Search for heavy BSM particles coupling to third generation quarks at CMS

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On behalf of the CMS Collaboration

Introduction

- **Many BSM models predict Heavy Resonances with large couplings to b- and/or t-quarks**

  Heavy bosons: $Z' \to t\bar{t}$, $W' \to tb$
  Excited quarks: $b^* \to tW$, $t^* \to tg$
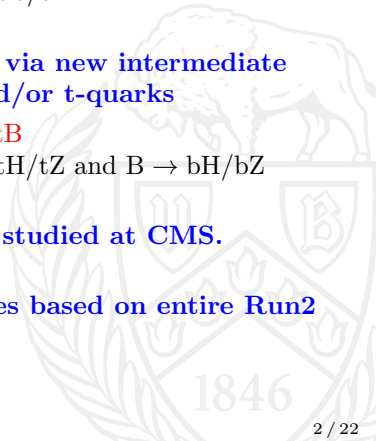 Vector-Like Quarks: $T \to tZ/Wb/tH$

- **BSM Heavy resonances can also decay via new intermediate particles, which in turn decay to b- and/or t-quarks**

  $Z' \to tT$, $Z' \to TT$, $W' \to Tb/tB$
 with intermediate VL quarks decaying $T \to tH/tZ$ and $B \to bH/bZ$

- **Many of these decay modes have been studied at CMS.**

- **Today highlighting more recent searches based on entire Run2 datasets, L_{int}=137 fb^{-1}.**

Introduction

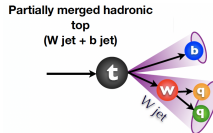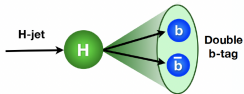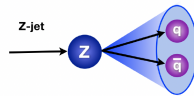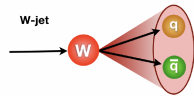- **Decay particles from heavy resonances have large Lorentz-boost.**
  ⇒ Their decay products are collimated.

- **hadronic decays often produce merged jets:**
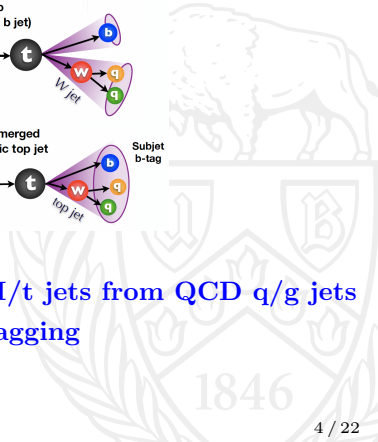 extensive use of jet substructure based tagging tools.
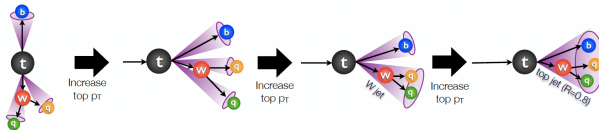
- **Leptonic decays produce leptons embedded in a jet:**
  non-isolated leptons at the trigger and offline level.
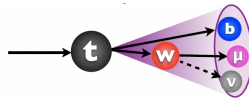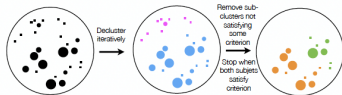
- **Fully or partially merged large-radius jets**
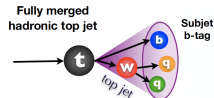
- **Challenge: distinguish boosted W/Z/H/t jets from QCD q/g jets**
- **Utilize jet substructure and subjet b-tagging**

Boosted Jet Tagging Tools

- ▶ **Jet grooming**
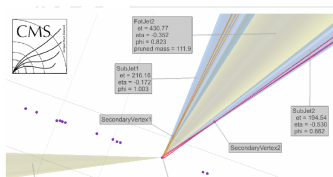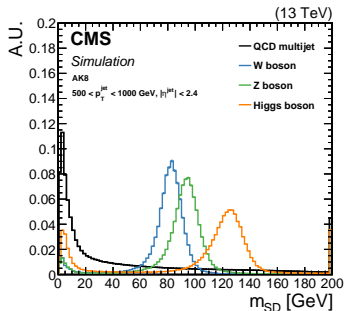 - • **Modified mass drop tagger (Soft Drop algorithm)**

- ▶ **N-subjettiness: Determines how consistent a jet is with having N or fewer subjets, τ_N**
  - • **Better discrimination by using ratios, such as τ_3/τ_2**

- ▶ **B-tagging, subjet b-tagging and double b-tagger**

CMS JME-18-002

Boosted Jet Tagging Tools

▶ **DEEPAK8 top-tag**
  - **Deep NN approach**
  - **Inputs: Jet constituent particle kinematic and angular information, track and secondary vertex information.**

▶ **ImageTop top-tag**
  - **Image recognition techniques using Deep Convolutional NNs**

▶ **HOTVR: "Heavy Object Tagger with Variable R"**
  - **Jet size varies up to $\Delta R = 1.5$**
  - **Allows the use of jet substructure tools for lower p_T tops**
  - **Tag jets using HOTVR mass, Nsubjets, minimum subjet pairwise mass, subjet p_T-ratio, and τ_3/τ_2**

▶ **SD-mass de-correlated versions of the taggers have also been developed.**

$b^* \to tW$: hadronic channel
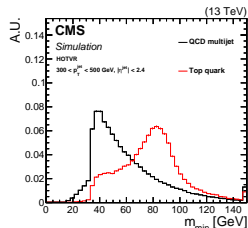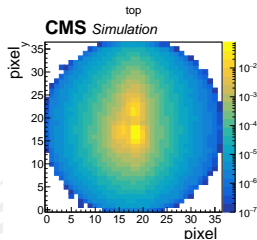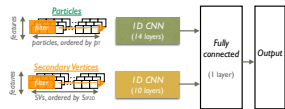
- **Search for a heavy particle which decays to a top quark and a W boson**
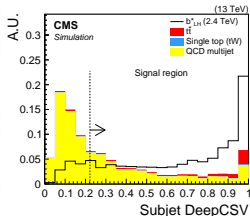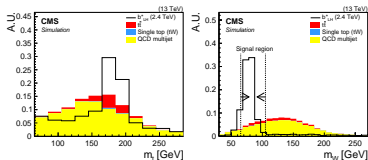
- **All hadronic final state:**
  Two well-separated AK8 jets

- **Top tag**
  - Soft-Drop jet mass
  - N-subjettiness ratio τ_3/τ_2
  - b-tagged subjet (Deep CSV algorithm)

- **W-tag**
  - Soft-Drop jet mass
  - N-subjettiness ratio τ_2/τ_1

b* → tW: **hadronic channel**
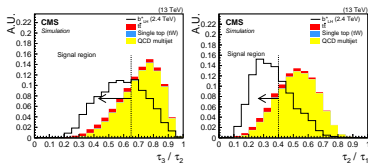
▶ **Background**

- **QCD:**
  dominant, estimated from data using control regions

- **Top quark pair production:**
  Estimated with both data and simulation

- **Single top:**
  estimated from simulation

▶ **Search**

- Binned maximum likelihood fit
- m_{tW} vs m_t distribution
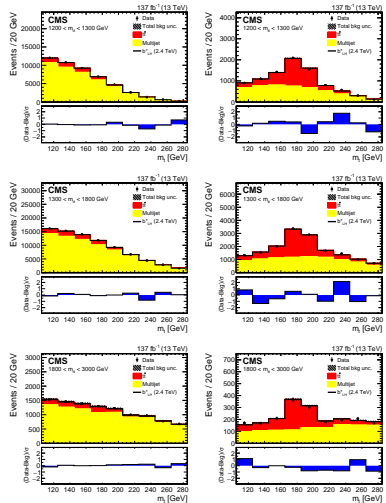
b* → tW: hadronic channel

- ▶ **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+RH).**
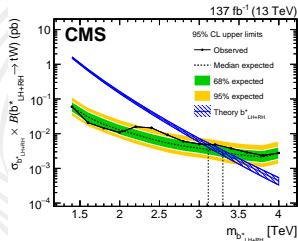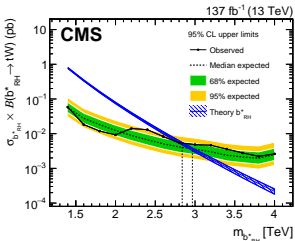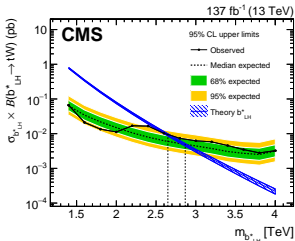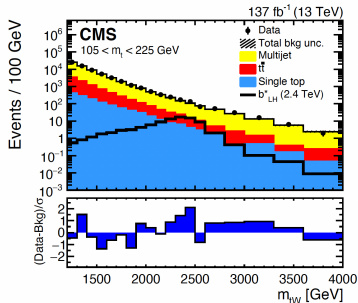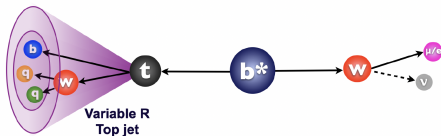
- **Search for a heavy particle decaying to a top quark and a W boson**
- **Lepton+jets final state:**
  Hadronic top decay, leptonic $W \to \mu/e + \nu$ decay
  Final state contains 1 lepton, missing $\overrightarrow{p}_T$, and 1 top-tagged jet.
  Isolated lepton allows for lower p_T trigger.
- **Top tag**
  HOTVR - Variable R allows to maintain efficiency at low p_T
- **Neutrino p4 reconstructed using the W mass constraint**
- **Chi-squared estimator used to measure how signal-like an event is**
- **Categorize events based on Nbtags**

$b^* \to tW$: lepton+jets channel

▶ **Backgrounds**

- **Top quark pair production**
  2 b-tag category control region is used to constrain systematic uncertainties associated with simulation.

- **Single top**

- **Non-top**
  Dominanted by W/Z+jets and diboson. Estimated with data using the 0 b-tag category and transfer function (alpha method).

▶ **Search**
- Binned maximum likelihood fit.
- b^* mass reconstructed from the tW system.

$b^* \to tW$: lepton+jets channel

- **No significant excess above the standard model background expectation.**

- **Limits set on the production cross section for left-handed (LH), right-handed (RH), and vector-like chiralities (LH+BH).**
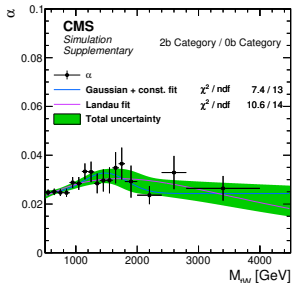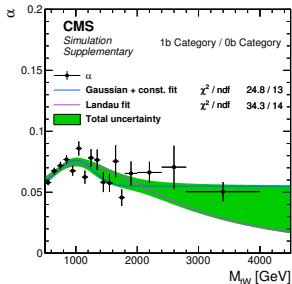
- **Lepton+jets results are combined with the all-hadronic analysis.**
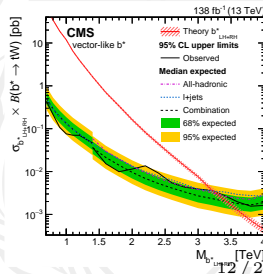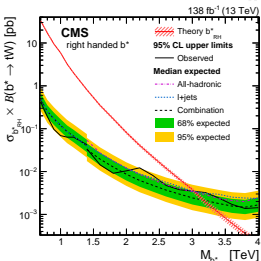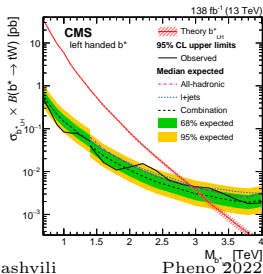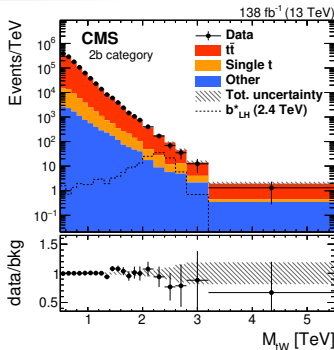
- **Heavy Spin-1 gauge boson W': Predicted in numerous models including Little Higgs, extra dimension, and left-right symmetric models.**

- **Fully hadronic final state:**
  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

W′ → tb: **hadronic channel**
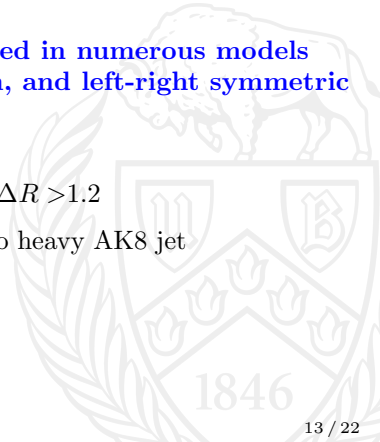
▶ **Background**

- **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 from simulated events and
  validated with data

▶ **Search**

- Bump hunt in the m_{tb} distribution
- Binned maximum likelihood fit
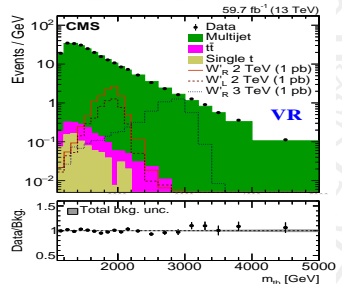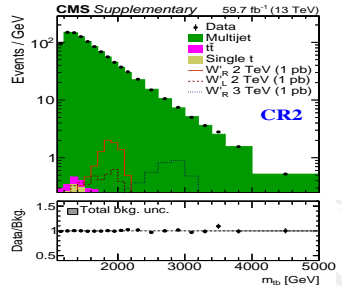
$W' \to tb$: hadronic channel

- No significant excess above the standard model background is observed.

- Limits set on the production cross section for both LH and RH W' bosons.

- W' mass below 3.4 TeV excluded at 95% CL for both scenarios.
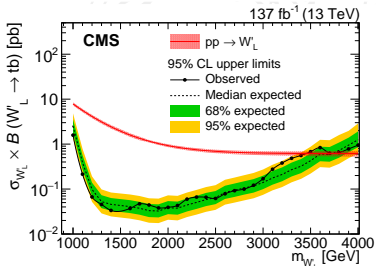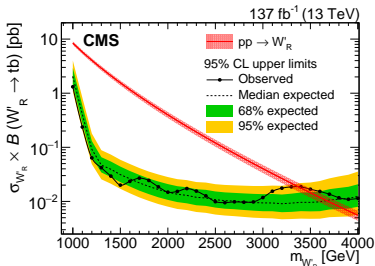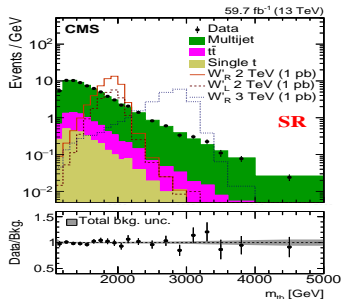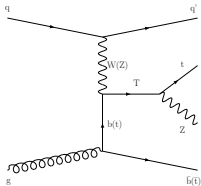
- ▶ **Banchmark: New heavy color-triplet fermions with nonchiral couplings – Vector Like Quarks.**

- ▶ **Single EW production of VLQ dominates for masses above 1 TeV.**

- ▶ $T \to tZ$ **channel with hadronic top** $t(\to jjb)$ **and invisible** $Z(\to \nu\nu)$ **decays. Accompanied by b-jet and 0/1 forward jet.**

- ▶ **Require central b-tagged AK4 jet, large** p_T^{miss}**, top-quark**

- ▶ **Top-tagginng:** SD mass and sub-jettiness τ_{32}
  W-tagging: SD mass and mass de-correlated sub-jettiness τ_{21}

- ▶ **Six signal categories:**
  (resolved, partially merged, fully merged top)$\times$(0,1 forward jet)

Single VLQ $T \to tZ$: jets + $\overrightarrow{p}_T^{\text{miss}}$

▶ **Backgrounds**

- $t\bar{t}$+jets, Z+jets, W+jets – significant backgrounds in all categories
- **Single top and QCD multijet** – smaller backgrounds
- $t\bar{t}$+jets – leading background for merged and partially merged categories.
- **Z+jets** – leading background for resolved categories.

- Backgrounds are estimated from simulated sample. Corrections are derived from background-enriched data control samples, and applied in signal region.

▶ **Search**
Bump hunt in the transverse mass distribution, $M_T(\text{top}, p_T^{\text{miss}})$

Single VLQ $T \to tZ$: jets + $\vec{p}_T^{\text{miss}}$
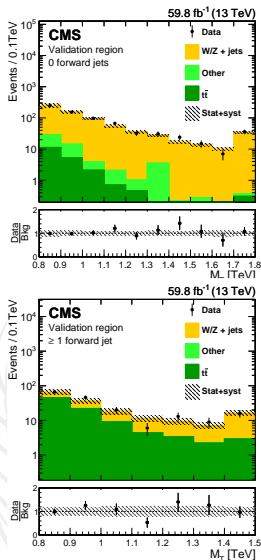
- **No significant excess above the standard model background is observed.**
  - The largest excess of 2.5σ (2.2σ global) found for the narrow-width T quark at 1.4 TeV mass – mainly due to a broad excess at $M_T > 1$ TeV in 2016 data for the resolved category with ≥ 1 forward jet.

- **Limits set on the T production cross section times branching ratio, $\sigma(Tbq) \times BR(T \to tZ)$, for several T width hypotheses (1%, 10%, 20%, 30%.)**

$W' \to tB/bT$: hadronic channel
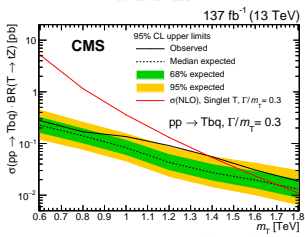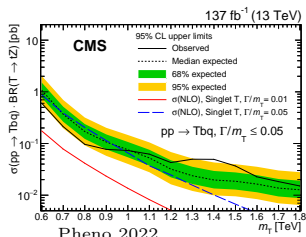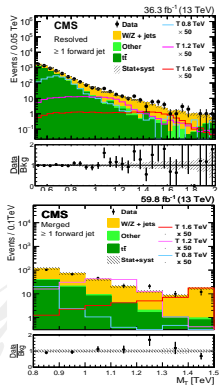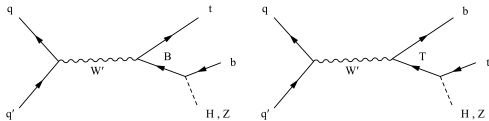
- **Benchmark: Composite Higgs model where W' decays via a intermediate resonance such as Vector-Like Quark (B, T).**

- **Equal branching fractions for $W' \to tB/bT$ decays.**
  Equal branching fractions for $VLQ \to qZ/qH$ decays.

- **Hadronic final state considered: t, H, Z decay hadronically**

- **Top candidate:** $p_T > 400$GeV AK8 jet. ImageTop + SD mass tagging.

- **H / Z candidate:** AK8 jet with $p_T > 400$GeV.
  H-tag: Double b-tag + SD mass
  Z-tag: N-subjettiness + SD mass

- **b candidate:** AK4 jet with $p_T > 200$GeV. Tagged with DeepFlavor tagger.

W′ → tB/bT: hadronic channel

▶ **Backgrounds**

- **QCD Multijet** – Dominant
  Data-based background estimation:
  Transfer functions TF(p_T, η) are derived
  in orthogonal samples. These are used to
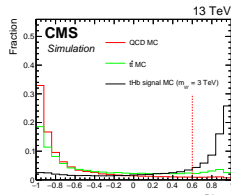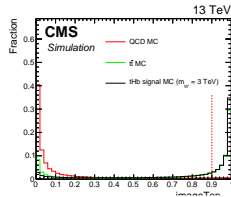 predict the QCD contribution in the
  signal sample.
  The method is validated using deticated
  validation regions.

- **Top quark production**
  Estimated using simulated sample and
  validated with data.

▶ **Search**
  Bump hunt in the W′ mass distributions,
  m_{tHb} or m_{tZb}

$W' \to tB/bT$: hadronic channel

- ▶ **No significant excess above the standard model background is observed.**

- ▶ **Limits set on W' the production cross section for several VLQ mass hypotheses.**

- ▶ **Extended beyond the benchmark model:**
  - Vary T and B branching fraction
  - Vary VLQ $\to$ qH/qZ branching fractions.

Summary

► **Broad search program at CMS for heavy BSM particles decaying to third generation quarks.**

► **Many more public results: CMSPublic/ PhysicsResultsB2G**

► **No significant hint in CMS Run 2 data.**

► **LHC Run3 is upon us. Expect more new results with both Run2 and Run3 data next year.**