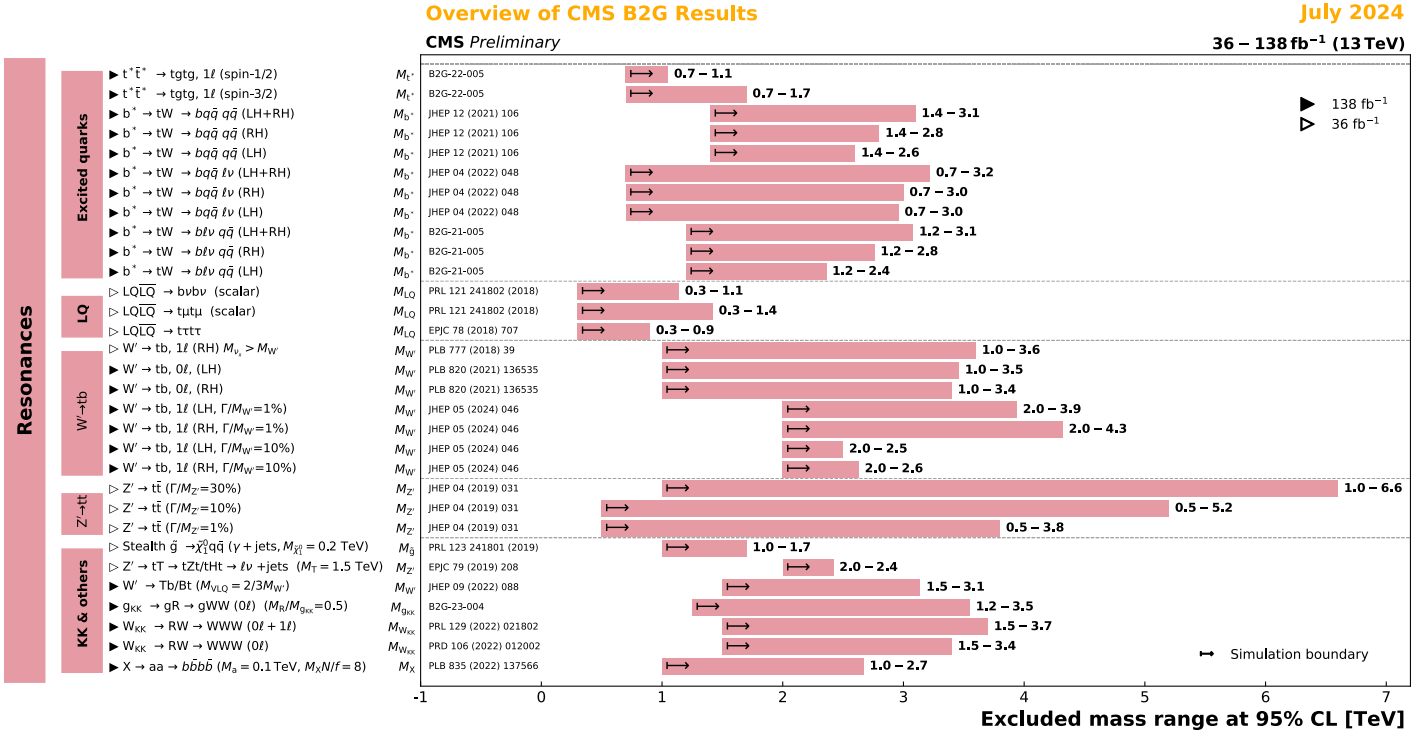


[3]

- Usually **large-radius** jets
- Cut-based approaches:
  - N-subjettiness τ_N, soft-drop mass m_{SD}
- Machine-learning based approaches[4]
- Dedicated jet algorithm: **HOTVR**[5,6]

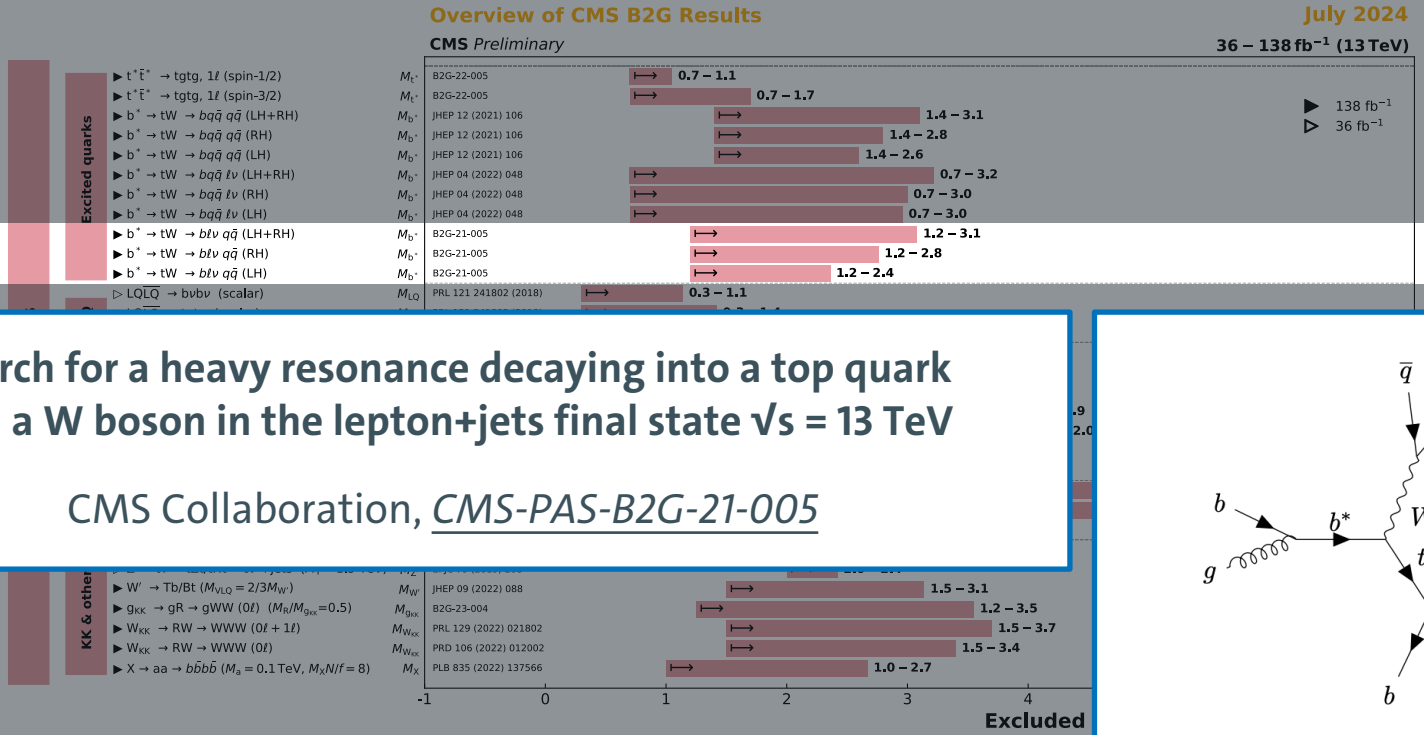
[1] E. Bols et.al. *JINST* 15 (2020) 12, P12012
[2] CMS collaboration *JINST* 13 (2018) 05, P05011
[3] E. A. Moreno et.al. *Eur.Phys.J.C* 80 (2020) 1, 58
[4] H. Qu, L. Gouskos Phys.Rev.D 101 (2020) 5, 056019
[5] T. Lapsien et.al. *Eur.Phys.J.C* 76 (2016) 11, 600
[6] CMS Collaboration CERN-CMS-DP-2024-038

CMS result summary



Click here for full result overview!

CMS result summary



Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state √s = 13 TeV

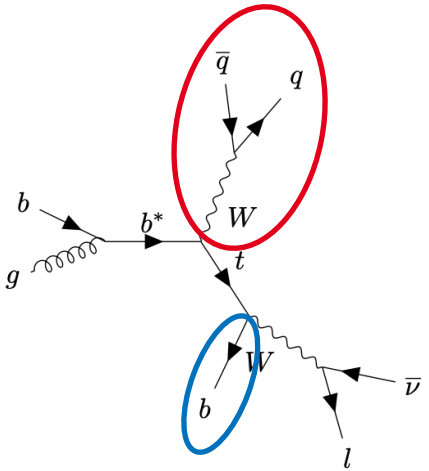
CMS Collaboration, *CMS-PAS-B2G-21-005*

b* → tW (t → 1ℓ): overview

CMS-PAS-B2G-21-005

- **Excited states of bottom quarks** predicted in compositeness models
  - Analyzing right-handed (RH), left-handed (LH) and vector-like b^*
  - Different analysis channels: fully hadronic, leptonic W, **leptonic t**

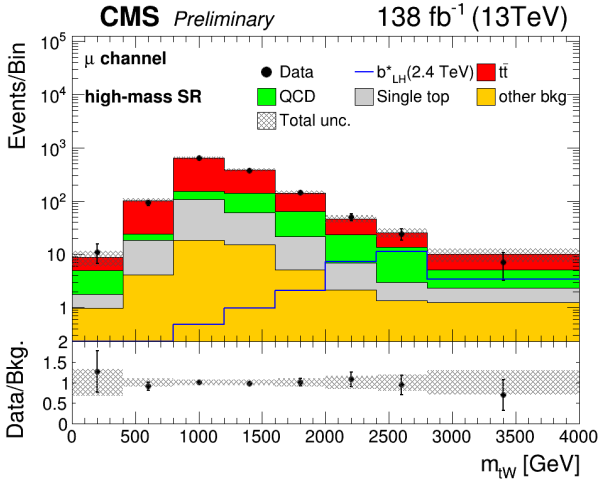
- Reconstruction of the b^* from its decay products
  - **b-tagged** small-radius jet with **DeepJet**
  - **W-tagged** large-radius jet with τ_2/τ_1 and m_{SD}
  - Lepton and $\vec{p}_T^{\,\text{miss}}$

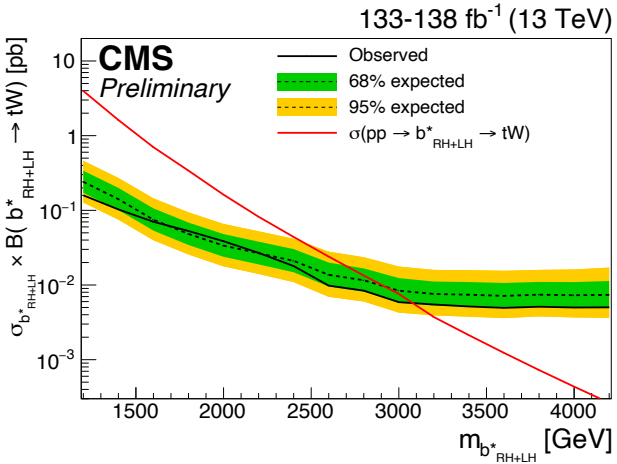


b* → tW (t → 1ℓ): results

CMS-PAS-B2G-21-005

- Main **SM backgrounds** in signal region: $t\bar{t}$ and QCD
  - Estimating $t\bar{t}$ using control region defined by τ_3/τ_2 and m_{SD}
  - Estimating **QCD using data** from control regions, defined by τ_2/τ_1





- Setting b^* mass exclusion limits:
  - **2.4 TeV** (LH)
  - **2.8 TeV** (RH)
  - **3.1 TeV** (vector-like)

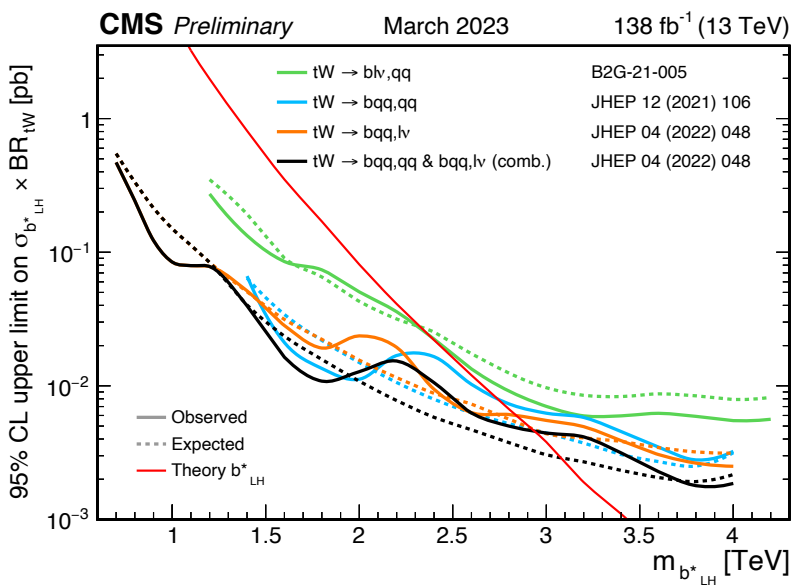
CMS b* result summary

Search for a heavy resonance decaying into a top quark and a W boson at √s = 13 TeV in the fully hadronic final state

CMS Collaboration, *JHEP 12 (2021) 106*

Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state at √s = 13 TeV

CMS Collaboration, *JHEP 04 (2022) 048*



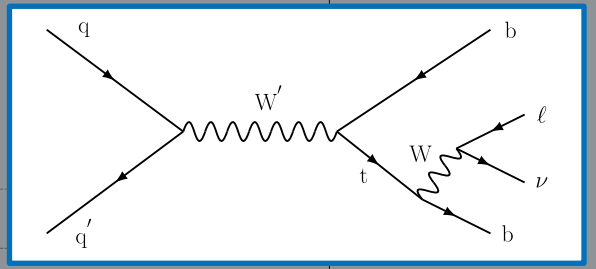
[1]

[1] B2G public results

CMS result summary

Search for W’ bosons decaying to a top and a bottom quark in leptonic final states in proton-proton collisions at √s = 13 TeV

CMS Collaboration, *JHEP* 05 (2024) 046

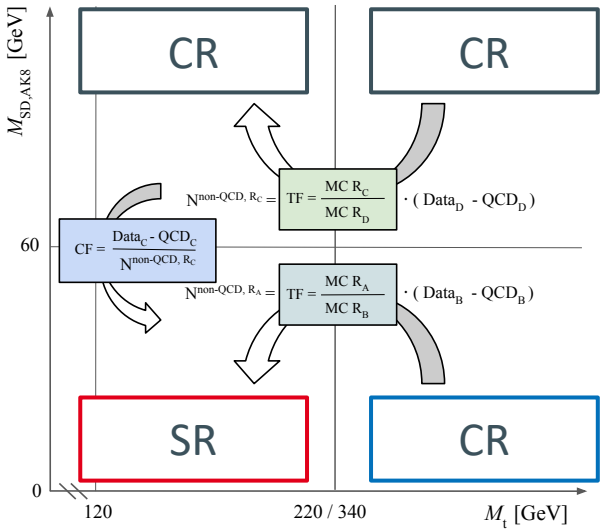


W′ → tb (1ℓ): overview

JHEP 05 (2024) 046

- Models with W' or Z' could help explain **flavor anomalies**
- Strategy: Reconstruction of $\boldsymbol{W'}$ from decay products
  - Lepton, $\vec{p}_T^{\,\text{miss}}$ and small- & large-radius jets
- Categorization with **b-tagged jets** using DeepJet:
  - Control region (0 b-jets), 3 signal regions (1 or 2 b-jets)
- Estimating dominant backgrounds **from data**
  - Using sub-regions based on M_t and m_{SD} of b-quark associated large-radius jet

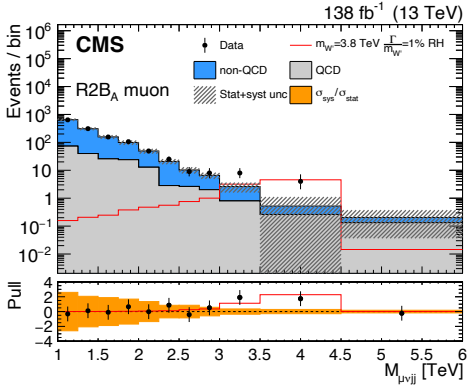
$$\boldsymbol{W' \rightarrow tb \rightarrow Wbb \rightarrow \ell\nu bb}$$



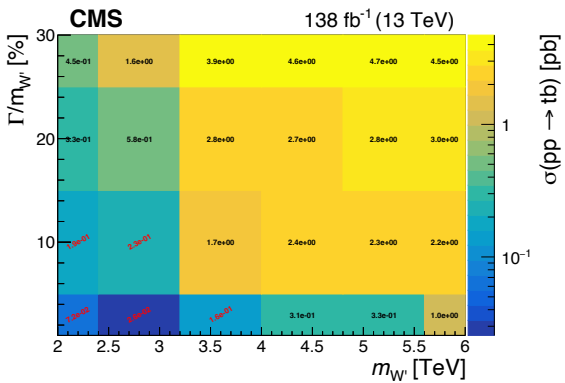
W′ → tb (1ℓ): results

JHEP 05 (2024) 046

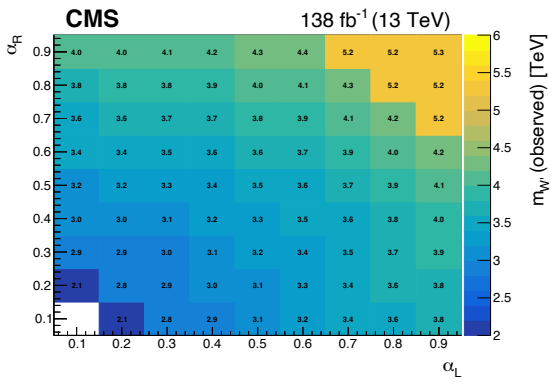
- Simultaneous **maximum likelihood fit** of three signal regions
  - Largest excess at 3.8 TeV, 1% width, RH: 2.6 (2.0) σ local (global)



SR distribution
with largest excess



Cross-section exclusion
limits for LH W's

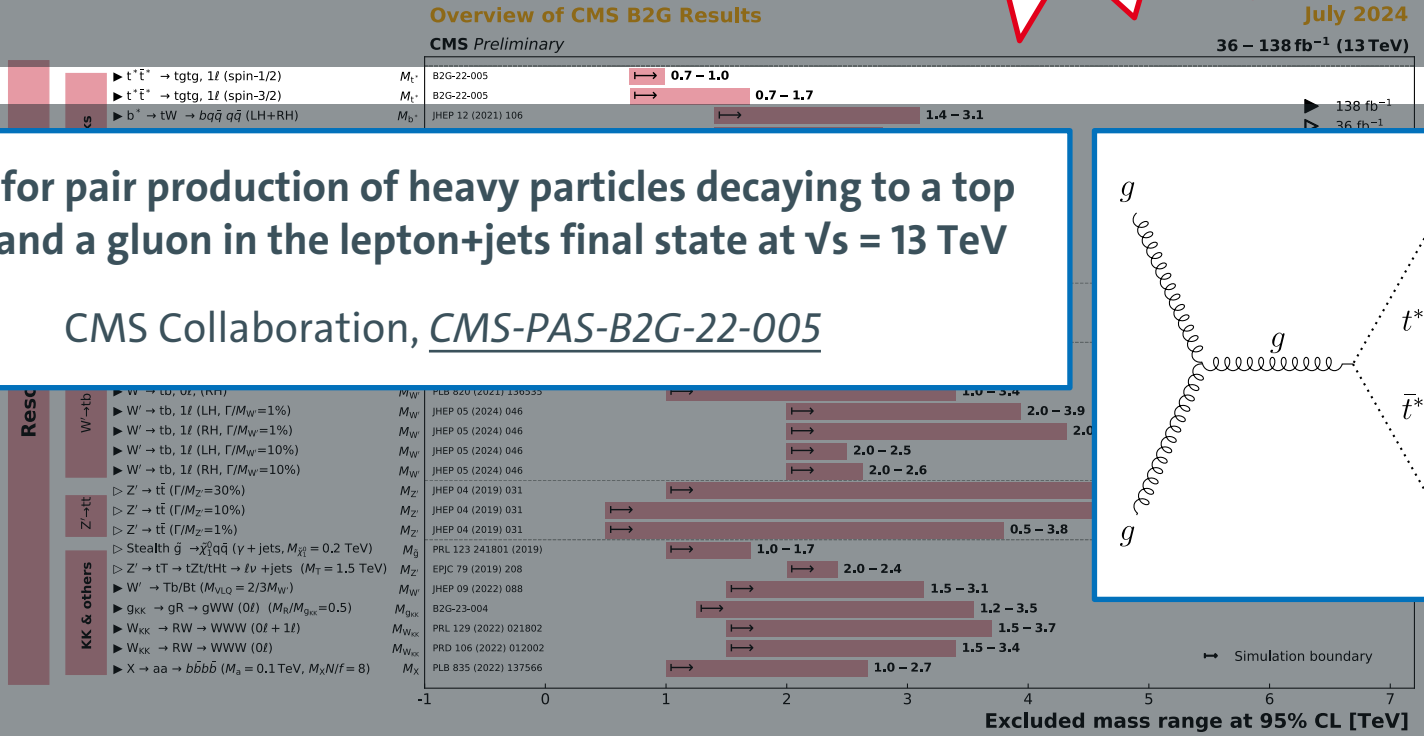


Mass exclusion limits assuming
mixed LH and RH for 1% width

- Many hypotheses tested, **first ever probe of both *W′* width and chirality**

CMS result summary

Brand-new!



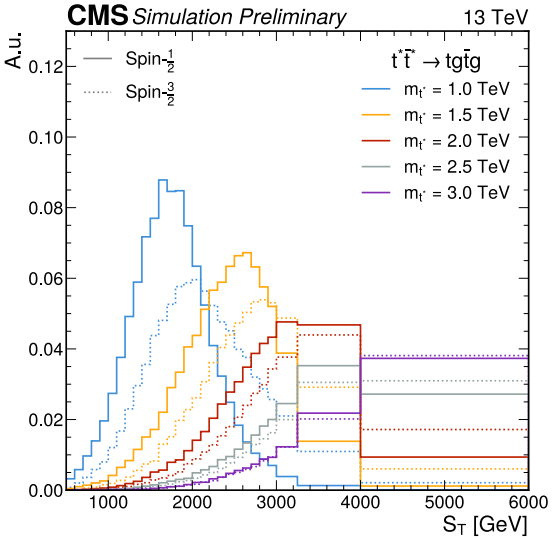
Search for pair production of heavy particles decaying to a top quark and a gluon in the lepton+jets final state at √s = 13 TeV

CMS Collaboration, *CMS-PAS-B2G-22-005*

t*t* → tgtg: overview

CMS-PAS-B2G-22-005

- **Top quark partner** predicted in many BSM theories
  - Could solve the Higgs mass naturalness problem
- Excited top quark t* characterized by decay: **t* → tg**
  - Search for **pair production** $t^*\bar{t}^* \rightarrow tg\bar{t}g$ (single ℓ)
  - Different **spin scenarios** possible:
    spin $\frac{1}{2}$ and spin $\frac{3}{2}$
- Final state similar to $t\bar{t}$, with two additional jets
  - Mass reconstruction challenging:
    instead use **energy sum** S_T as sensitive variable



$$S_T = p_T^{\ell} + p_T^{\text{miss}} + \sum p_T^{\text{jets}}$$

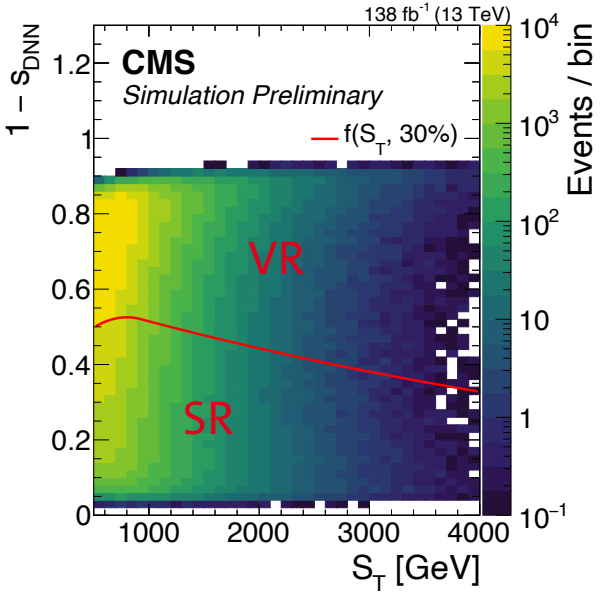
t*t* → tgtg: strategy

CMS-PAS-B2G-22-005

- **HOTVR** jets: allow access to wide range of jet momenta, due to variable radius

- **Event classification** deep neural network (DNN):
  - Discriminating $t^*\bar{t}^*$ from $t\bar{t}$
  - DNN inputs include jet substructure

- DNN S_T**-sculpting** to be avoided:
  - Weights remove S_T info from training
  - Creating decorrelated tagger by introducing a S_T-dependent threshold



DNN score vs. S_T for simulated $t\bar{t}$ events

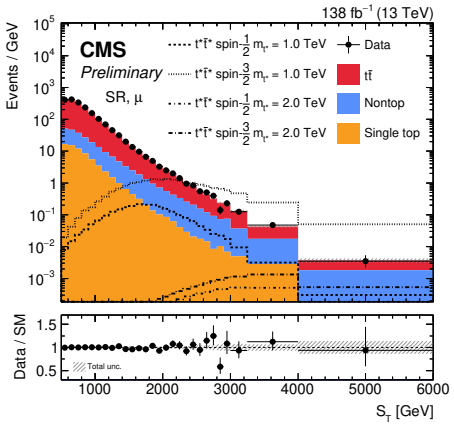
t*t* → tgtg: results

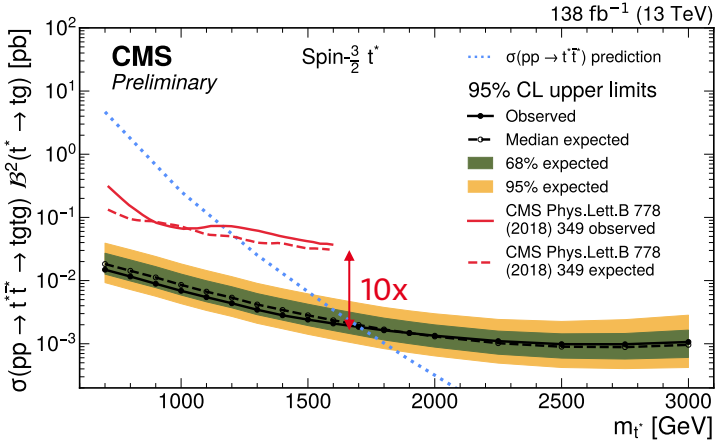
CMS-PAS-B2G-22-005

- **Maximum likelihood fit** in signal region
  - Estimating **non-top backgrounds from data** using transfer function from CR

CR: enriched in non-top events by b-jet veto

- No deviation from SM predictions observed: setting upper cross-section limits



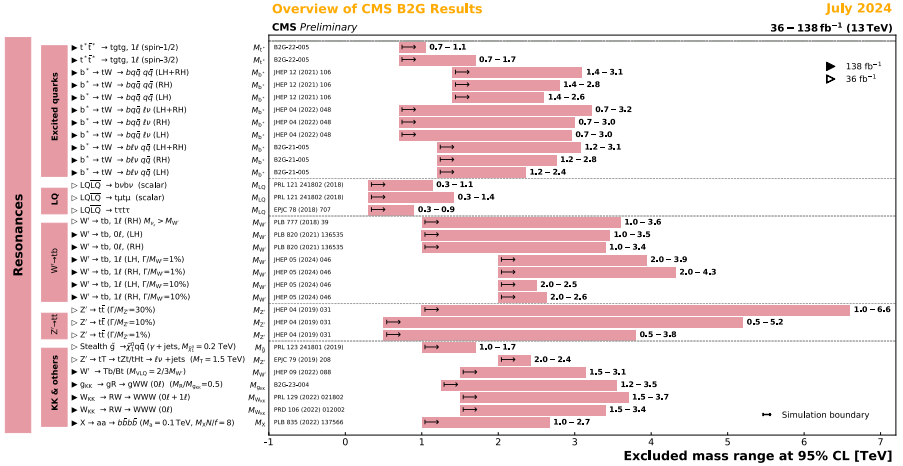


- Improved sensitivity due to updated analysis techniques
- Mass exclusion limits assuming 100% BR:
  - **Spin $\frac{3}{2}$: 1700 GeV**
  - **Spin $\frac{1}{2}$: 1050 GeV**

Summary

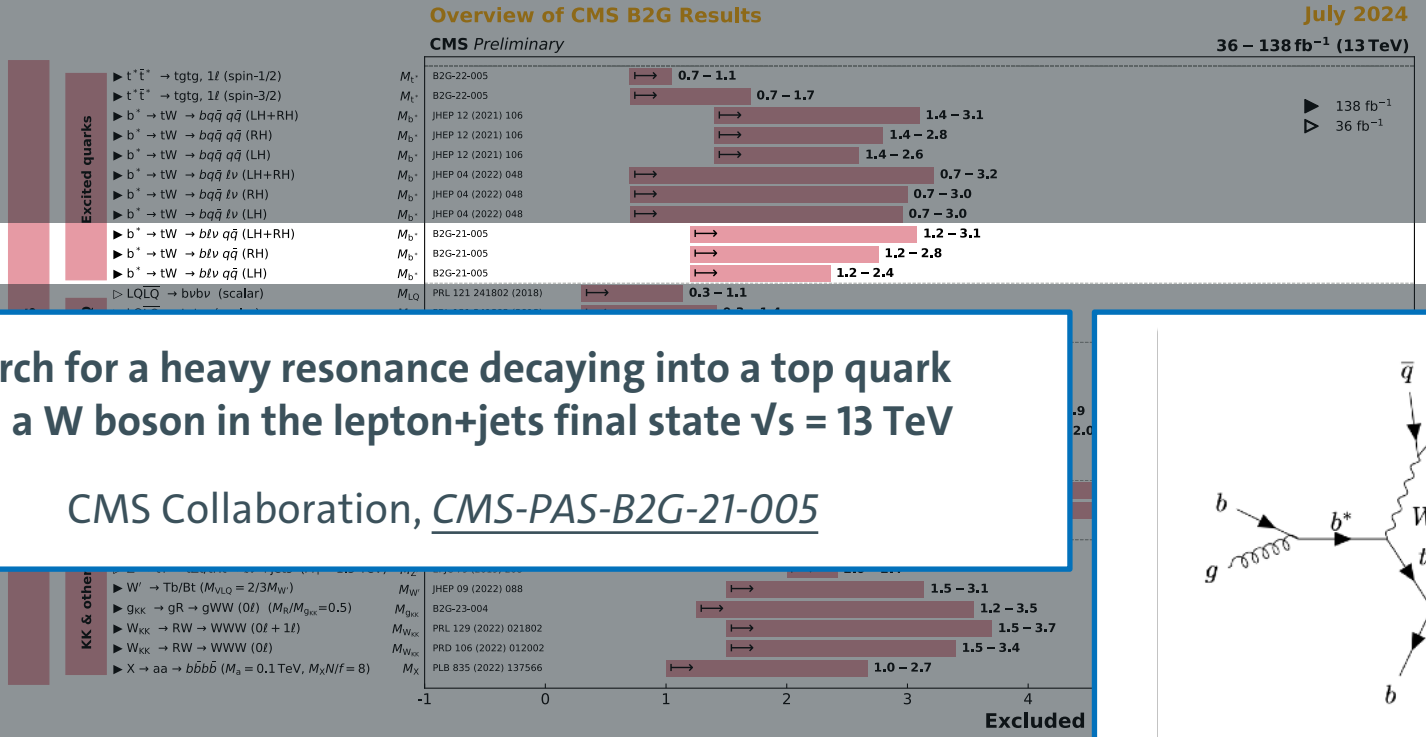
- Exciting physics with **heavy resonances** coupling to **third generation** quarks
  - Several new results with **2016 – 2018 (run 2)** data
  - **Jet substructure analysis** crucial to new physics searches

- Stay tuned for future results!
  - More **run 2 results** on the way
  - **Run 3** ongoing right now
- Great potential for new jet sub-structure analysis techniques



Backup

CMS result summary



Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state √s = 13 TeV

CMS Collaboration, *CMS-PAS-B2G-21-005*

b* → tW (t → 1ℓ): selection

- Cut-based selection steps:
  - Exactly one lepton: $p_T > 53$ GeV
  - At least one b-tagged AK4 jet ($p_T > 30$ GeV)
  - Exactly one W-tagged AK8 jet ($p_T > 200$ GeV)
  - Lepton-jet 2D isolation
  - $\Delta R(j_b,\ j_W) > 0.8$ to remove boosted top quark events

- **Signal region**: $\tau_2/\tau_1 < 0.4$ or 0.45 (2016 or 2017-2018), $65 < m_{SD} < 105$ GeV
- $t\bar{t}$ **control region**: $\tau_3/\tau_2 < 0.6, 105 < m_{SD} < 220$ GeV

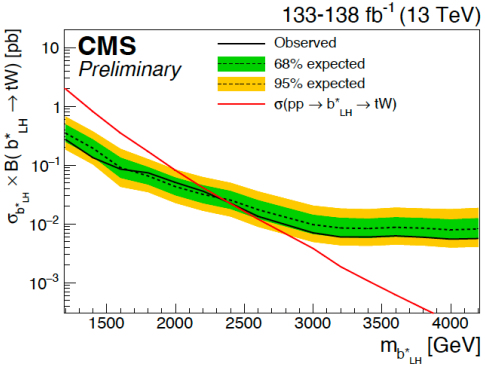
b* → tW (t → 1ℓ): background estimate

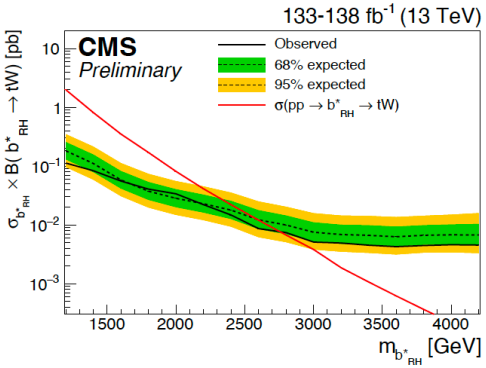
- Background estimation using **ABCD method**
  - Muon channel sidebands: τ_{21} and 2D isolation variable
  - Electron channel sidebands: τ_{21} and N_B
- Constructing likelihood in five regions (4 from ABCD and $t\bar{t}$ CR = E)

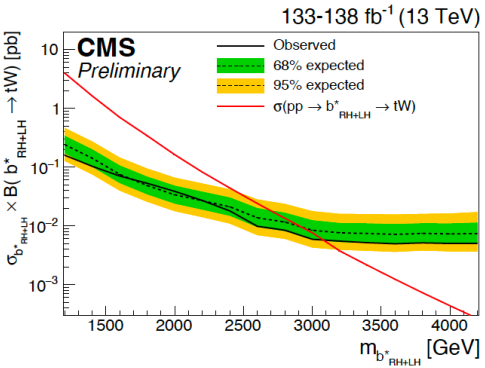
$$\mathcal{L} = \prod_{i}^{N_{\text{bins}}^{\ell,\text{year}}} \prod_{r}^{\text{ABCDE}} \text{P}\left(n_{r,i} \middle| \text{QCD}_{r,i} + \sum_{k} \text{Bkg}_{r,i}^{k} + \mu \text{Sig}_{r,i} \right)$$

- $\text{QCD}_{r,i}$ yield parameters related by $\text{QCD}_{B,i} = \text{QCD}_{A,i} * \text{QCD}_{D,i}/\text{QCD}_{C,i}$
- Final QCD yield in region B (SR) obtained in simultaneous fit

b* → tW (t → 1ℓ): complete results



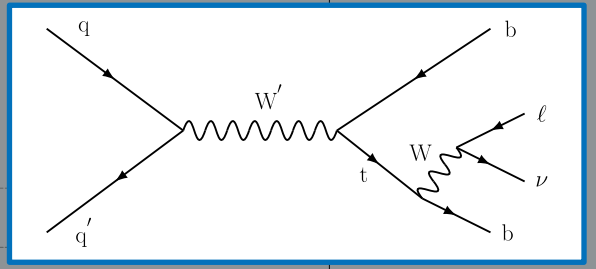




CMS result summary

Search for W′ bosons decaying to a top and a bottom quark in leptonic final states in proton-proton collisions at √s = 13 TeV

CMS Collaboration, *JHEP* 05 (2024) 046



W′ → tb (1ℓ): selection & reconstruction

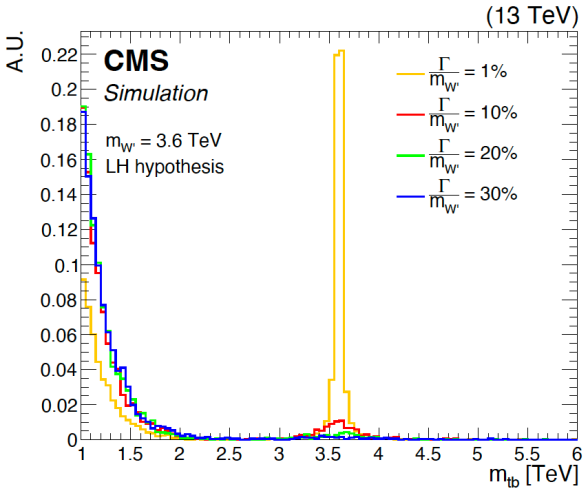
$$I_{\text{mini}} = \frac{S_I(R)}{p_{\text{T}}^{\ell}}, \text{with } R = \frac{10\,\text{GeV}}{\min(\max(p_{\text{T}}^{\ell}, 50\,\text{GeV}), 200\,\text{GeV})}$$

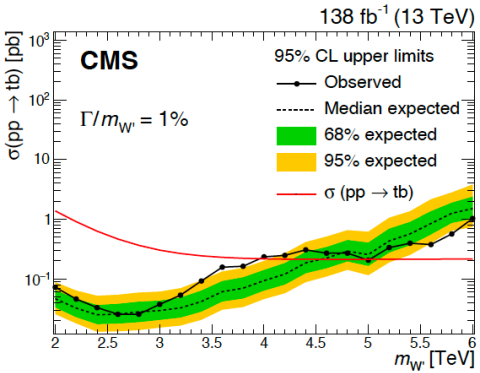
- Cut-based selection steps:
  - Exactly one lepton: $p_T > 55$ GeV (muon) or $p_T > 50$ GeV (electron), $I_{\text{mini}} < 0.1$
  - At least two AK4 jets ($p_T > 300$ GeV, $p_T > 150$ GeV)
  - At least two AK8 jets ($p_T > 170$ GeV)
  - $p_T^{\text{miss}} > 120$ GeV

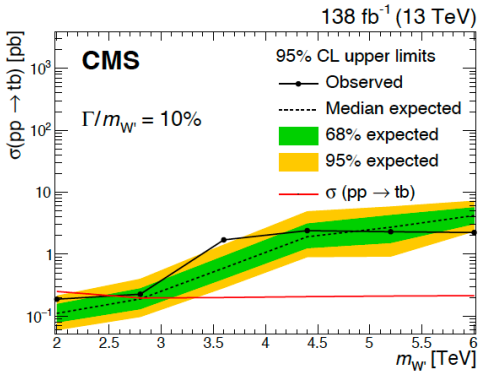
- Reconstruction criteria, applied to b-jets if two or more, otherwise all jets:
  - Top jet j_t criteria: M_t close to world average, min($\Delta R(j_t, \ell)$), sub-leading jet
  - W‘ jet $j_{W'}$ assignment criteria: highest p_T jet that is not j_t

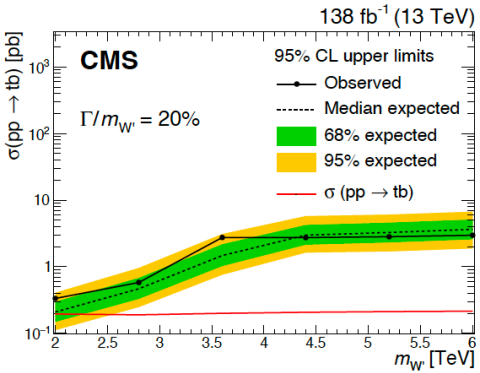
W' → tb (1ℓ): LH results

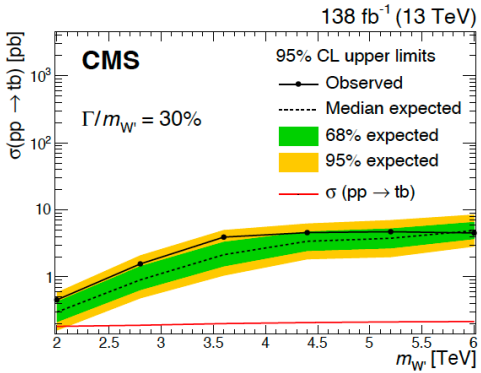
- Expected and observed cross section exclusion limits
  - Evaluating different W' width
  - Assuming left-handed W'





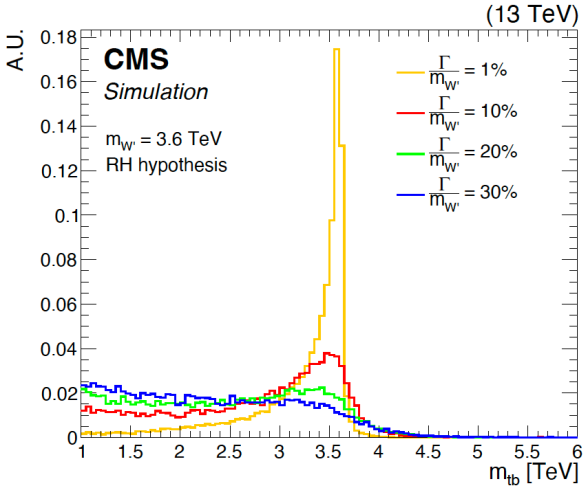


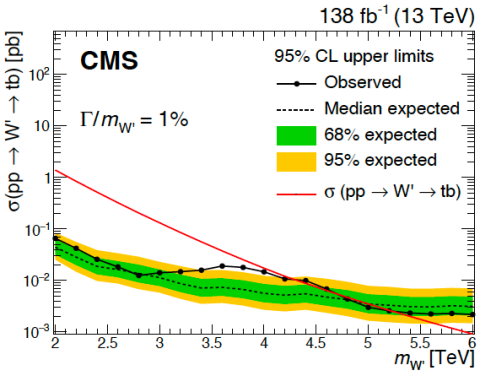


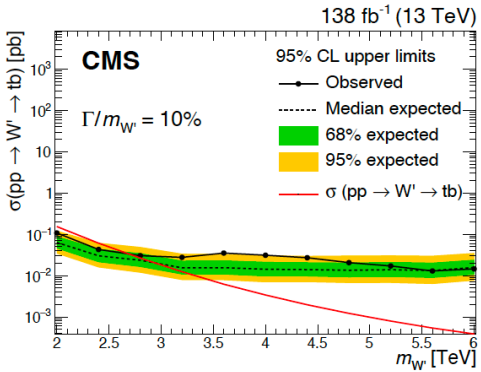


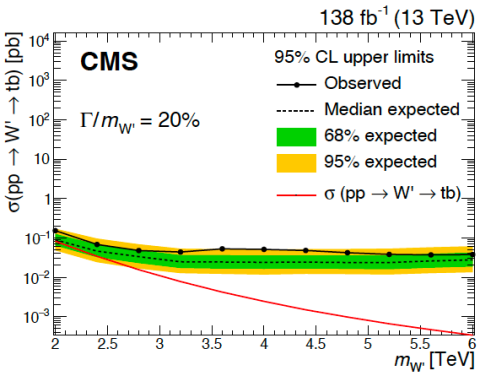
W' → tb (1ℓ): RH results

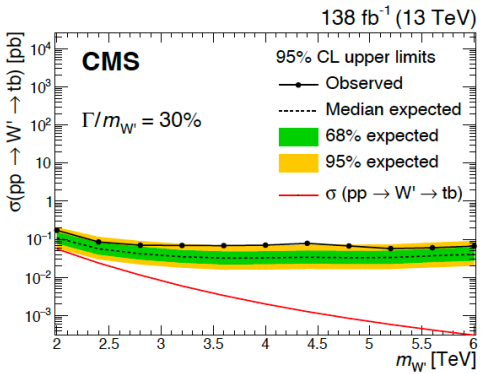
- Expected and observed cross section exclusion limits
  - Evaluating different W' width
  - Assuming right-handed W'







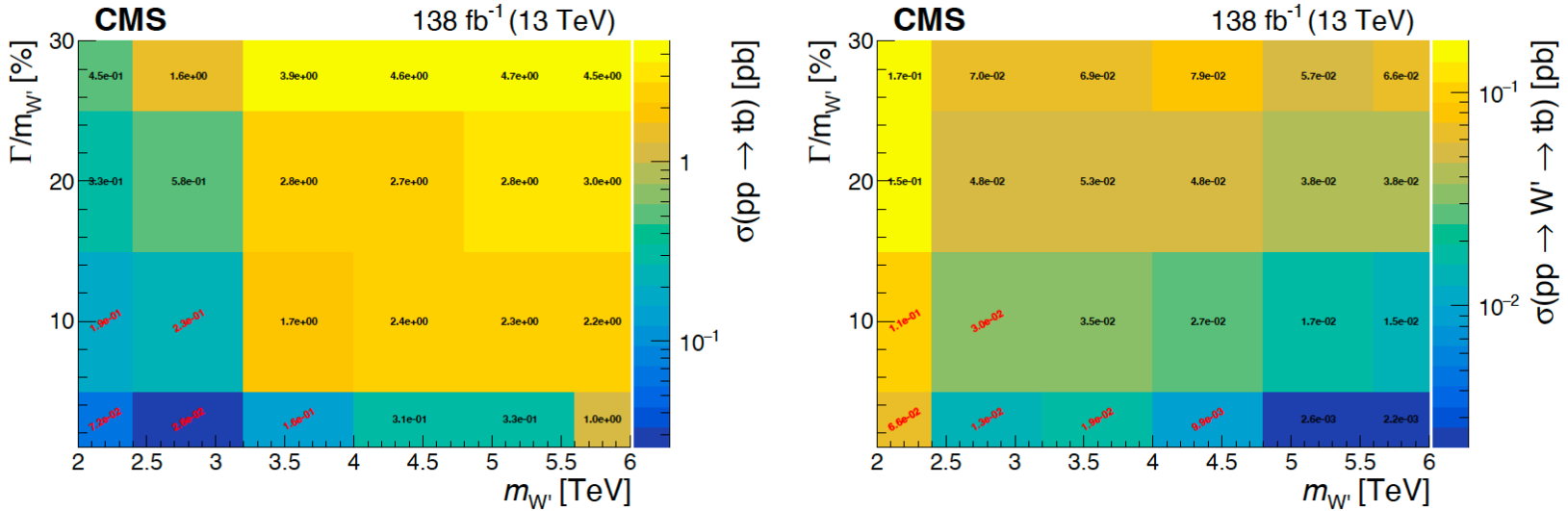




W′ → tb (1ℓ): Cross-section exclusions

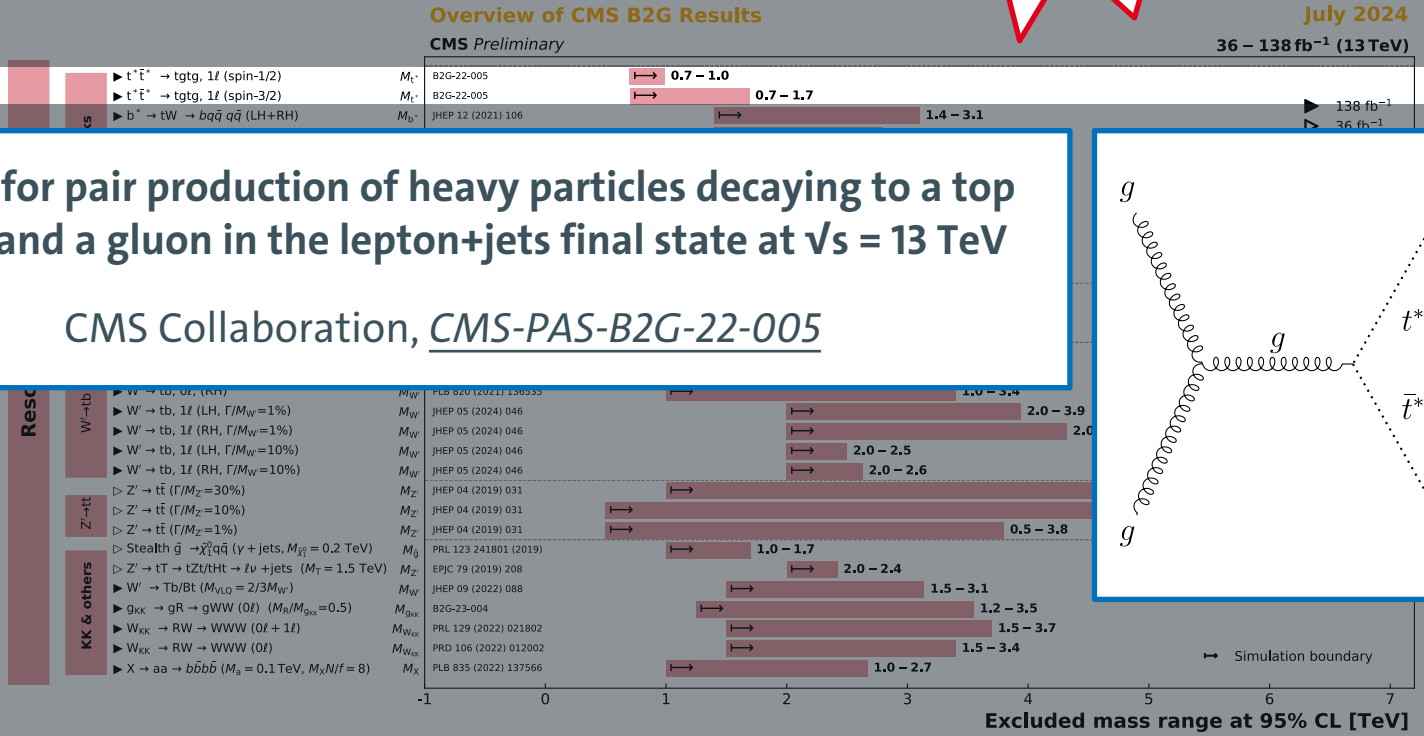
Overview on the cross-section exclusion limits for LH (left) and RH (right).

Red numbers show regions excluded when comparing to predicted cross-sections.



CMS result summary

Brand-new!

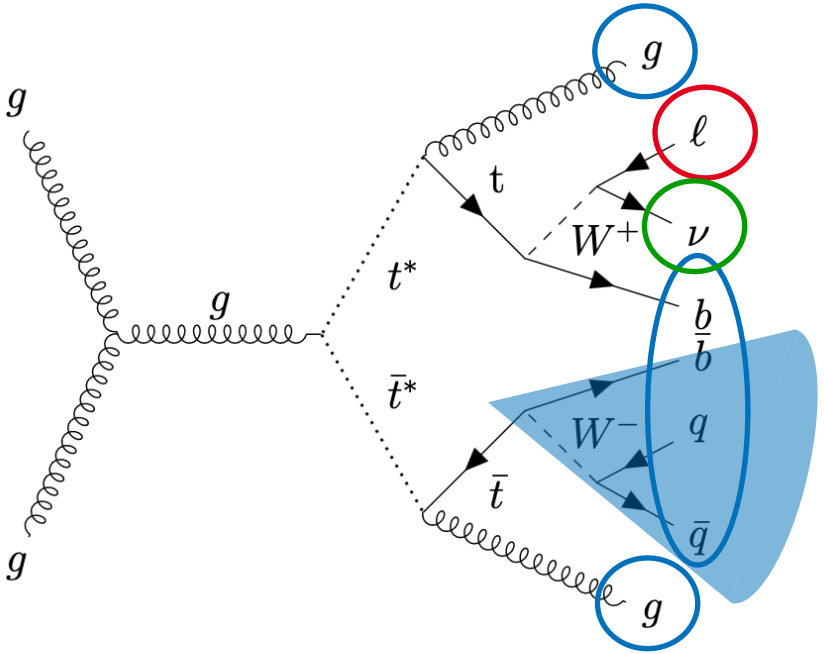


Search for pair production of heavy particles decaying to a top quark and a gluon in the lepton+jets final state at √s = 13 TeV

CMS Collaboration, *CMS-PAS-B2G-22-005*

t*t* → tgtg: selection

- Single lepton trigger (μ or e)
- Exactly one lepton (μ or e)
- ≥ 4 AK4 jets
- ≥ 1 HOTVR jet
- MET > 50 GeV
- ≥ 1 medium DeepJet b-tag
- Custom lepton isolation
- $S_T > 500$ GeV



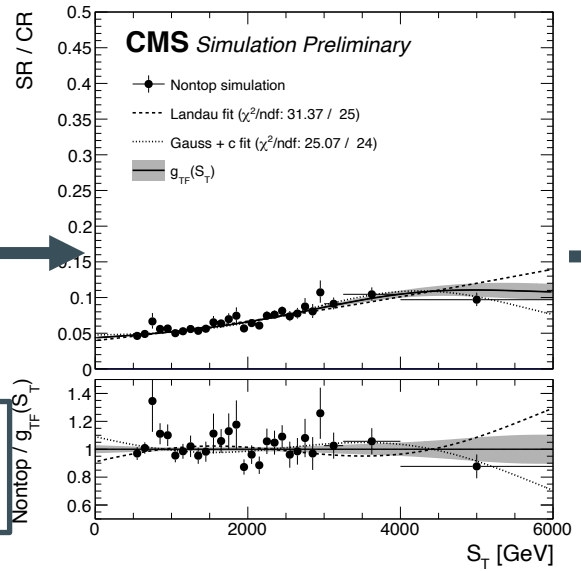
Feynman diagram of $t^*t^* \rightarrow tgtg \rightarrow bbqqgg\ell\nu$

t*t* → tgtg: background estimation I

- Using a transfer function fit to a MC ratio to estimate non-top backgrounds
  - Procedure performed for both SR (for statistical analysis) and VR (for validation)

Control region
Enriched in non-t backgrounds with veto on b-jets

Subtract contribution from t-backgrounds

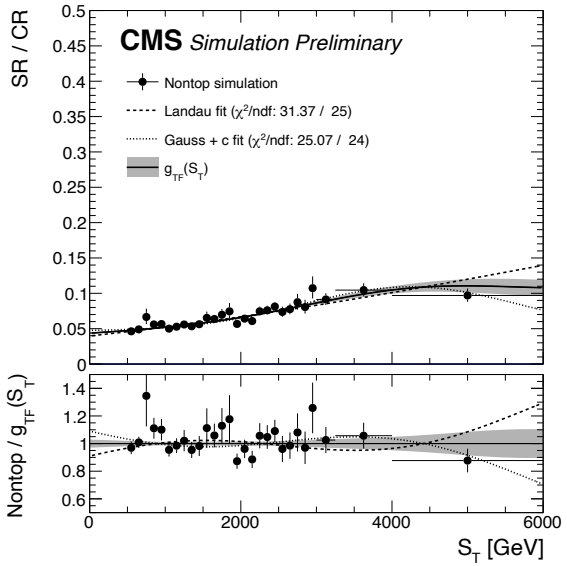


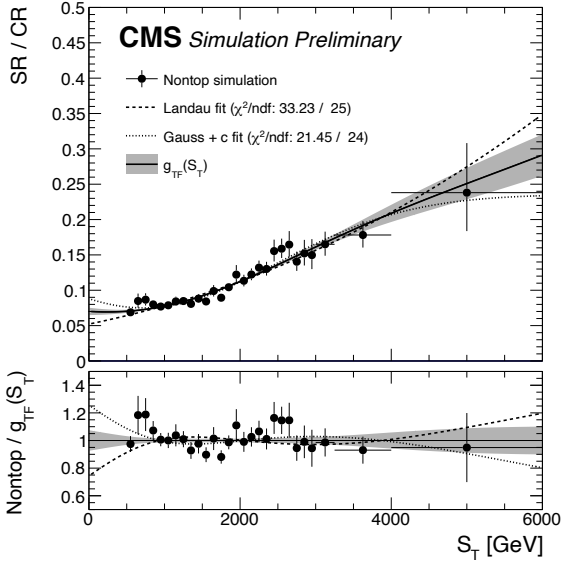
Signal region
non-t backgrounds

Validation region
non-t backgrounds

t*t* → tgtg: background estimation II

Background estimation functions for electron (left) and muon channel (right)





t*t* → tgtg: spin ½ limits