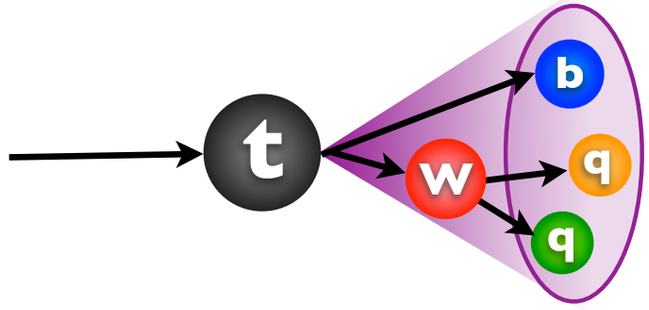
Search for new resonances coupling to third generation quarks at CMS



James Dolen
Purdue University Northwest

Phenomenology 2021 International Symposium - May 24th, 2021

Introduction

Goal: Search for resonant production of new particles with a large branching fraction to top and bottom quarks

1. **Heavy resonances which decay directly to standard model particles (including top and bottom quarks)**

   Examples:

   Z` → tt, W` → tb, excited quarks (b* → tW, t* → tg), leptoquarks (LQ → tτ, LQ → tμ)

2. **Heavy resonances which decay to new intermediate particles which then decay to standard model particles**

   Examples:

   Z` → tT, Z` → TT, W` → Tb/Bt

Notes:
T represents a vector-like top quark partner
B represents a vector-like bottom quark partner

Introduction

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2. **Heavy resonances which decay to new intermediate particles which then decay to standard model particles**

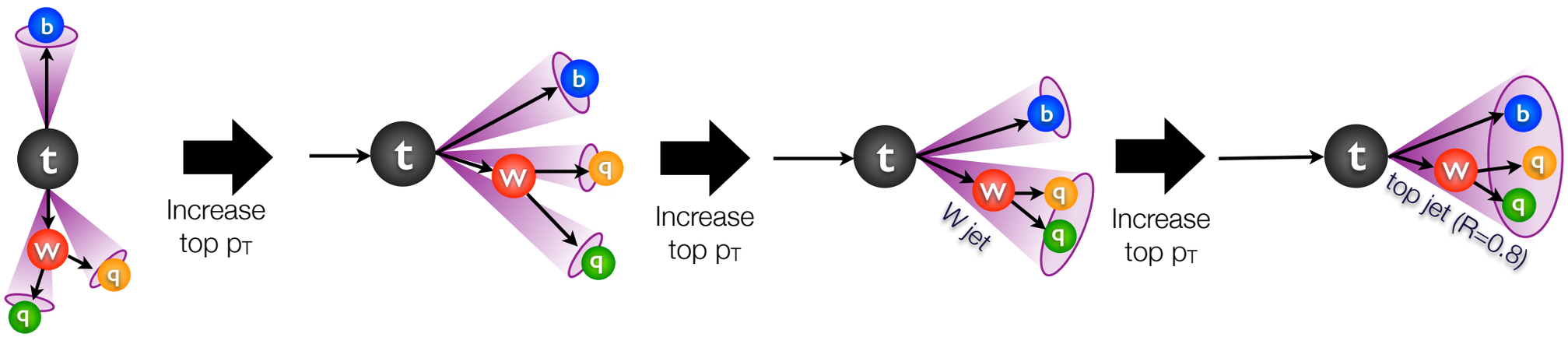
Examples:

Z` → tT, Z` → TT, **W` → Tb/Bt**

Today: Highlight the most recent searches in these categories, all of which use the full CMS Run II dataset

Introduction

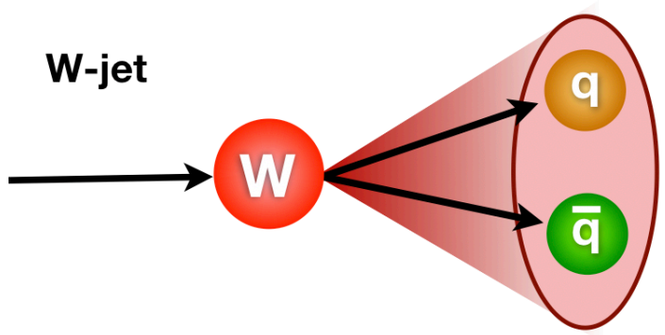
Searching for heavy resonances
→ decay products are highly boosted
→ hadronic decays often merge within one jet

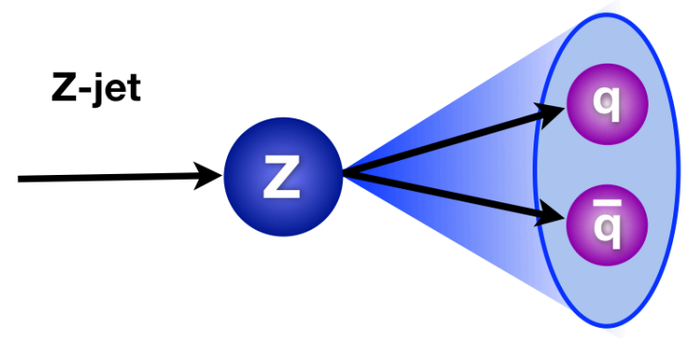


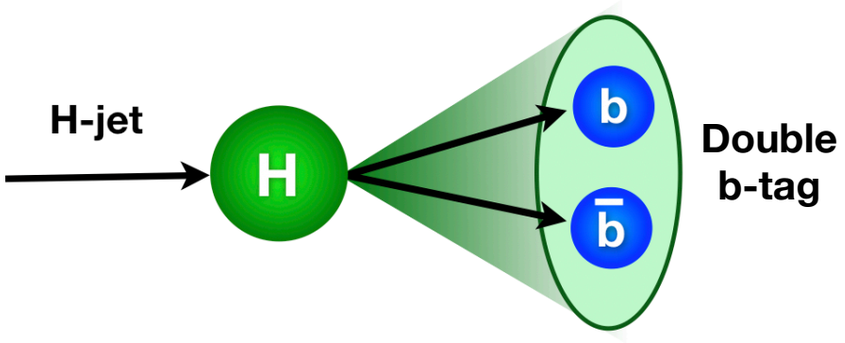
Extensive use of jet substructure based tagging tools

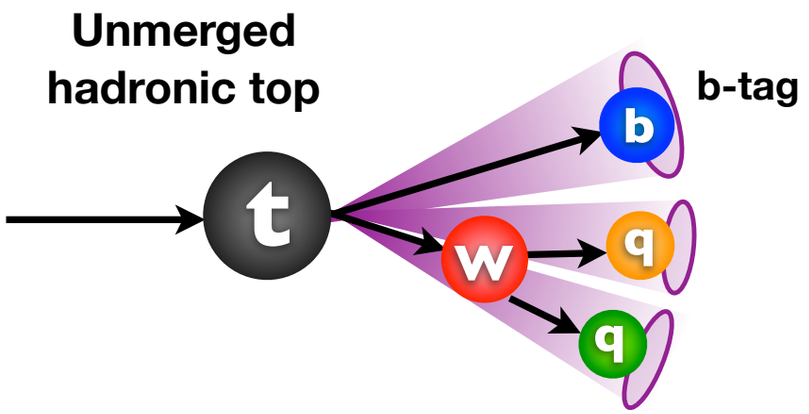
Jet-tagging Menu

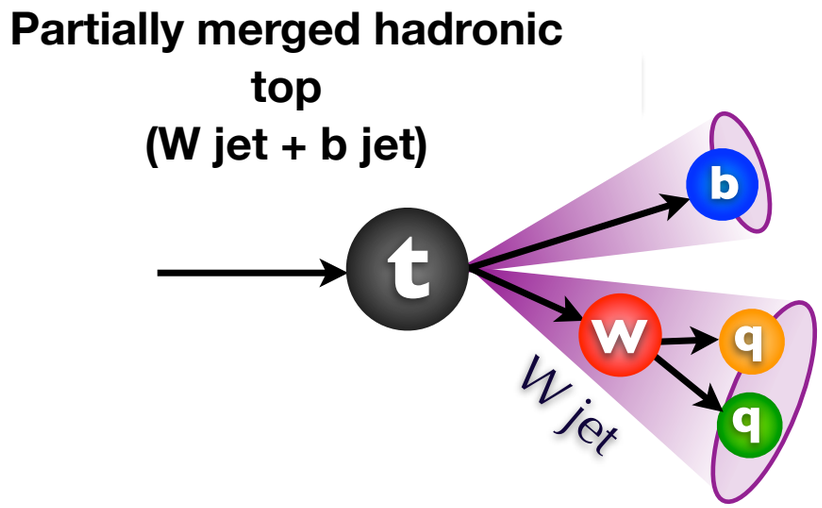
Utilize jet substructure to tag partially or fully merged jets

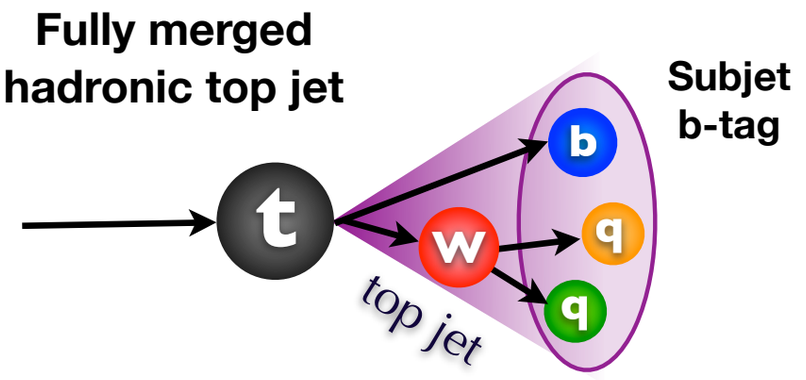


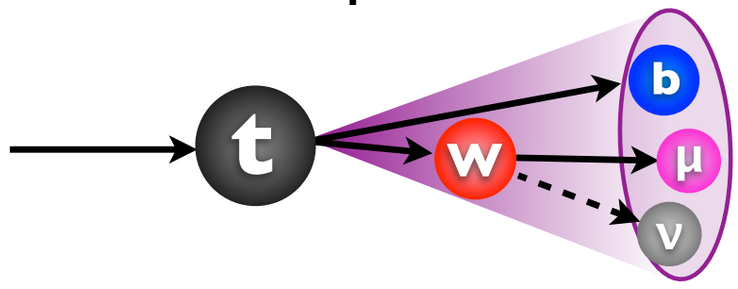






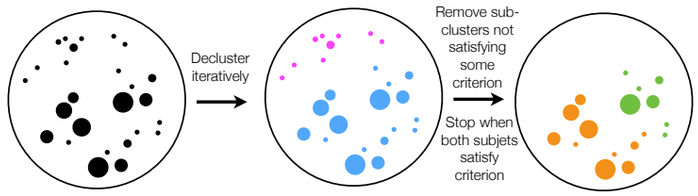




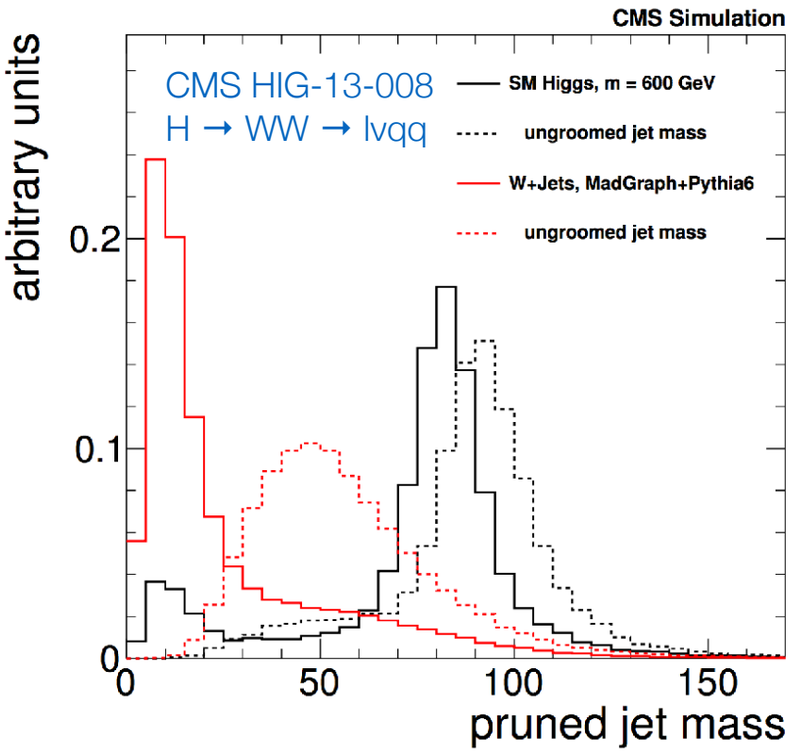


Jet Tagging Tools

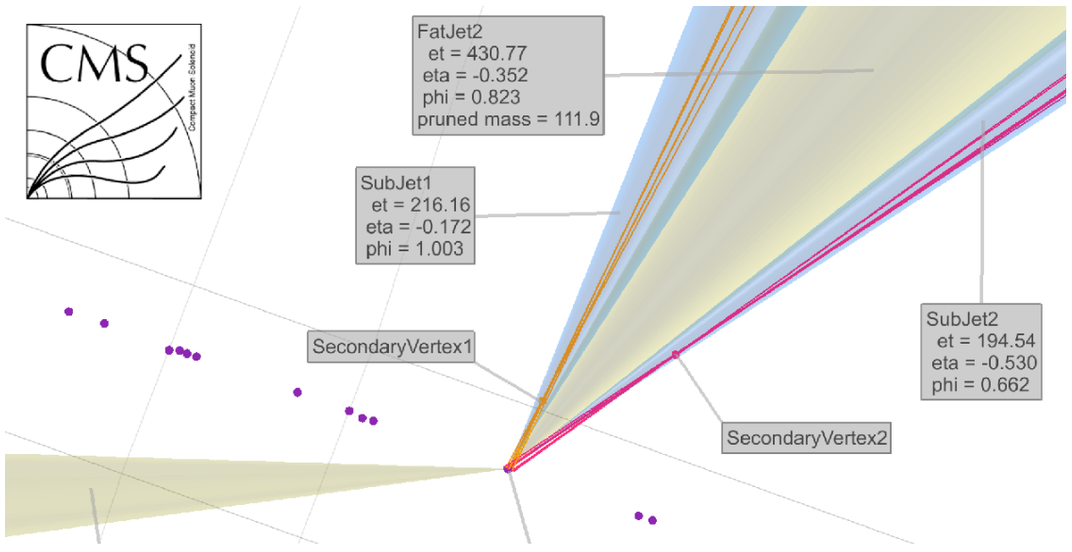
- Jet grooming
  - Modified mass drop tagger (soft drop algorithm)
  - Improve mass discrimination and resolution

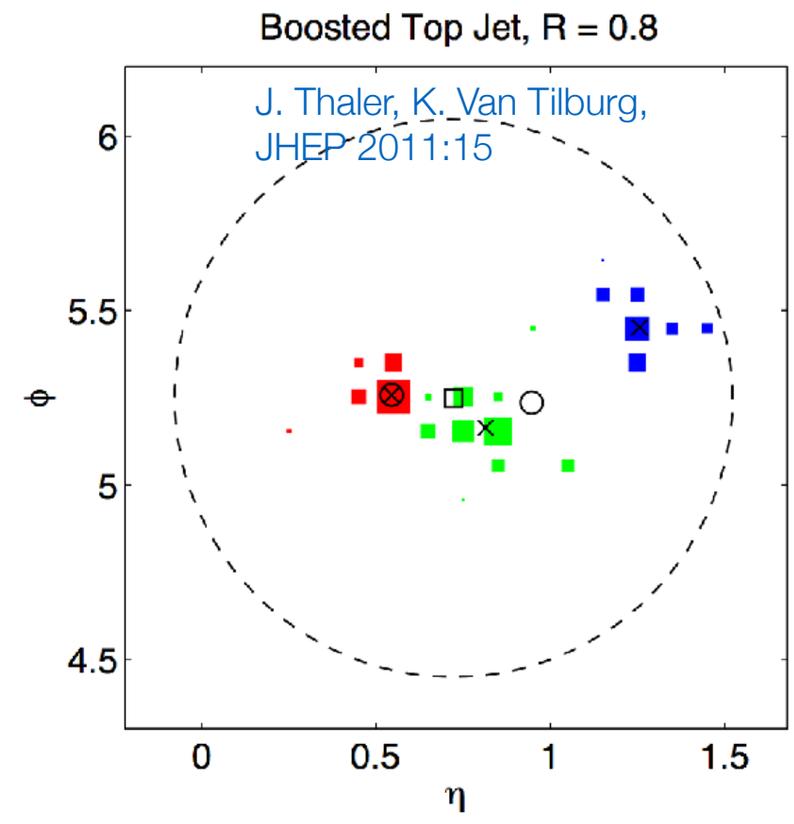


- N-subjettiness
  - Determines how consistent a jet is with having N or fewer subjets
  - Better discrimination by using ratios (ex. τ_3/τ_2)



- B-tagging, subjet b-tagging, and a double b-tagger

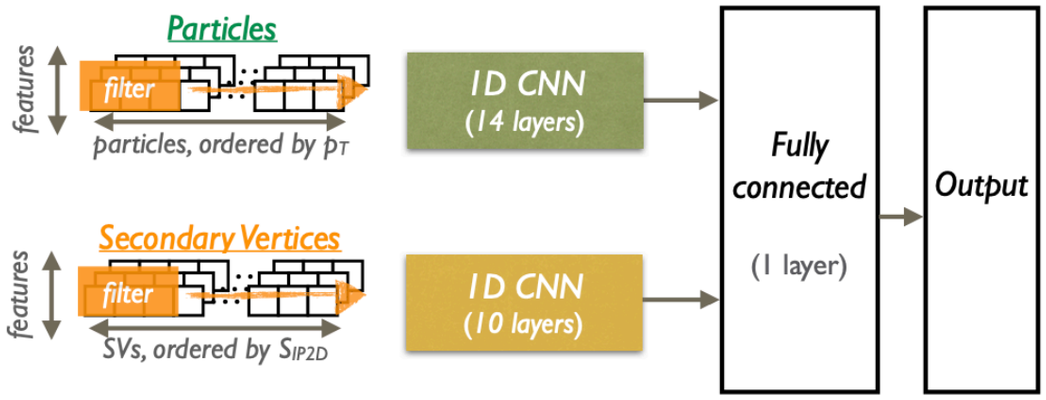


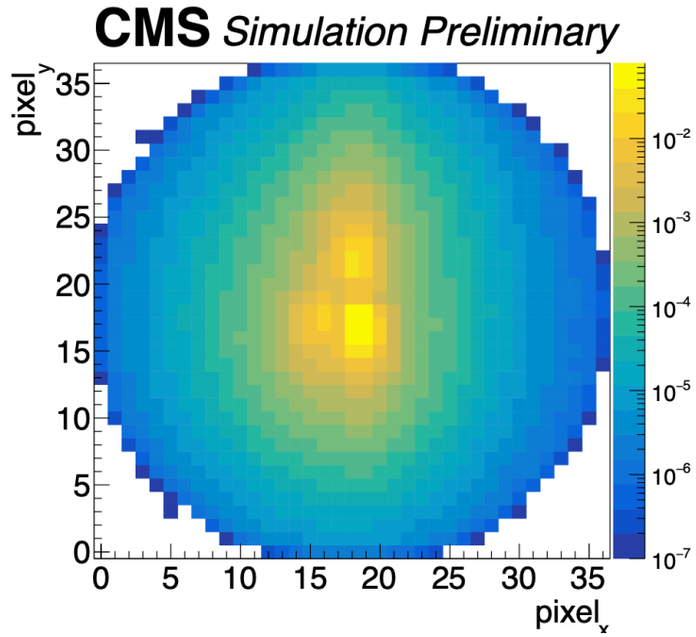


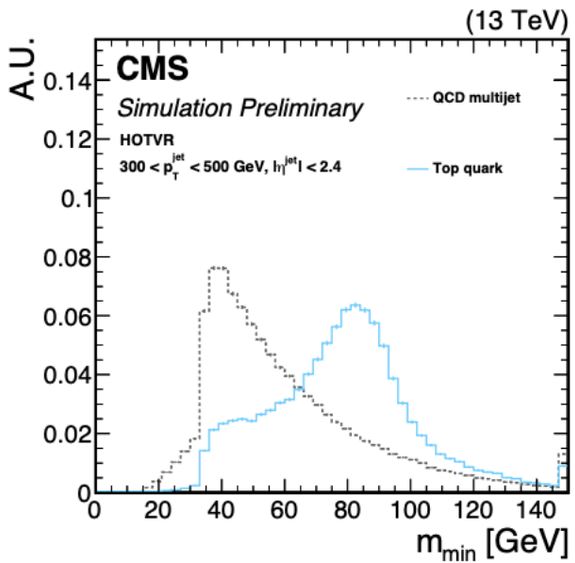
Jet Tagging Tools - Novel Top Taggers

CMS JME-18-002

- DEEPAK8 top-tag
  - Deep Neural Network approach
  - Inputs: Jet constituent particle kinematic and angular information, track information, and secondary vertex information.
- ImageTop top-tag
  - Image recognition techniques using Convolutional Neural Networks
- HOTVR
  - “Heavy Object Tagger with Variable R”
  - Jet size varies up to ΔR = 1.5
  - Allows the use of jet substructure tools for lower momentum tops
  - Tag jets using HOTVR mass, Nsubjets, minimum subjet pairwise mass, subjet pT ratio, and τ_3/τ_2



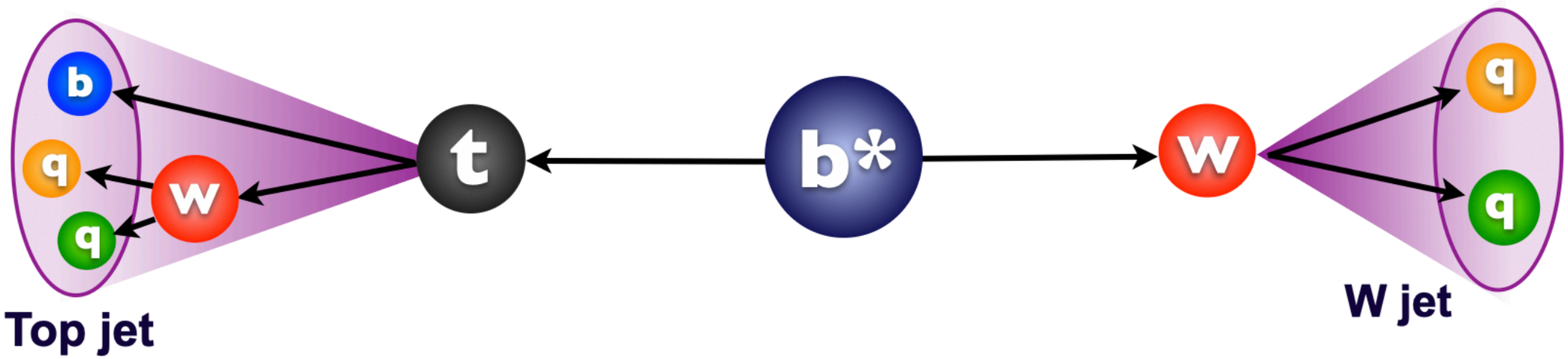




Search for a heavy resonance decaying to a top quark and W boson in the all-hadronic final state

Search for a heavy resonance decaying to t and W in the all-hadronic final state

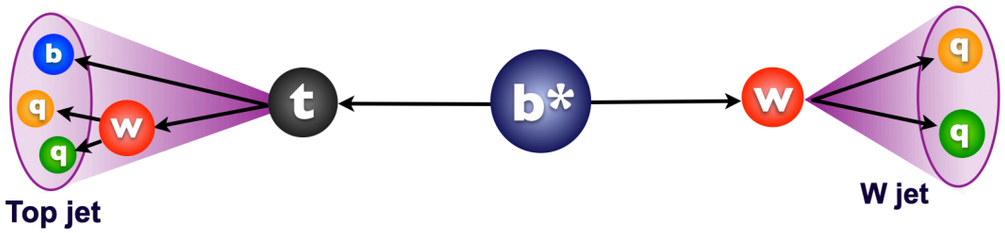
- Search for a heavy particle which decays to a top quark and a W boson
  - Benchmark Model: Excited bottom quark “b*”
- All-Hadronic final state considered



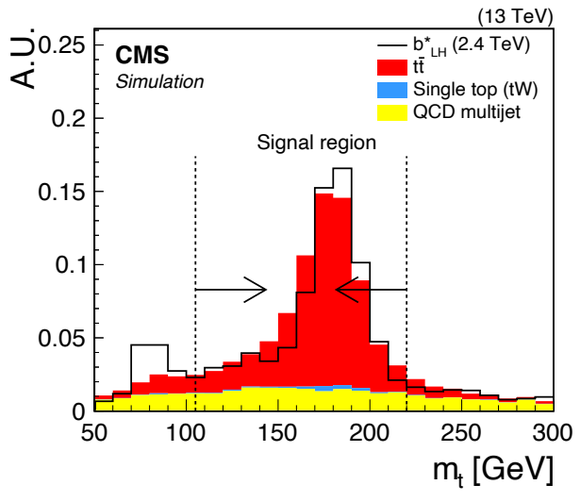
http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-19-003/index.html

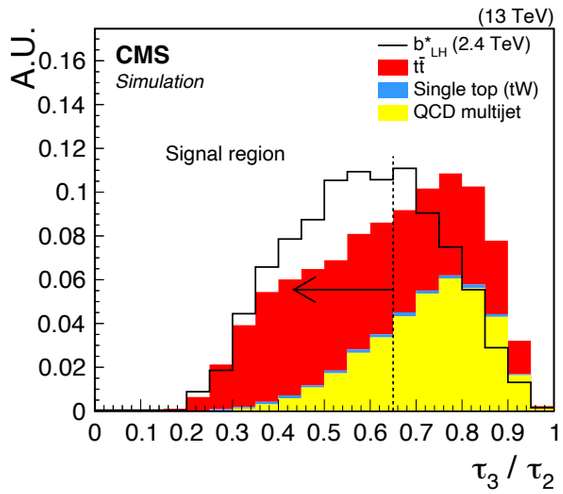
Submitted to J. High Energy Phys.

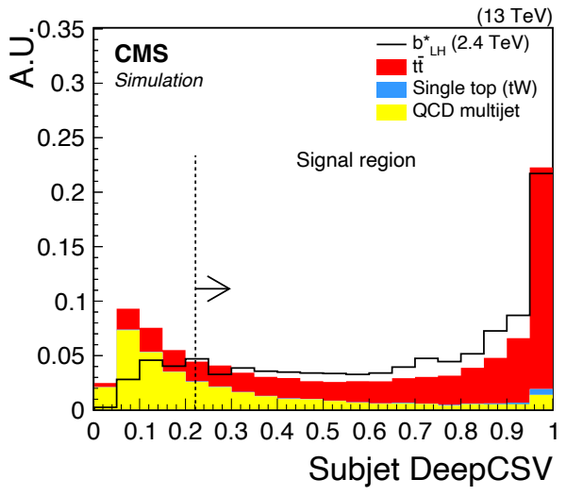
Event Selection

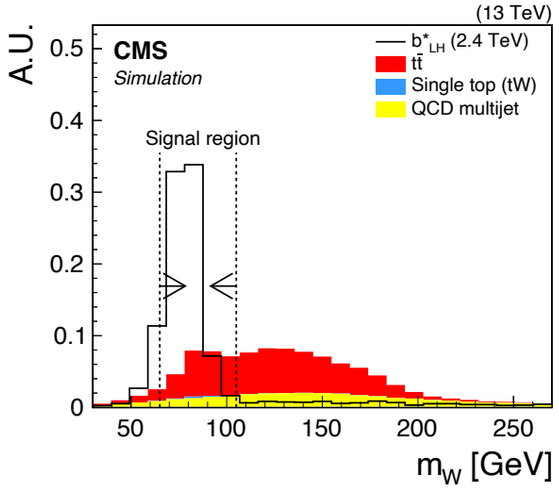


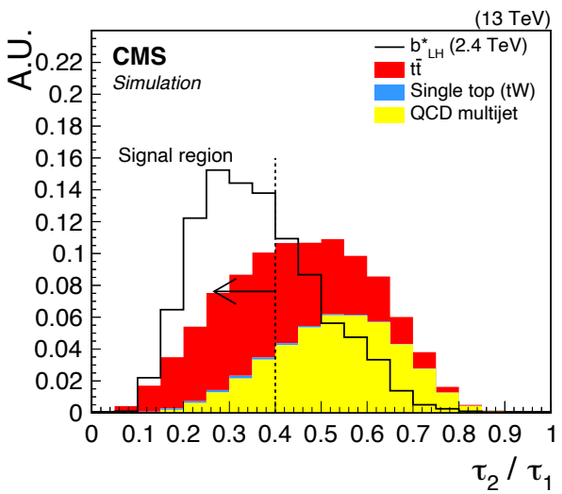
- CMS Run II data (2016-2018)
  - Integrated luminosity 137 fb^{-1}
- Require two well-separated AK8 jets
- Top tag
  - Soft-drop groomed jet mass
  - N- subjettiness ratio τ_3/τ_2
  - B-tagged subjet (Deep CSV algorithm)
- W-tag
  - Soft-drop groomed jet mass
  - N-subjettiness ratio τ_2/τ_1





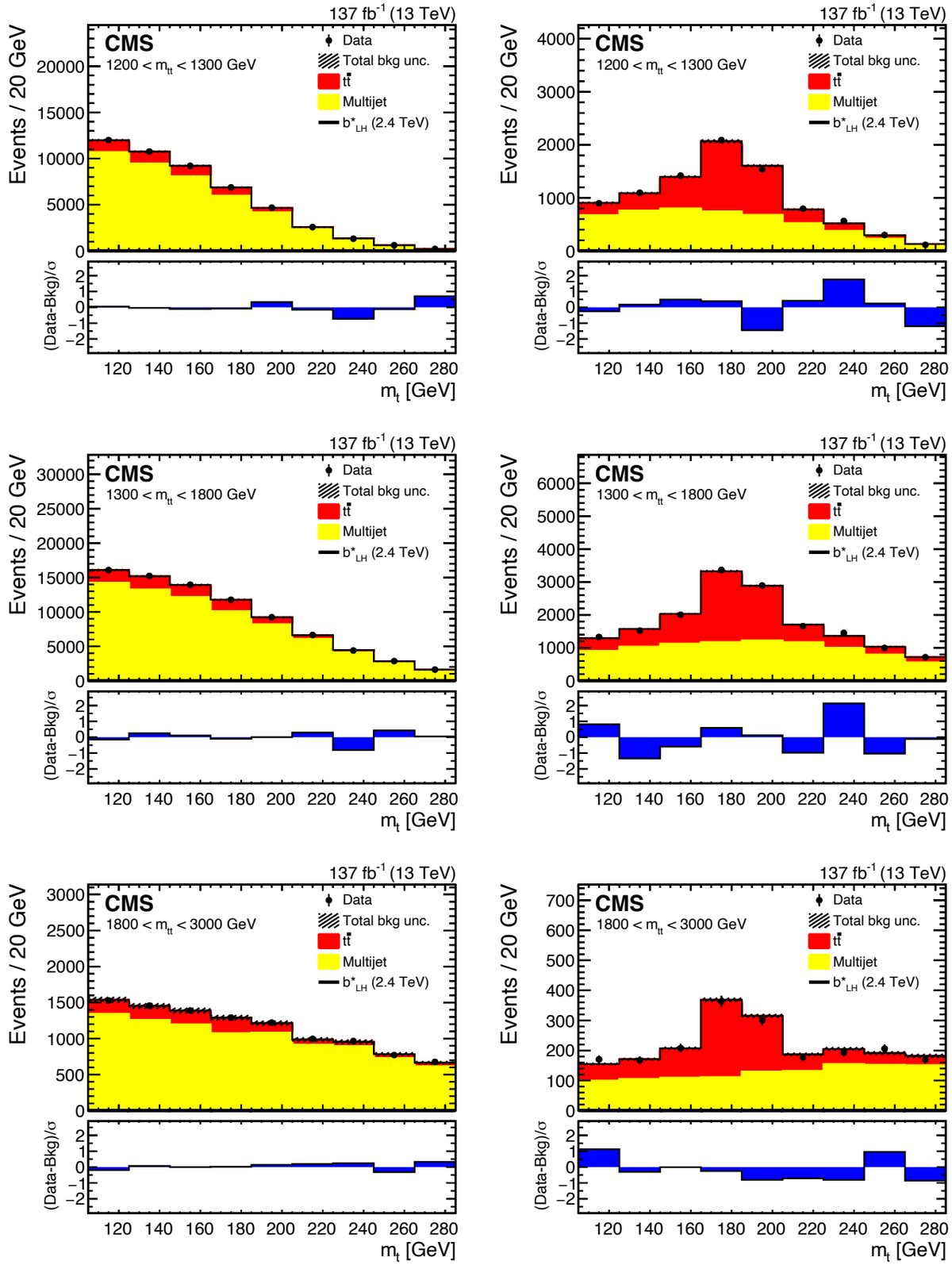






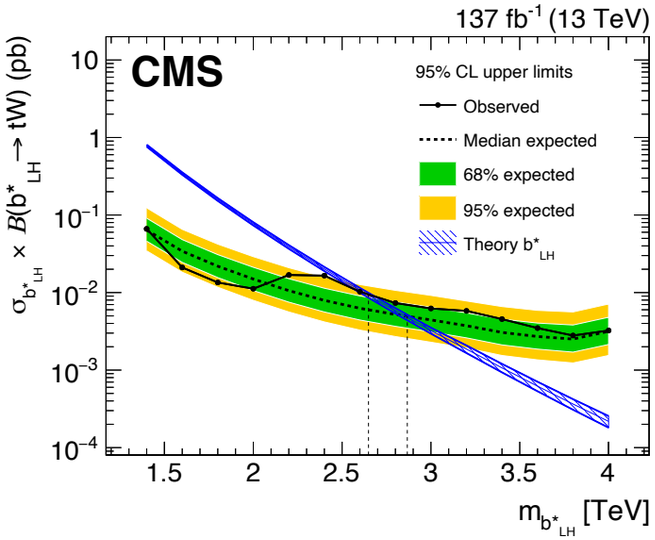
Search Information

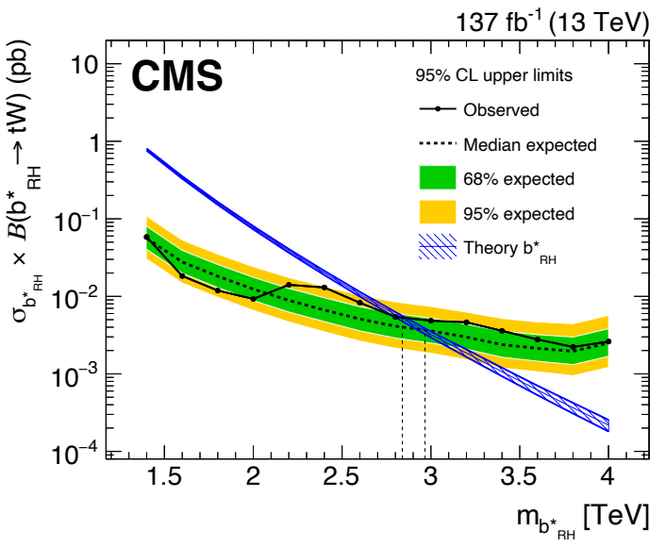
- Backgrounds
  - QCD Multijet
    - Dominant
    - Estimated using control regions
  - Top quark pair production
    - Estimated with both data and simulation
  - Single top
    - Simulated
- Search
  - Binned maximum likelihood fit
  - m_{tW} vs m_t distribution

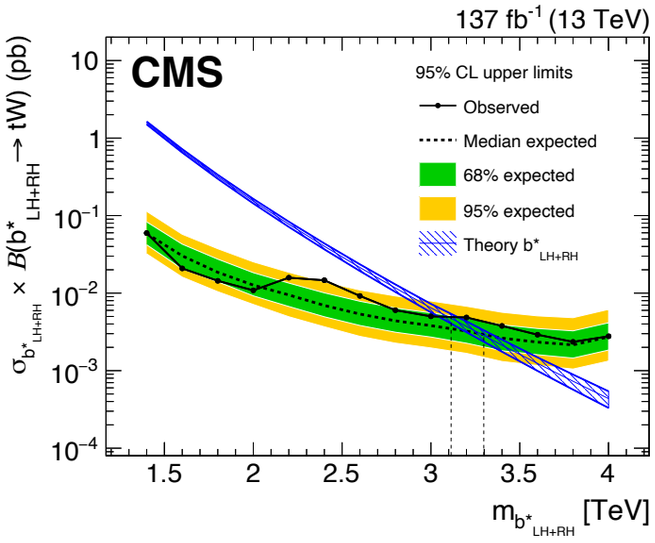


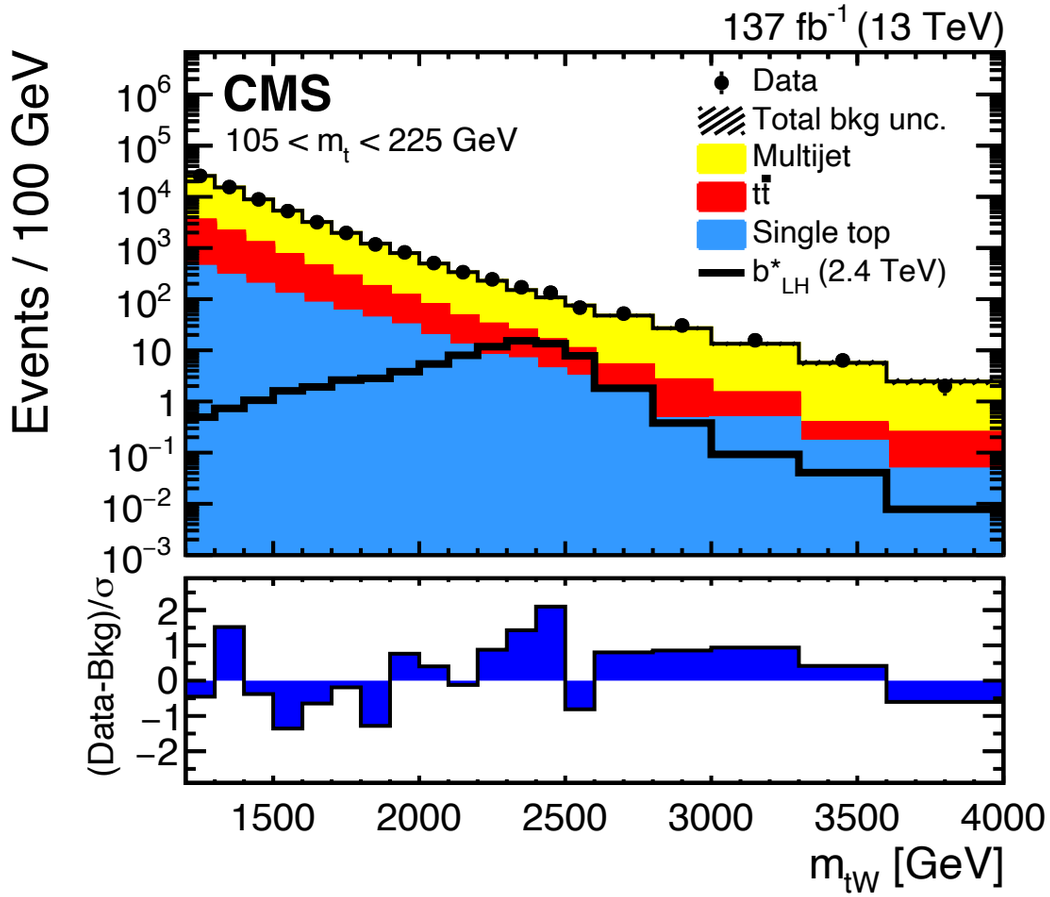
Results

- No significant excess above the standard model background is observed.
- Limits set on the production cross section for left-handed (LH), right-handed (RH), and vector- like chiralities (LH+BH).





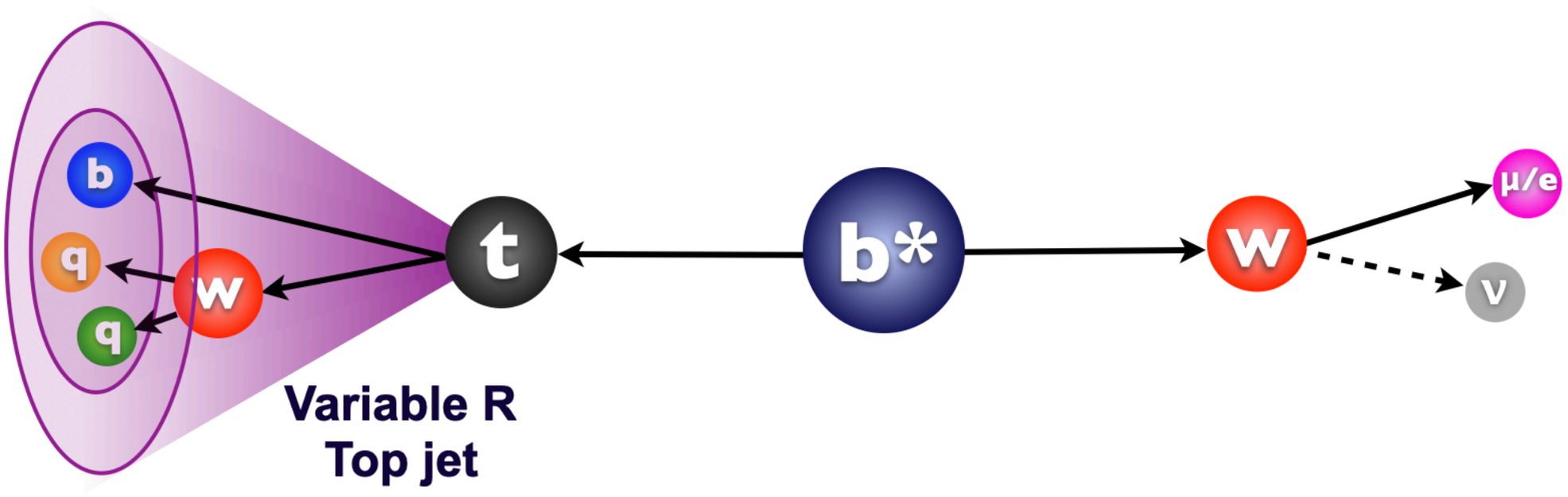




Search for a heavy resonance decaying to a top quark and W boson in the lepton+jets final state

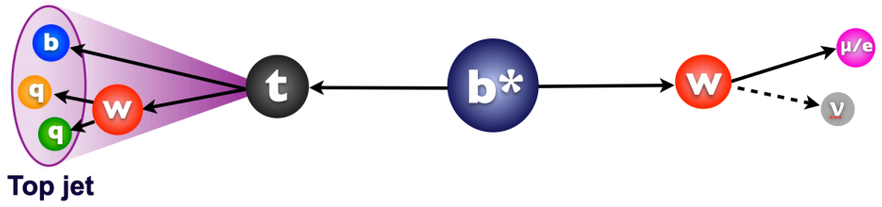
Search for a heavy resonance decaying to t and W in the lepton+jets final state

- Search for a heavy particle which decays to a top quark and a W boson
  - Benchmark modle: Excited bottom quark “b*”
- Lepton+jets final state considered
  - Hadronic top decay
  - W-boson decays to a muon or electron and a neutrino



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-20-010/index.html

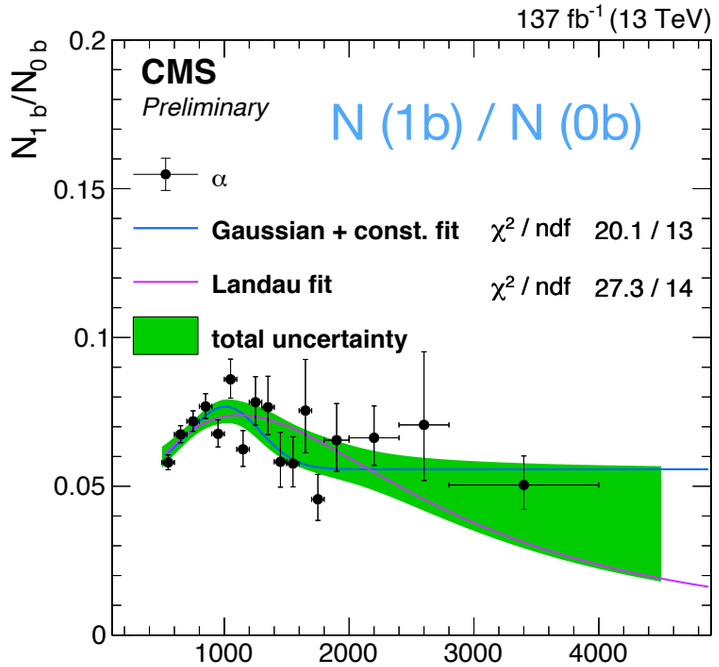
Event Selection

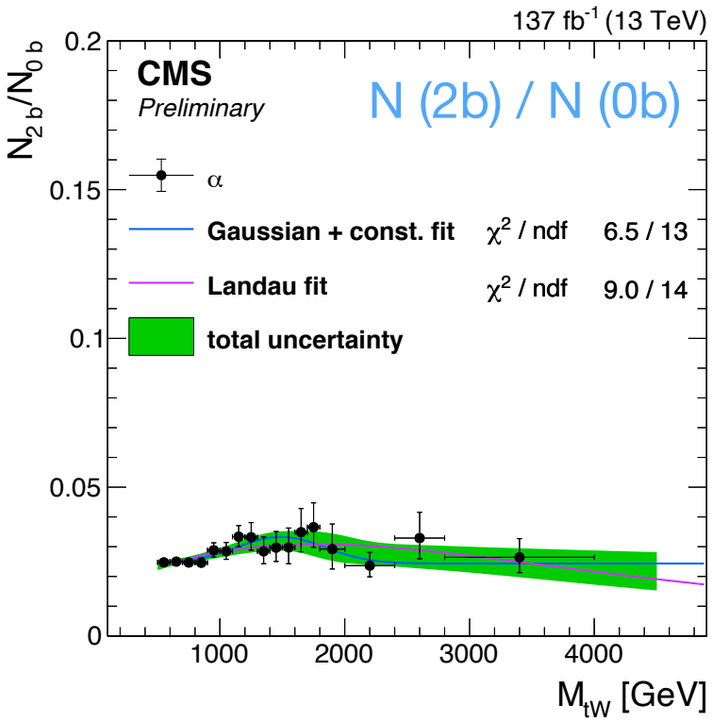


- CMS Run II data (2016-2018)
  - Integrated luminosity 137 fb^{-1}
- Final state - 1 lepton, missing transverse momentum, and 1 top-tagged jet
  - Lepton allows for lower p_T trigger
- Top tag
  - HOTVR - Variable R allows one to maintain efficiency at low p_T
- Neutrino reconstructed using the W mass as a constraint
- Chi-squared estimator used to measure how signal-like an event is
- Categorize events based on N_{btags}

Search Information

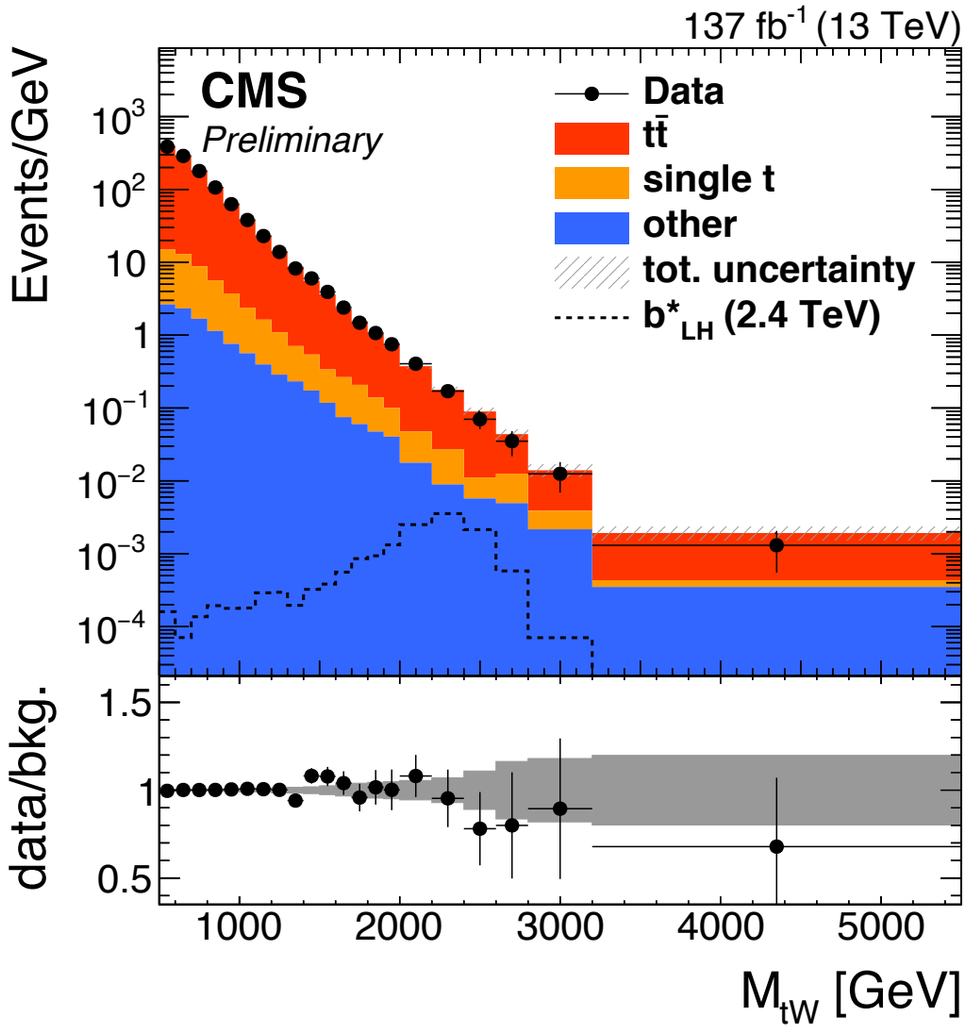
- Backgrounds
  - Top quark pair production
    - Control region: 2 b-tag category is used to constrain systematic uncertainties associated with simulation
  - Single top
  - Non-top
    - Dominantly W/Z+jets and diboson
    - Estimated with data using the 0 b-tag category
    - Transfer function (alpha method)
- Search
  - Binned maximum likelihood fit
  - b* mass is reconstructed from the tW mass

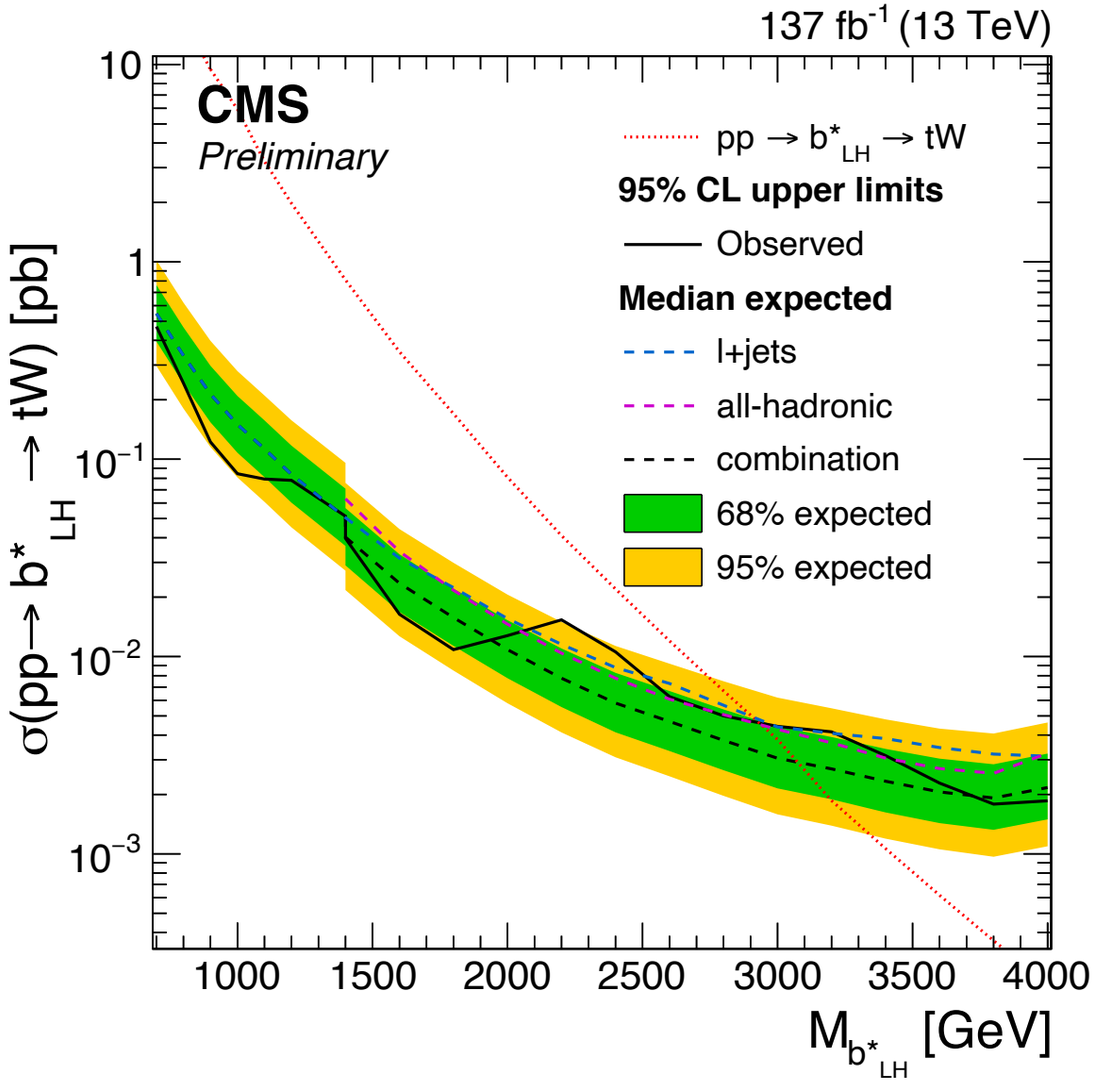




Results

- No significant excess above the standard model background is observed.
- Limits set on the production cross section for left-handed (LH), right-handed (RH), and vector-like chiralities (LH+BH).
- Lepton+jets results are combined with the all-hadronic analysis

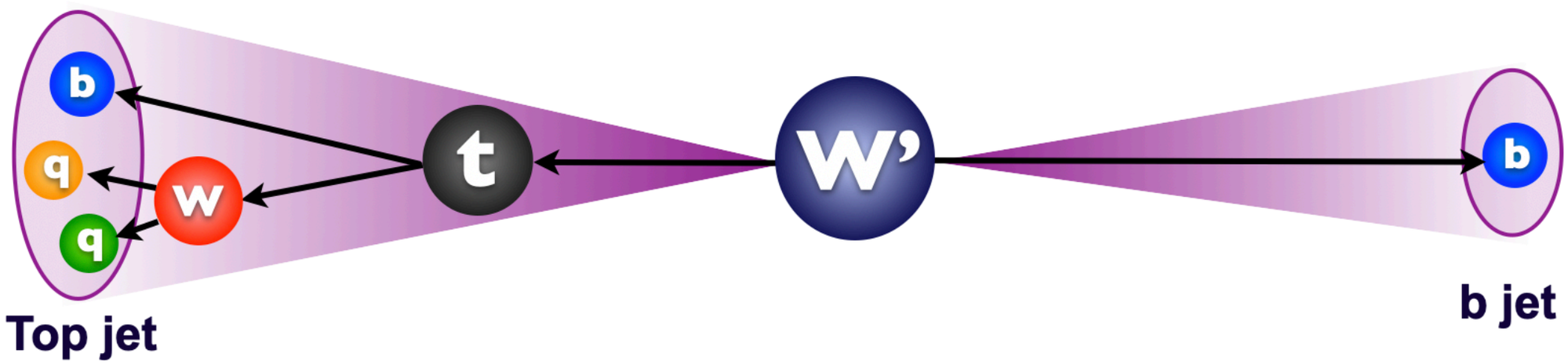




Search for a W' boson decaying to t and b

Search for a W' boson decaying to t and b

- W' boson: Spin-1 gauge boson
  - Predicted in numerous models including Little Higgs, extra dimensional, and left-right symmetric models.
- Hadronic final state considered

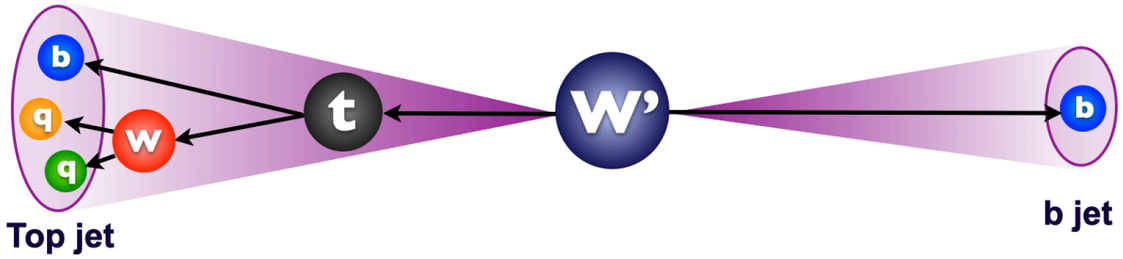


http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-20-005/index.html

Submitted to Phys. Lett. B

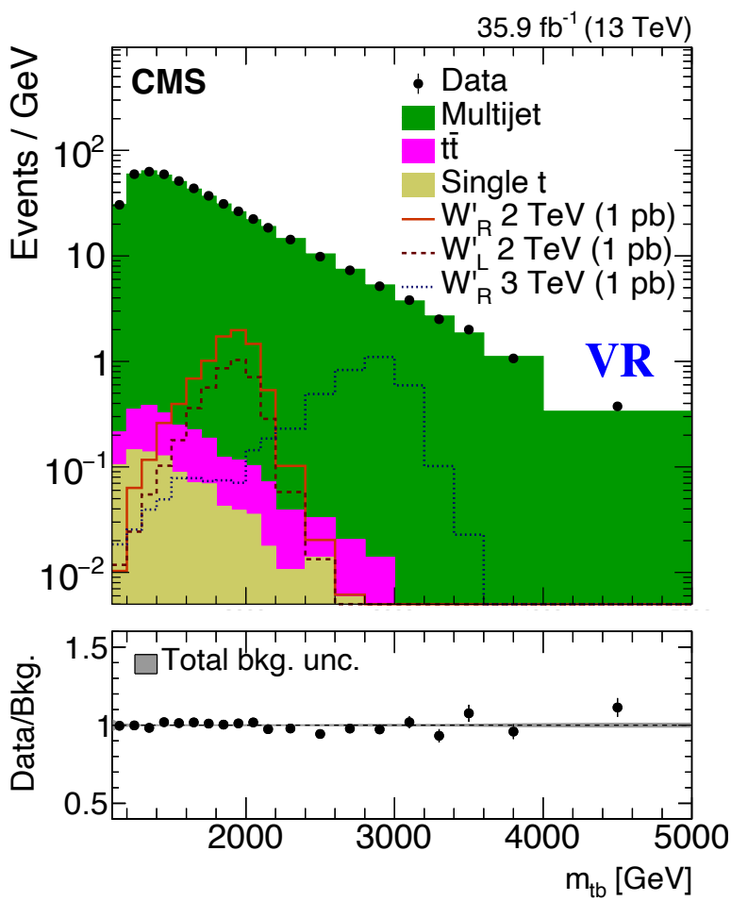
Event Selection

- CMS Run II data (2016-2018)
  - Integrated luminosity 137 fb^{-1}
- Require 1 AK8 and 1 AK4 jet separated by $\Delta R>1.2$
- Reject pairwise top - make sure there is no heavy AK8 jet near the AK4 jet
- Top tag
  - DEEPAK8 top-tag
- b-tag
  - DEEPJET b-tagger



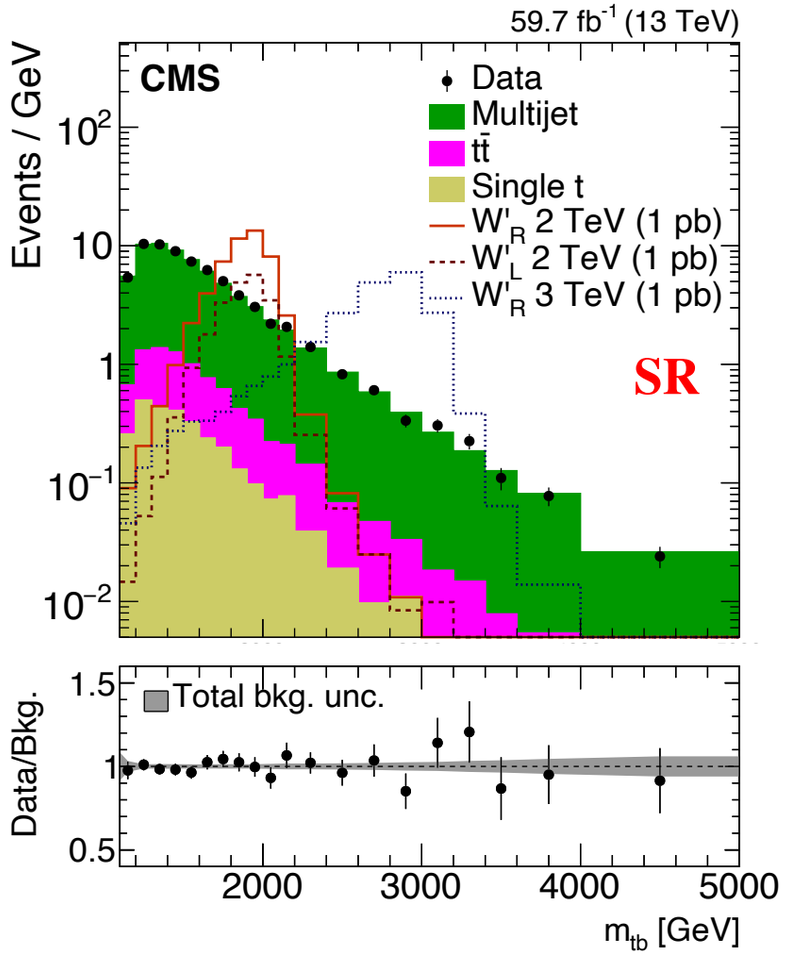
Search Information

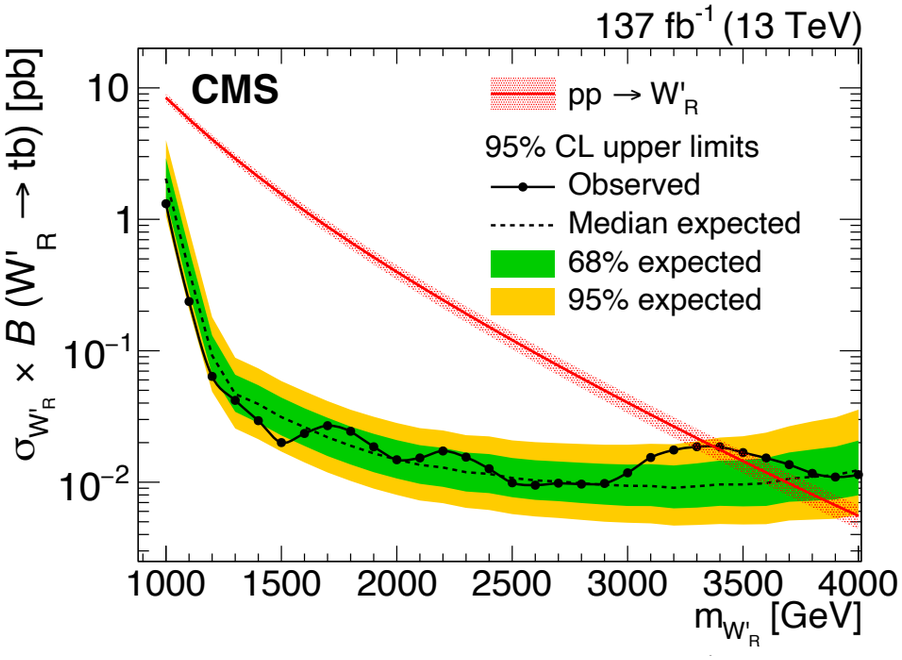
- Backgrounds
  - QCD Multijet
    - Dominant
    - Data-based background estimation
      - Control region used to estimate the multi jet background in the signal region and validated with the validation region.
  - Top quark pair production
    - Estimated with simulation and validated with data
- Search
  - Bump hunt in the m_{tb} distribution
  - Binned maximum likelihood fit

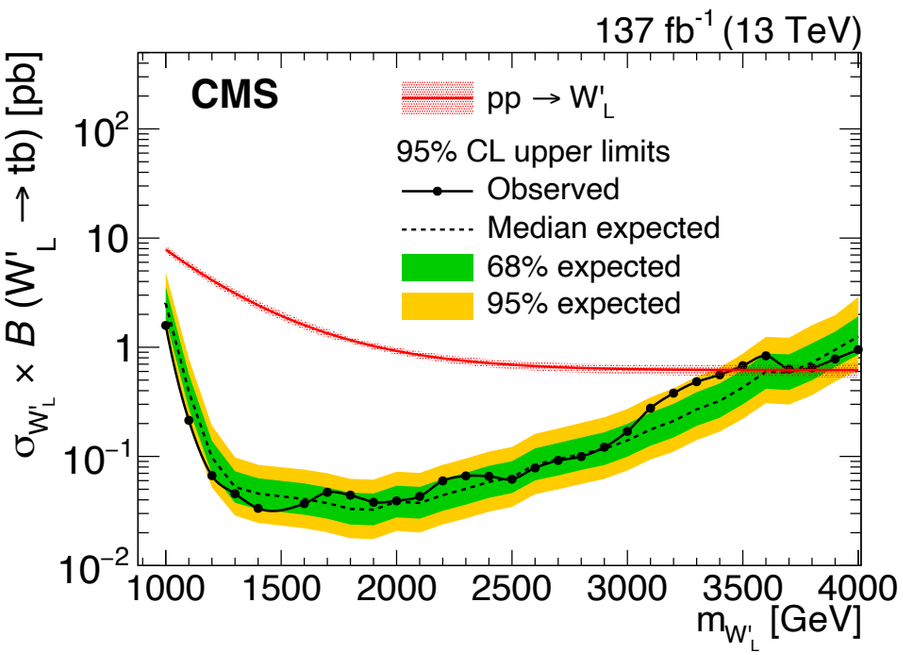


Results

- No significant excess above the standard model background is observed
- Limits set on the production cross section for both left-handed and right-handed W' bosons
  - Both excluded for masses below 3.4 TeV at 95% confidence level



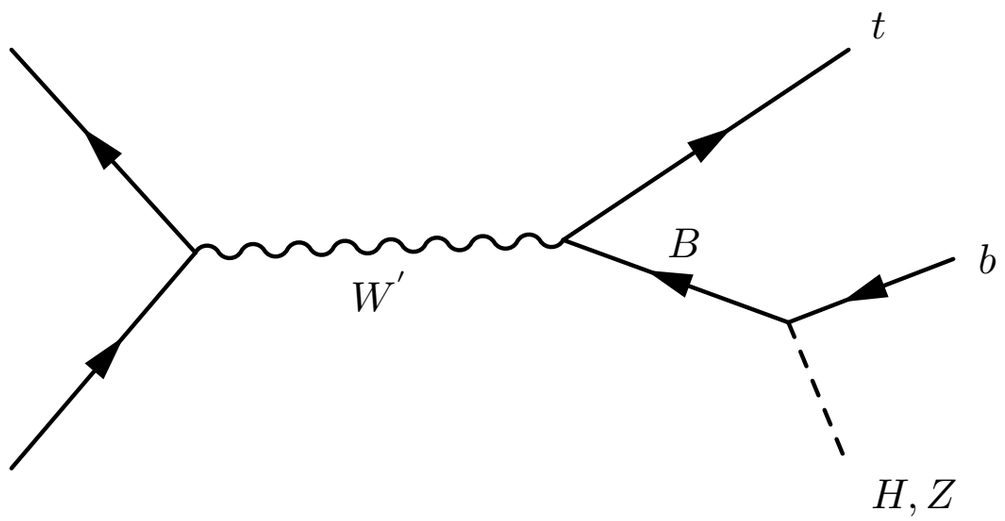


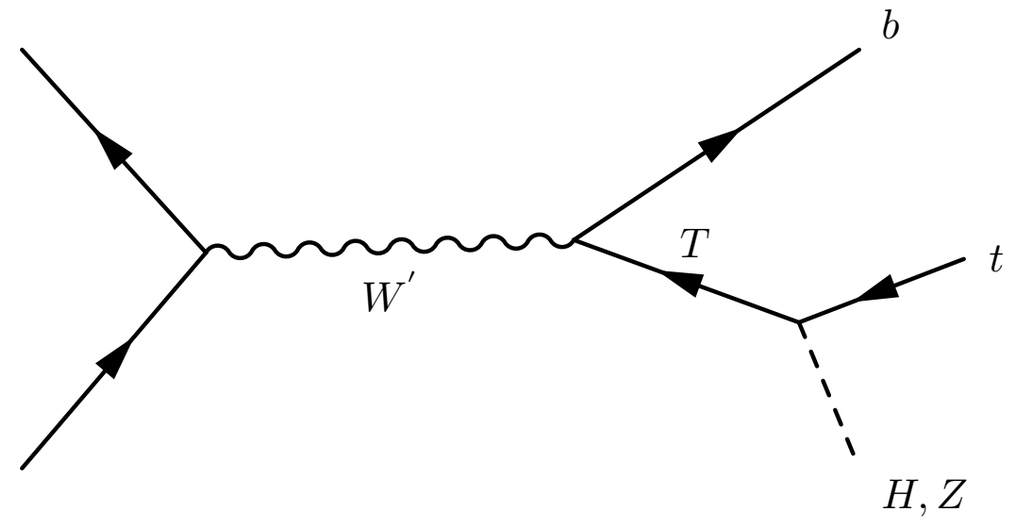


Search for a W' boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state

Search for a W' boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state

- W' → tB/bT
  - Benchmark Model: Composite Higgs model with W' → VLQ branching fraction equally distributed between tB and bT and VLQ branching fractions equally distributed between qZ and qH
- Consider the case where the W' decays through an intermediate resonance such as a vector-like quark (B, T)
- Hadronic final state considered (t, H, Z decay hadronically)





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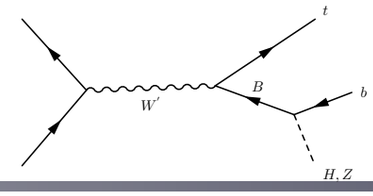
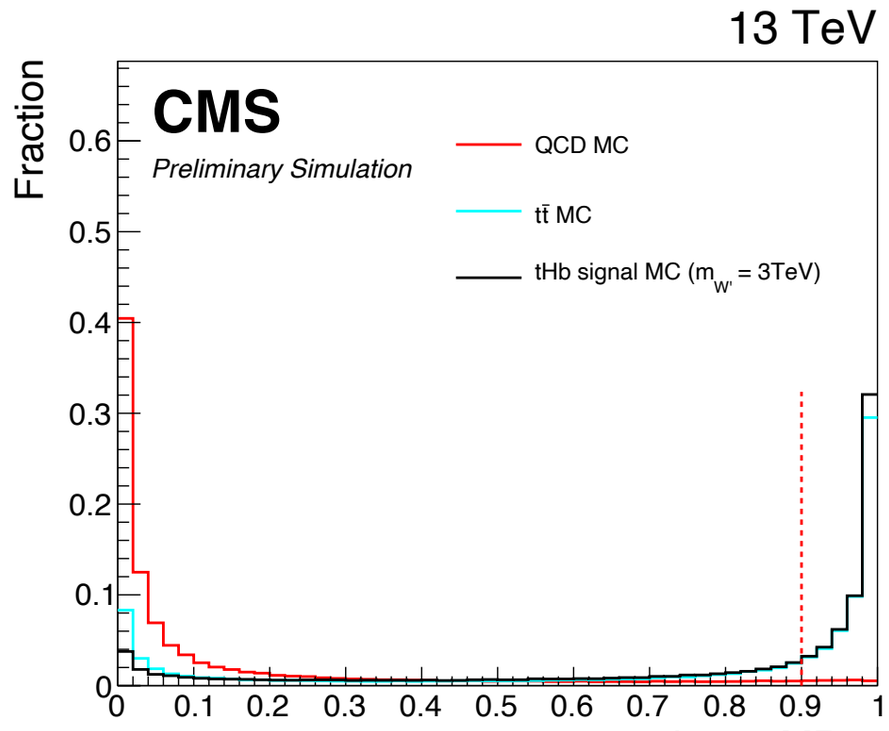
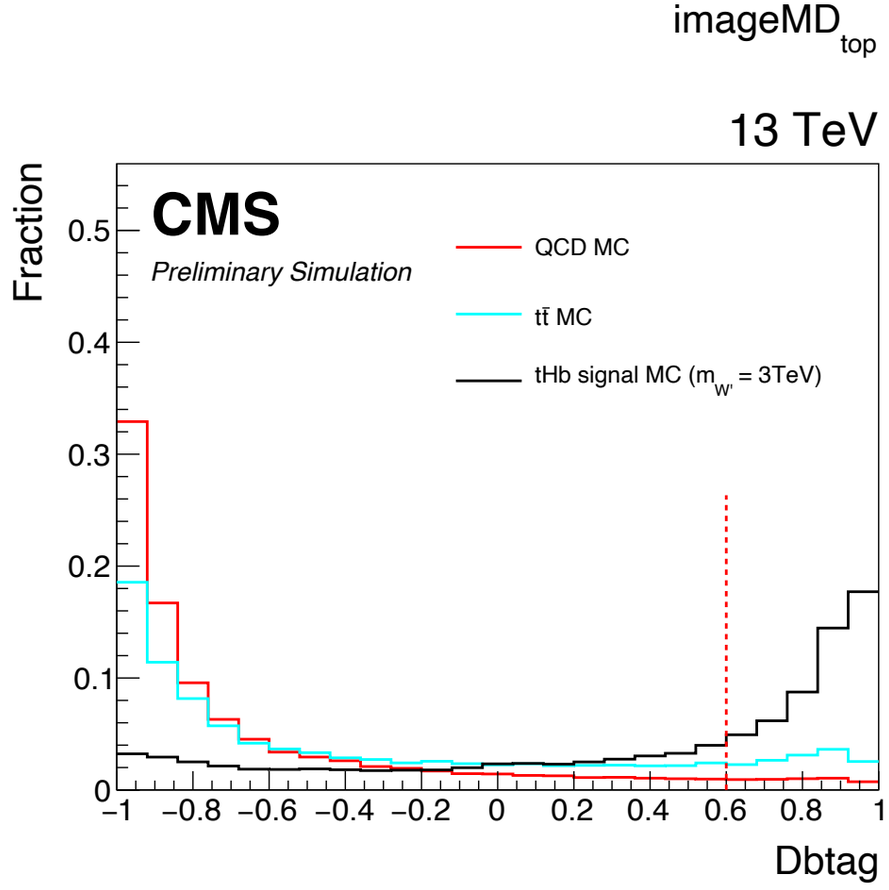
Event Selection



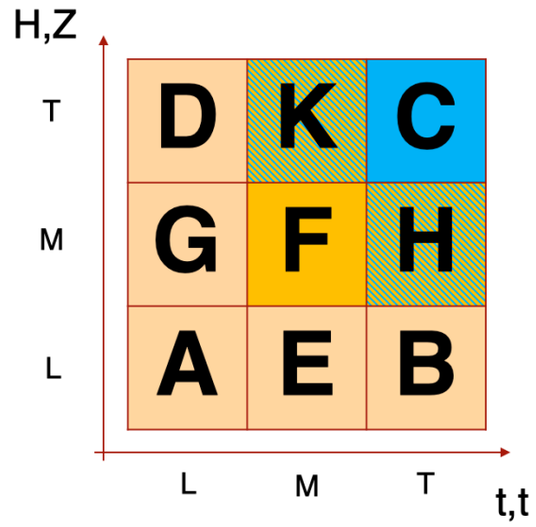
- CMS Run II data (2016-2018)
  - Integrated luminosity 137 fb^{-1}
- Final state: top quark, H/Z boson, b quark
  - Top candidate: 1 AK8 jet p_T>400
  - H/Z candidate: 1 AK8 jet p_T>400
  - b candidate: 1 AK4 jet p_T> 200
- Top tag: ImageTop + SoftDrop mass
- H tag: Double b-tag + SoftDrop mass
- Z tag: N-subjettiness + SoftDrop mass
- b-tag: DeepFlavor tag





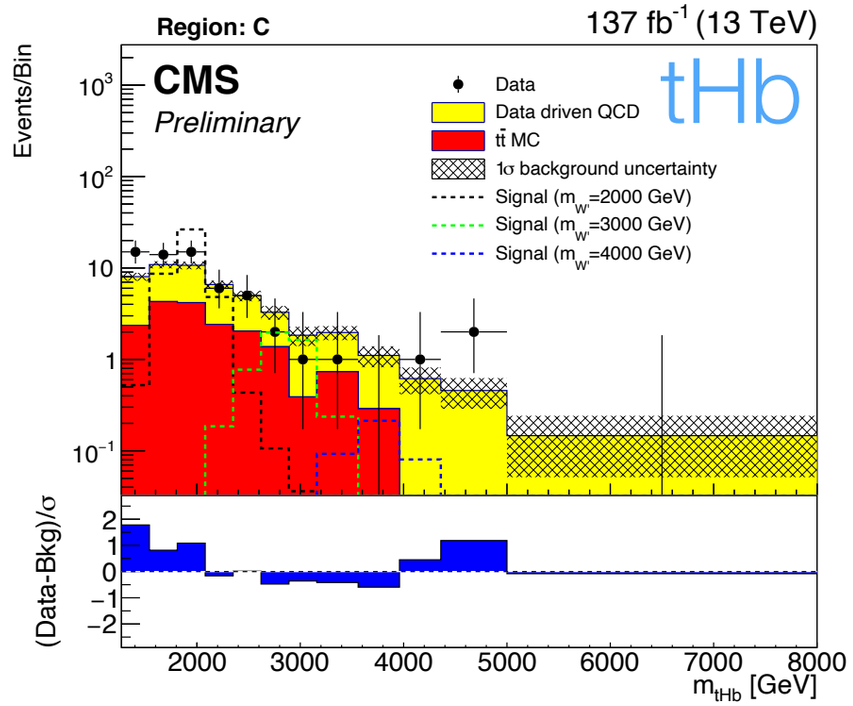
Search Information

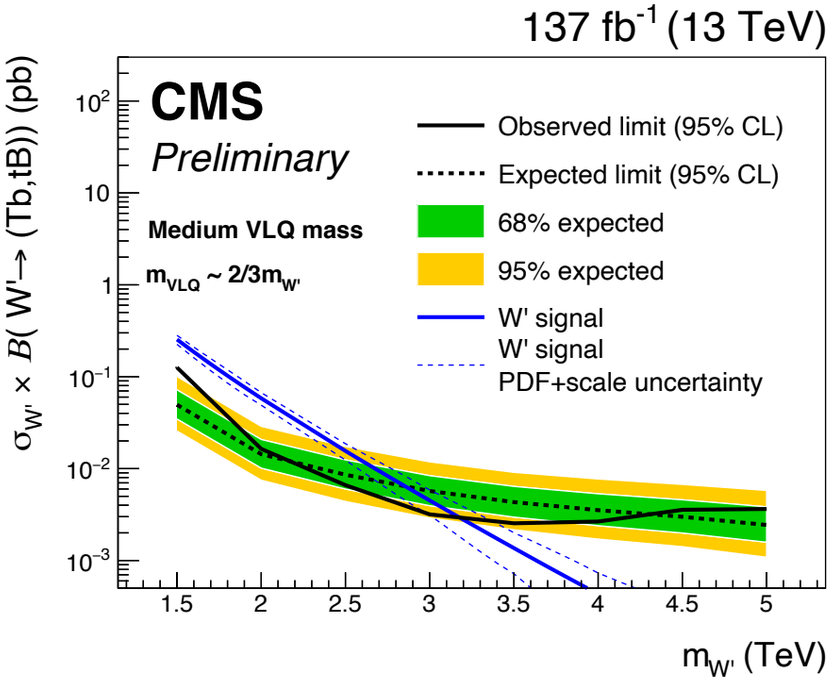
- Signal region: 1 tight-tagged top jet, 1 tight-tagged Higgs or Z boson jet, and 1 b-tagged jet
- Backgrounds
  - QCD Multijet
    - Dominant
    - Data-based background estimation
      - Transfer function used to predict the signal region using a defined background estimation region
      - Validation regions used to test the procedure
  - Top quark pair production
    - Estimated with simulation and validated with data
- Search
  - Bump hunt in the W' mass distribution (m_{tHb} or m_{tZb})

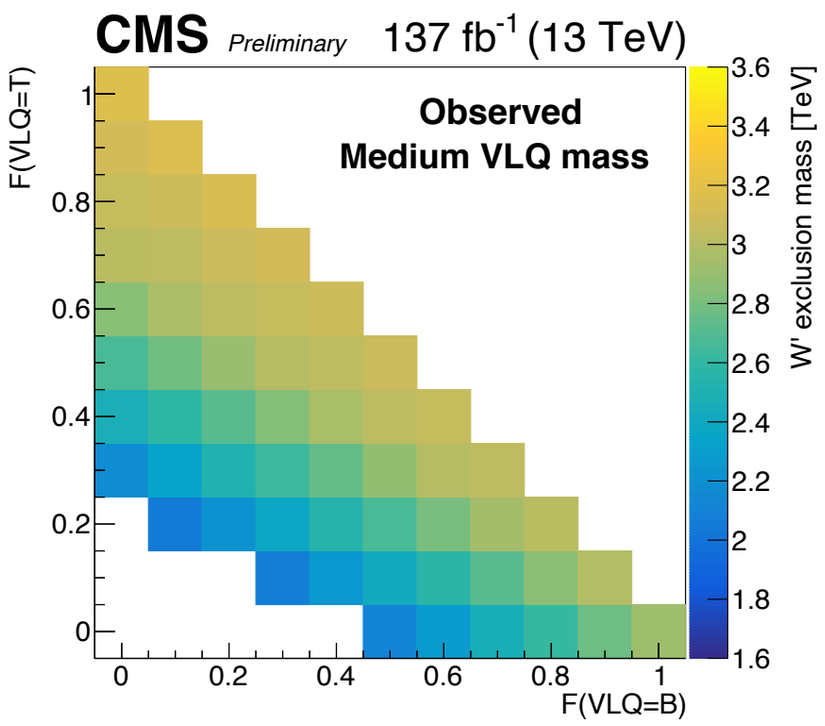


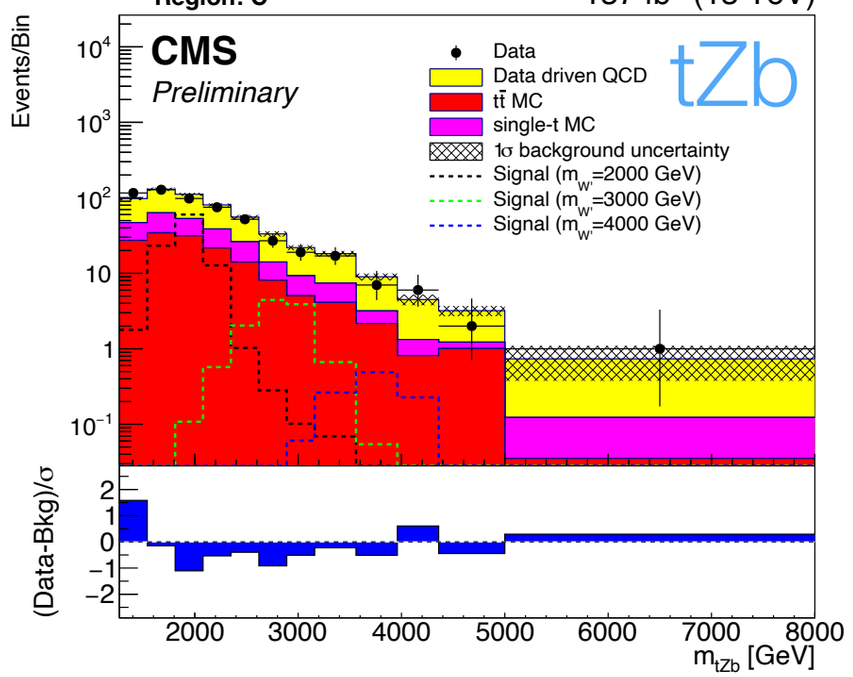
Results

- No significant excess above the standard model background is observed
- Limits set on the production cross section for W' boson mass for several vector-like quark mass hypotheses.
- Extended beyond the benchmark model:
  - Vary T and B branching fraction
  - Vary VLQ decay branching fraction (qH, qZ)









Conclusions

- Broad search program at CMS for heavy BSM particles decaying to third generation quarks
  - Public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- Well motivated models
- No significant excess found in CMS Run II data

1. **Heavy resonances which decay directly to standard model particles (including top and bottom quarks)**

   Examples:
   Z` → tt, **W` → tb**, excited quarks (**b* → tW** t* → tg), leptoquarks (LQ → tτ, LQ → tμ)

2. **Heavy resonances which decay to some new intermediate particle which then decay to standard model particles**

   Examples:
   Z` → tT, Z` → TT, **W` → Tb/Bt**

These are not just ideas!
Broad search program at CMS.
Completed analyses for many signal topologies available here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G