# Search for new resonances coupling to third generation quarks at CMS

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## Introduction

- Final states with **t**/**b** quarks may indicate new physics
- Searches for heavy resonances at TeV scale
- ▶ Highly energetic particles ⇒ large Lorentz boost decay products of t quarks or bosons can be collimated and clustered in one large-radius jet



### large-R jet (AK8)

### Jet tagging

Jets from hadronic decays of heavy particles (t/H/W/Z) present signatures that allow us to distinguish them from q/g-initiated jets  $\rightarrow$  exploit jet substructure

## Jet substructure

### Substructure variables

- $m_{SD}$ : groomed jet **mass** with *soft-drop* algorithm  $\rightarrow$  removes soft and collinear radiation
- **N-subjettiness**  $\tau_N$ : probability of jet to consist of up to N subjets.

Ratio  $\tau_{NM} = \tau_N / \tau_M$  as discriminating variable

• Flavour content: b/c quarks in the jet



high pT hadronic decays

### • PUPPI

- The PUPPI<sup>(1)</sup> algorithm is used to mitigate the effects of pileup, multiple pp collisions in the same bunch crossing
- $\rightarrow$  Especially important for *large-R* jet reconstruction and substructure variables

## Jet tagging

- Extensive performance studies in <u>JINST 15 (2020) P06005</u>
  - **Cut-based** approach with substructure variables
  - Jet clustering and identification with Variable R: HOTVR<sup>(1)</sup>
  - Machine learning based taggers: DeepAK8, ImageTop



## **CMS** results

#### **Overview of CMS B2G Results**

November 2021



CMS Beyond 2 Generations <u>publications</u>, <u>preliminary results</u>

Z'→tt (Γ/M<sub>7'</sub>=1%)

Z'→tt (Γ/M<sub>Z'</sub>=10%)

Z'→tt (Γ/M<sub>Z'</sub>=30%)

 $Z' \rightarrow tT \rightarrow (tZt, tHt)$ 

W'→tb (1ℓ, RH)

W'→tb (0ℓ, RH)

W'→tb (0ℓ, LH)

LQ<u>LQ</u>→tµtµ

LQ<u>LO</u>→tτtτ

LQ<u>LO</u>→bvbv

t<sup>\*</sup>t<sup>\*</sup>→tgtg

b<sup>\*</sup>→tW (0ℓ, LH)

b<sup>\*</sup>→tW (0ℓ, RH)

b<sup>\*</sup>→tW (0ℓ, LH+RH)

 $b^* \rightarrow tW (0\ell + 1\ell, LH)$ 

 $b^* \rightarrow tW (0\ell + 1\ell, RH)$ 

 $b^* \rightarrow tW (0\ell + 1\ell, LH + RH)$ 

G<sub>KK</sub>→tt (Kaluza-Klein)

W' $\rightarrow$ Tb/Bt ( $M_{VLQ} = 2/3M_{W'}$ )

 $W_{KK} \rightarrow RW \rightarrow WWW (0\ell + 1\ell)$ 

 $W_{KK} \rightarrow RW \rightarrow WWW (1\ell)$ 

## In this talk



- Searches with bosons covered in "Searches for heavy resonances decaying into Z, W and Higgs bosons at CMS"
- Searches for VLQ covered in "Searches for vector-like quarks and leptons at CMS"

### **b\*** → **tW** 0*ℓ*

#### CMS-B2G-19-003 JHEP 12 (2021) 106

Search for  $b^* \rightarrow tW$  in all-hadronic final state

### back-to-back topology

- t and W: AK8 PUPPI jets
- tagging with **substructure variables**:

 $m_{SD}$ ,  $\tau_{21}/\tau_{32}$ , subjet b-tag





- SR and CR defined with tagging requirements
- Multijet QCD bkg estimated from data
- $t\bar{t}$  bkg estimated from MC

## $b^* \rightarrow tW \ 0\ell$

#### CMS-B2G-19-003 JHEP 12 (2021) 106

- Search in 2D plane ( $m_{tW}$ ,  $m_t$ )
- Analysis sensitive to  $m_{b^*} > 1.4 \text{ TeV}$

#### **Results**:

•  $m_{b^*}$  excluded up to 2.6 (LH), 2.8 (RH) and 3.1 (VL) TeV





### **b\*** → **tW** 1*ℓ*

#### CMS-B2G-20-010 arXiv:2111.10216

Search for  $b^* \rightarrow tW$  in semileptonic final state First time HOTVR used in LHC search!

 $W \rightarrow Iv: 1 e/\mu, p_T^{miss}$ 

t →bqq': 1 HOTVR PUPPI jet

### HOTVR

### Heavy Object Tagger with Variable R (1)

 $\rightarrow$  adapts dynamically jet radius to jet  $p_T$ 

$$R_{eff}(p_T) = \frac{\rho}{p_T}$$

- $\rightarrow$  high efficiency at low and high  $p_T$
- → t-tagging: HOTVR criteria +

N-Subjettiness  $au_{32}$ 



R. Kogler: Advances in Jet Substructure at the LHC



### **b\*** → **tW** 1*ℓ*



- *M<sub>b</sub>*\* excluded up to 2.95(LH), 3.03(RH) and 3.22(VL) TeV
- 1 $\ell$  analysis: extend reach down to 0.7 TeV

#### CMS-B2G-20-010 arXiv:2111.10216

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- $M_{tW}$  sensitive variable
- Categories using # of b-jets with DeepJet
- Bkg estimated from data and simulation in 0b and 2b cat.



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## **W' → tb** 0*ℓ*

#### CMS-B2G-20-005 PLB 820 (2021) 136535

Search for  $W' \rightarrow tb$  in all-hadronic final state Both RH and LH W', LH includes *interference* with SM single top





### back-to-back topology

- Multijet QCD bkg estimated from data in CR
- $m_{tb}$  sensitive variable

### b-jet

AK4 jet with **DeepJet** tagger

### t →bqq′

1 AK8 PUPPI jet with DeepAK8-MD tagger

## DeepAK8

- ML based tagger 1D convolutional NN
  - multi-classifier for boosted decays of t/H/W/Z
  - particles and secondary vertices as inputs



## **W'** → **tb** 0*ℓ*

#### CMS-B2G-20-005 PLB 820 (2021) 136535

#### **Results**:

- Limits for both RH and LH W', including *interference* with SM single top
- $m_{W'_{RL}}$  excluded up to 3.4 TeV



## $W' \rightarrow Tb/Bt \ 0\ell$

#### CMS-B2G-20-002 arXiv:2202.12988

Search for new heavy resonance W' and for VLQ T/B in  $W' \rightarrow Tb/Bt \rightarrow tHb/tZb$ 

Final states: tHb, tZb All-hadronic decays of t/H/Z: AK8 jets  $m_{SD}$  as discriminant





### b-jet

1 AK4 jet with **DeepJet** tagger

### t →bqq′

1 AK8 PUPPI jet tagged with ImageTop-MD

and  $m_{SD}$ 

First time ImageTop used in CMS search!

## ImageTop

- ML-based tagger using image recognition
- Pixelated image from jet energy deposit
- Colors: PF flavours and subjet b-tagging
- $\blacktriangleright$  Decorrelated from jet  $p_T$  and mass by reweighing QCD distributions to match



CMS: JINST 15 (2020) P06005

## **W' → Tb/Bt** 0*ℓ*

#### CMS-B2G-20-002 arXiv:2202.12988



### Results:

- $m_{W'}$  excluded up to 3.1 TeV for  $m_{VLQ} = 2/3 \ m_{W'}$
- Close to achieve sensitivity for  $m_{VLQ} = 1/2 \ m_{W'}$  and  $3/4 \ m_{W'}$

- SR and CRs defined by tagging requirements
- Multijet QCD bkg estimation from data using transfer function
- Sensitive variable  $m_{tZb}$  or  $m_{tHb}$



## Summary

- New physics coupling to 3<sup>rd</sup> gen quarks
- Variety of novel tagging techniques: jet substructure variables, HOTVR, ML based taggers (DeepAK8, ImageTop)
- Presented latest CMS analyses with full Run2 data
- Many new results on the way: stay tuned!



# BACKUP

## PUPPI

- In hadron colliders: main interaction + additional collisions
   (pileup) in the same bunch crossing.
- The PileUp Per Particle Identification (**PUPPI**) algorithm is a pileup mitigation technique. Each particle gets a weight: probability to originate from the leading or a pileup vertex.
- PUPPI shows very good performance and high pileup stability default pileup mitigation in Run3





D. Bertolini, P. Harris, M. Low et al.: <u>J. High Energ. Phys. 2014, 59 (2014)</u> Ksenia de Leo

## HOTVR

### •Heavy Object Tagger with Variable R

•The *radius* of the jet is adjusted dynamically:

$$R_{eff}(p_T) = \frac{\rho}{p_T}$$

•Mass-jump veto for grooming and resolving substructure •Top tagging:  $N_{subjet} \ge 3$ ,  $f(p_T) < 0.8$ ,  $140 < m_{jet} < 220$ GeV,  $\tau_{32} < 0.56$ ,  $m_{ii}^{min} > 50$  GeV





## DeepAK8

- Multiclassifier using AK8 jets
- 1D convolutional NN based on ResNet
- Mass decorrelated DeepAK8-MD with adversarial training technique:
  - mass predictor added to the network
  - ▶ reweighed to flat  $p_T$  and  $m_{SD}$

### Two lists of inputs:

### Particle list

- up to 100 PF candidates per jet
- ordered by decreasing  $p_T$
- 42 features:  $p_T$ , change, energy, angular separation, tracking info..

### Secondary Vertex list

- up to 7 SVs
- ordered by 2D impact parameter significance
- 15 features: displacement, kinematics, quality criteria..



#### CMS: <u>JINST 15 (2020) P06005</u> Ksenia de Leo

## ImageTop



CMS: JINST 15 (2020) P06005

## Mass decorrelation

- In many ML-based taggers the mass of a jet is learned by the algorithm, even if it is not used as input
- "Mass sculpting": the jet mass of background similar to signal after application of tagger
  (13 TeV)
- Undesirable feature if:
  - mass itself is used to separate signal from background
  - mass of signal in unknown
- Mass-decorrelated versions of taggers: mass sculpting largely reduced, at the cost of a (slight) loss in performance
- DeepAK8-MD: with adversarial training
- ImageTop-MD: by reweighing training samples



## **Performance comparison**

Performance evaluated with signal efficiency  $\epsilon_S$  and background efficiency  $\epsilon_B$ :



- At low  $p_T$ : HOTVR and N3-BDT show best performance thanks to large radius of the jets
- At high p<sub>T</sub>: higher efficiency with ML-based taggers (DeepAK8, ImageTop)
- DeepAK8 best at high  $p_T$
- HOTVR high efficiency at low & high  $p_T$

## W' → Tb/Bt

#### CMS-B2G-20-002

#### **Results**:

- $m_{W'}$  excluded up to 3.1 TeV for  $m_{VLO} = 2/3 \ m_{W'}$
- Not yet sensitive to  $m_{VLQ} = 1/2 \ m_{W'}$  and  $3/4 \ m_{W'}$ , but hitting the boundary



