

# Search for charged Higgs boson with the $H^{\pm} \rightarrow tb$ decay in fully hadronic final state

B2G Resonances meeting

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Many BSM theories need to enlarge their Higgs sector to two Higgs doublets

- ▶ The minimal two-Higgs-doublet models (2HDMs) predict 5 physical states:
  - ▶ two neutral,  $\mathcal{CP}$ -even particles  $h$  and  $H$  ( $m_h \leq m_H$ )
  - ▶ one neutral,  $\mathcal{CP}$ -odd particle  $A^0$
  - ▶ two charged Higgs bosons  $H^\pm$

SM fermion coupling to 2HDs (no FCNCs):

I All quarks & leptons couple to  $\Phi_2$

II All  $u$ -type to  $\Phi_2$  and all  $d$ -type &  $\ell$  to  $\Phi_1$

X Both  $u$  &  $d$  types couple to  $\Phi_2$ , all  $\ell$  to  $\Phi_1$

Y Roles of two doublets reversed wrt type II

Type	$u$	$d$	$\ell$
I	$\Phi_2$	$\Phi_2$	$\Phi_2$
II	$\Phi_2$	$\Phi_1$	$\Phi_1$
III (X)	$\Phi_2$	$\Phi_2$	$\Phi_1$
IV (Y)	$\Phi_2$	$\Phi_1$	$\Phi_2$

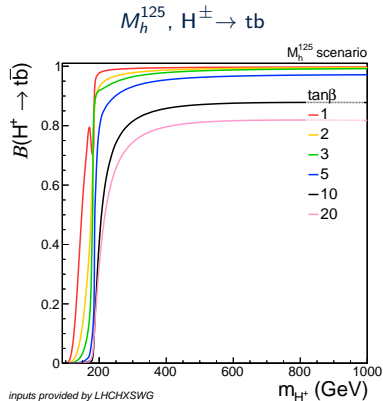
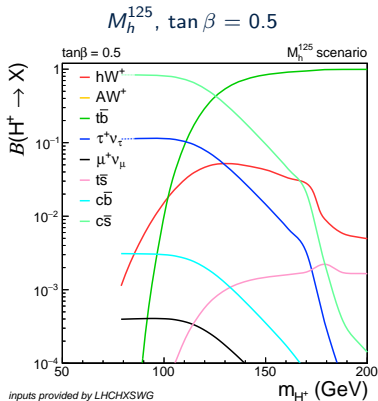
For each 2HDMs type there are 7 free parameters (incl.  $m_h$ ,  $m_H$ ,  $m_A$ ,  $m_{H^\pm}$ ):

- 5  $\tan \beta \equiv \frac{v_2}{v_1}$ , the ratio of the Higgs doublet VEVs
- 6  $\sin(\beta - \alpha)$ ,  $\alpha$ : the mixing angle of the  $\mathcal{CP}$ -even states
- 7  $m_{12}$ , diagonal term of the mass matrix of the Higgs doublets

Three mass categories are commonly defined in  $H^\pm$  searches:

- Light  $m_{H^\pm} < m_t - m_b$ , intermediate  $m_{H^\pm} \sim m_t$ , heavy  $m_{H^\pm} > m_t + m_b$

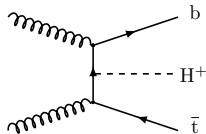
Decay BRs model-dependent  $\Rightarrow$  different searches constrain different scenarios.



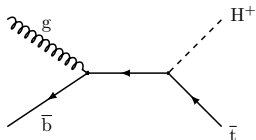
BRs of  $H^\pm \rightarrow tb$  dominates at high  $m_{H^\pm}$ , for wide range of  $\tan\beta$

This analysis searches for a heavy  $H^\pm$

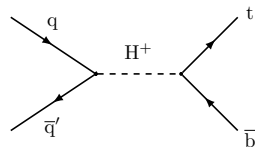
4FS



5FS

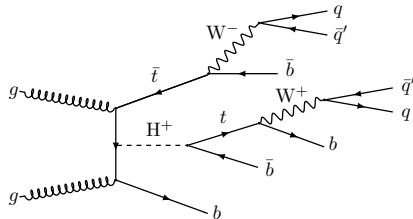


s-channel



**Fully-hadronic** final state of associated production characterised by:

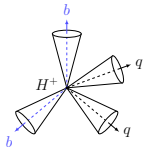
- High jet & b jet multiplicities
- ✓ Large branching ratio  $\mathcal{B} \simeq 46\%$
- ✓ Invariant mass reconstruction of  $H^\pm$
- ✗ QCD multijet &  $t\bar{t}$  background
- ✗ Combinatorial (self-)background



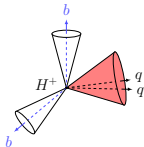
Various  $m_{H^\pm}$  reconstruction techniques available due to signal process kinematics:

- **Resolved t**: At moderate  $m_{H^\pm}$  &  $p_{T,H^\pm}$  the decay products of  $H^\pm$  are well separated
- **Boosted W/t**: As  $m_{H^\pm}$  increases the  $H^\pm$  decay products become boosted
- **Boosted  $H^\pm$** : As  $p_{T,H^\pm}$  increases its decay products become collinear

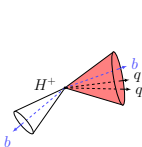
resolved t



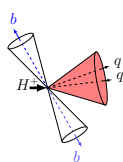
boosted W



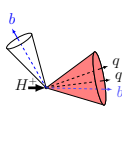
boosted t



boosted  $H^\pm$



boosted  $H^\pm$



### Previous results

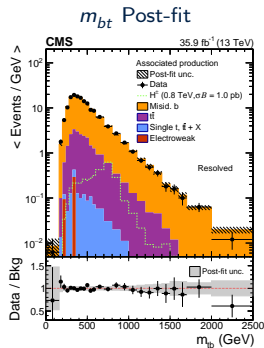
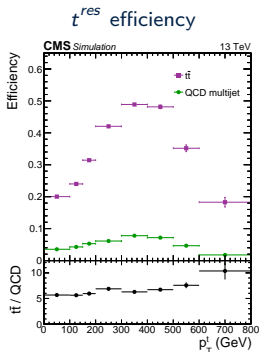
- **Resolved t, Boosted W/t**  
studied separately by dedicated analyses
- 2016 ReReco data
- CADI [HIG-18-015](#)

### This work

- **Resolved t, Boosted t**
- Full Run II data
- This talk: status of 2017-2018 data
- Last report (HExtended): [25 Oct 2021](#)

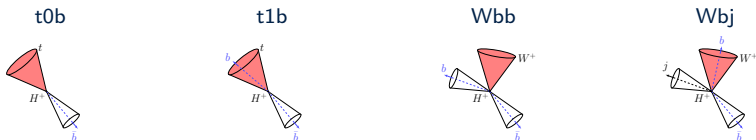
## Resolved (UCY, HIP)

- Resolved  $t$  ( $t^{\text{res}}$ ) identification: custom top tagger (BDT)
- Selected events contain  $\geq 7$  jets,  $\geq 3$  b-tagged, 2  $t^{\text{res}}$
- $H^\pm$  mass reconstruction ( $m_{bt}$ ): leading  $p_T t^{\text{res}}$  + leading  $p_T$  b jet
- Main background:
  - Misid. B: From data using CRs (ABCD method)
  - Genuine B: from simulation
- $m_{bt}$  is used to extract the signal in the presence of the SM background.



## Boosted (MIT, BUAP)

- Events are split in four main categories



- Boosted  $t/W$  identification: Based on  $m_{SD}$ ,  $\tau_N$ ,  $N_b$  subjects

- $H^\pm$  mass reconstruction ( $m_{bt}$ ):  $t$  + leading  $p_T$   $b$  jet

- Further categorization according to:

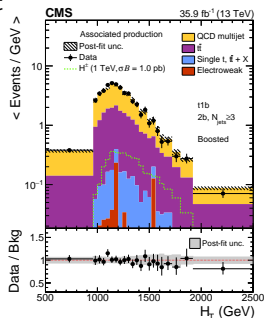
- $N_b \in [1, 2, \geq 3]$
- $N_j^{extra} \in [< 3, \geq 3]$
- $m_{tb} \in [\text{below, in, above}]$  of FWHM of signal

- Main background

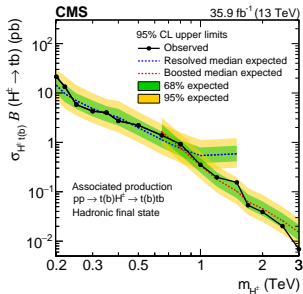
QCD : from data using CRs (inverted  $\tau_N$ ),  
sidebands with  $m_{tb} \in [\text{below, above}]$

$t\bar{t}$  : from sim., normalized in CR with 1  $\ell$

- $H_T$  is used to extract the signal from SM background inside the  $m_{bt}$  window.

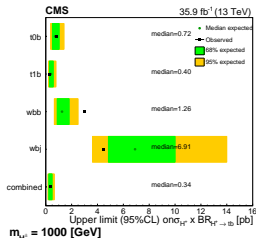
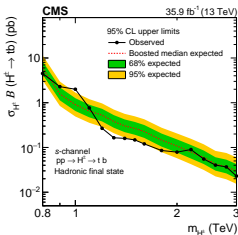


## Associated production



s-channel

Assoc. boosted categories



## Resolved and Boosted analysis overlayed limits

- ▶ Boosted: best sensitivity for  $m_{H^\pm} > 0.8$  TeV
- ▶ Reported limit at each mass value is determined by the analysis with the best expected sensitivity.
- ▶ 21.3 to 0.007 pb for masses 0.2 to 3 TeV
- ▶ No excess above the estimated background
- ▶ Interpretation in hMSSM: maximum  $\tan \beta = 0.88$  is excluded for  $m_{H^\pm} = 0.20$ -0.55 TeV

- ▶ Boosted analysis sets upper limits in the s-channel production
  - ▶ 4.5-0.023 pb for  $m_{H^\pm} 0.8$  to 3 TeV
- ▶ Boosted categories
  - ▶ Most sensitive main category is  $t1b$
  - ▶ Least sensitive category is  $Wbj$



## Signal region (SR):

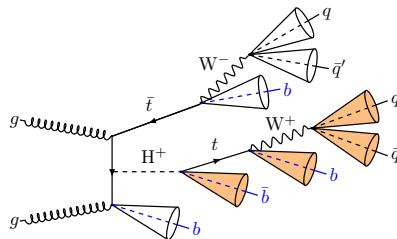
Trigger	$H_T + \text{multijet} + 1 \text{ or } 2 \text{ b jets}$
e veto	$p_T > 10 \text{ GeV},  \eta  < 2.4, \text{ Loose minilso, cutBasedElectronID (veto)}$
$\mu$ veto	$p_T > 10 \text{ GeV},  \eta  < 2.4, \text{ Loose minilso isCutBasedIDLoose}$
$\tau$ veto	$p_T > 20 \text{ GeV},  \eta  < 2.3, \text{ DeepTau } D_e^{\text{vloose}}, D_\mu^{\text{medium}}, D_j^{\text{loose}}$
$\geq 7 \text{ jets}$	$p_T^{6th} > 40 \text{ GeV}, p_T^{7th} > 30 \text{ GeV},  \eta  < 2.4, \text{ Tight ID}, H_T > 500 \text{ GeV}$
$\geq 3 \text{ b jets}$	$p_T > 40 \text{ GeV}, \text{ DeepJet Medium WP}$
$\geq 1 \text{ resolved top } (t^{\text{res}})$	custom DNN medium, $130 < m_{t^{\text{res}}} < 210 \text{ GeV}$

## SR categorization based on $t^{\text{res}}$

- $1M1L_{t^{\text{res}}}$ : medium  $t_{H^\pm}^{\text{res}}$   
loose-not-medium  $t_{\text{assoc}}^{\text{res}}$
- $2M_{t^{\text{res}}}$ : both  $t^{\text{res}}$  medium tagged

## Invariant $H^\pm$ mass reconstruction:

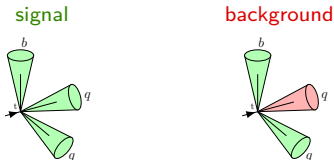
$$m_{tb} = t_{ldg}^{\text{res}} p_T + bjet_{ldg}^{\text{free}} p_T$$



# RESOLVED top tagging

A fully connected NN is developed to reconstruct resolved top-quarks

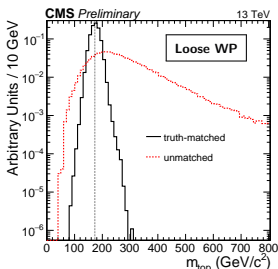
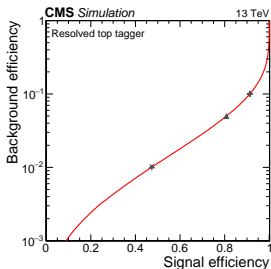
- Distinguishes trijets from top-quark decays and trijets from combinatorial background.
- Training on simulated  $t\bar{t}$  events
  - **Signal**: truth-matched trijets
  - **Background**: non-matched trijets



Mass decorrelation using sample reweighting:

- **Background** is reweighted such that  $m_{top}$  matches the **signal**.

SF vs  $t^{res} p_T$  measured in a region with 1 isolated  $\ell$



HIG-21-010 Submitted to JHEP  
Documentation: [AN 2021/019](#)  
Approved by [JMAR group](#)

Main background for the  $H^\pm \rightarrow tb$  fully hadronic final state:

- ▶ QCD multijet DATA DRIVEN
- ▶ EWK processes (mainly  $t\bar{t}$ ) SIMULATION

## QCD background measurement

Defining 3 orthogonal control regions (CR) for each SR

- ▶  $t_{assoc}^{res}$  **mass**: In-mass  $\rightarrow$  Off-mass “sidebands”
- ▶  $t_{H^\pm}^{res}$  **mva**: t-tagged (t)  $\rightarrow$  non t-tagged (!t)

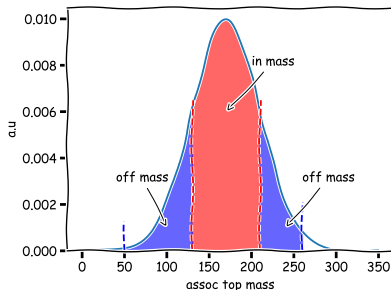
“ABCD” method

$$N_{QCD}^{SR} = \sum_i^{bins} N_{QCD,i}^{CR(off-mass,t)} \cdot \left( \frac{N_{QCD,i}^{CR(in-mass,t)}}{N_{QCD,i}^{CR(off-mass,t)}} \right)$$

- ▶ Performed in 3 bins of the  $t_{assoc}^{res} p_T$ :

- ▶  $p_T \in [0, 100, 300, \infty]$  GeV FIXME

Sidebands



A parameterized DNN is developed to extract signal from SM background

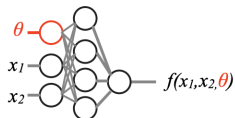
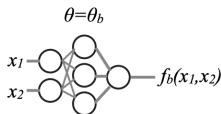
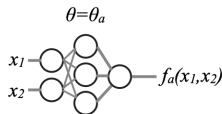
- **Signal:**  $H^\pm \rightarrow t\bar{b}$  for different mass hypotheses
- **Background:**  $t\bar{t} \rightarrow \text{SR, Combinatorial} \rightarrow \text{CR}^{(\text{off-mass}, t)}$

$t\bar{t}$  MC

## Input variables

- 1  $\Delta\theta(t_{H^+}, b_{H^+})$  in  $H^\pm$  CM
- 2  $H_{T,3b}$
- 3  $p_T(\text{bb}_{dRmin})$
- 4  $m(\text{bb}_{maxPt})$
- 5  $y_{23} = p_{T,j3}^2 / (p_{T,j1} + p_{T,j2})^2$
- 6  $p_{T,b(H^\pm)} / H_{T,3b}$
- 7  $m_{H^\pm}$
- 8  $p_T^{Asym}(H^\pm, b_{H^\pm})$
- 9 Circularity
- 10 Sphericity
- 11 Aplanarity
- 12 Number of medium tops
- 13 **True mass**

## Parameterized DNN



- **True mass** is the  $\theta$  parameter
- In background events, the true mass is randomly assigned to the same values used for signal
- Training (test) is done using 2017 (2018) data

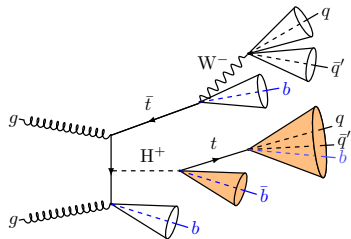
## Signal region (SR): FIXME

Trigger	$H_T + \text{multijet} + 1 \text{ or } 2 \text{ b jets}$ $H_T + \text{AK8 jet} + \text{trim mass}$
$\ell$ veto	same as resolved
$= 1$ boosted top ( $t^{bst}$ )	loose ID, $p_T > 400 \text{ GeV}$ , $ \eta  < 2.4$ , $m_{SD} \in [105, 210] \text{ GeV}$ , $\tau_{32} < 0.67$ , $N_{b \text{ subjects}} \geq 1$
$\geq 4$ jets	$p_T > 40 \text{ GeV}$ , $ \eta  < 2.4$ , tight ID, $H_T > 500 \text{ GeV}$
$\geq 2$ b jets	$p_T > 40 \text{ GeV}$ , DeepJet Medium WP
$\geq 1$ $t^{res}$	same as resolved
Kinematic requirements	$\Delta R(t^{bst}, b^{ldg}) > 1.0$ $\max(m_{bb}) > 200 \text{ GeV}$

## SR categorization FIXME

Invariant  $H^\pm$  mass reconstruction:

$$m_{tb} = t^{bst} + bjet^{ldg} p_T$$



# BACKUP