

# CMS Overview on Searches for Charged Higgs

Charged Higgs Online workshop, 30-31 August 2021

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on behalf of the CMS Collaboration

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- ▶ Most extensions of the SM involve additional neutral and/or charged Higgs states in their spectra
- ▶ Two Higgs Doublet Model (2HDM) predicts:
  - ▶  $\mathcal{CP}$ -even  $h^0$  and  $H^0$ ,  $\mathcal{CP}$ -odd  $A^0$
  - ▶ Two singly-charged Higgs bosons,  $H^\pm$
- ▶ Several ways to couple the two Higgs doublets to SM fermions:

Model:	Type I	Type II	Type X	Type Y
$\Phi_1$	-	$d, \ell$	$\ell$	$d$
$\Phi_2$	$u, d, \ell$	$u$	$u, d$	$u, \ell$

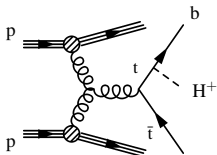
- ▶ Higgs triplet models introduce scalar triplets:
  - ▶ Georgi-Machacek (GM): one real & one complex  $SU(2)$  triplet
  - ▶ Tree-level  $H^\pm W^\pm Z^0$  coupling
  - ▶ Presence of doubly-charged Higgs boson,  $H^{\pm\pm}$
- ▶ Detection of a charged higgs boson would point to physics beyond the SM

# EXPERIMENTAL SIGNATURES

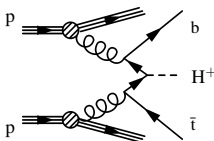
Charged Higgs bosons searched in three mass regions with different production modes:

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

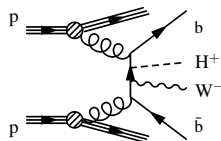
double-resonant  $t$



single-resonant  $t$

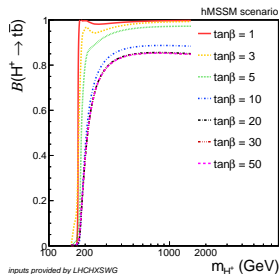
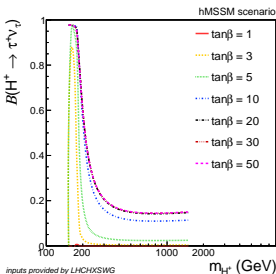
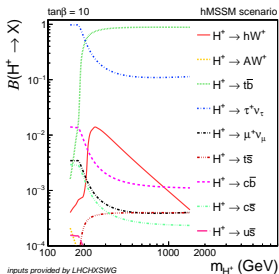


non-resonant  $t$



- ▶ Model-dependent  $H^\pm$  BRs

Type-II 2HDM:  $H^\pm \rightarrow \tau\nu$  almost exclusively for light  $H^\pm$ ,  $H^\pm \rightarrow tb$  for heavy  $H^\pm$



# OVERVIEW OF RUN-II SEARCHES

- Several  $H^\pm/H^{\pm\pm}$  searches, targeting various decay modes, final states & topologies

Full Run-II

2016

Light

$$m_{H^\pm} < m_t - m_b$$

Intermediate

$$m_{H^\pm} \approx m_t$$

Heavy

$$m_{H^\pm} > m_t - m_b$$

$H^\pm \rightarrow cs$   
semi-leptonic

$35.9 \text{ fb}^{-1}$ , 80 – 160 GeV  
10.1103/PhysRevD.102.072001

$H^\pm \rightarrow W^\pm A^0$   
leptonic

$35.9 \text{ fb}^{-1}$ , 100-160 GeV  
10.1103/PhysRevLett.123.131802

$H^\pm \rightarrow W^\pm Z^0$ ,  $H^{\pm\pm} \rightarrow W^\pm W^\pm$   
leptonic

$137 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1140/epjc/s10052-021-09472-3

$H^\pm \rightarrow W^\pm Z^0$ ,  $H^{\pm\pm} \rightarrow W^\pm W^\pm$   
semi-leptonic

$35.9 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1016/j.physletb.2019.134985

$H^\pm \rightarrow W^\pm Z^0$   
leptonic

$35.9 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1016/j.physletb.2019.05.042

$H^\pm \rightarrow tb$   
hadronic

$35.9 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1007/JHEP07(2020)126

$H^\pm \rightarrow tb$   
leptonic

$35.9 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1007/JHEP012020096

$H^{\pm\pm} \rightarrow W^\pm W^\pm$   
leptonic

$35.9 \text{ fb}^{-1}$ , 200-3000 GeV  
10.1103/PhysRevLett.120.081801

$H^\pm \rightarrow \tau^\pm \nu_\tau$   
leptonic + hadronic

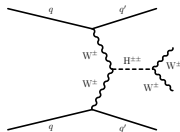
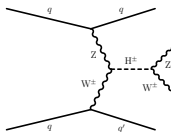
$35.9 \text{ fb}^{-1}$ , 80-3000 GeV  
10.1007/JHEP07(2019)142

# DOUBLY-CHARGED HIGGS $H^\pm \rightarrow W^\pm Z^0$ & $H^{\pm\pm} \rightarrow W^\pm W^\pm$

- ▶  $H^\pm$  &  $H^{\pm\pm}$  produced via VBF and decay to  $WZ$  and  $W^\pm W^\pm$  boson pairs, respectively
- ▶ Leptonic decays:  $W^\pm W^\pm \rightarrow \ell^\pm \nu \ell'^\pm \nu$  &  $W^\pm Z^0 \rightarrow \ell^\pm \nu \ell'^\pm \ell'^\mp$
- ▶ First results with full Run-2 data  $\sim 137 \text{ fb}^{-1}$

- ▶ Candidate events characterised by\*:

- 1  $2\ell^{SS}$  or  $3\ell$  with total charge of  $\pm 1$
- 2 missing transverse momentum ( $p_T^{\text{miss}}$ )
- 3 2 forward jets with large  $\Delta\eta_{jj}$  &  $m_{jj}$



- ▶ Background: EW- and QCD-induced diboson + 2 jets,  $tZq$ ,  $t\bar{t}$ ,  $tW$ ,  $t\bar{t}X$ ,  $VV$ 
  - ▶ non-prompt  $\ell$ : partially suppressed by tight ID & isolation requirements, remaining estimated in data (tight-to-loose method)
  - ▶ e sign mismeasurement: corrections from  $Z^0 \rightarrow ee$  events
  - ▶ 3 CRs for normalization of non-prompt  $\ell$ ,  $tZq$  and  $ZZ$  events from data
  - ▶  $WW$  &  $WZ$  production: normalization from SM predictions & validation in CR

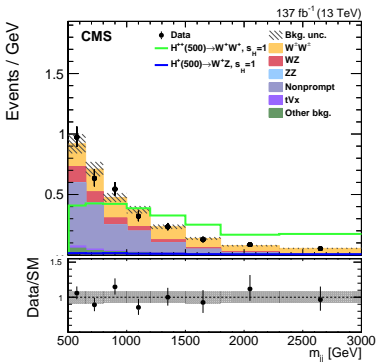
\* Detailed event selection requirements in backup slides

# DOUBLY-CHARGED HIGGS $H^{\pm} \rightarrow W^{\pm}Z^0$ & $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

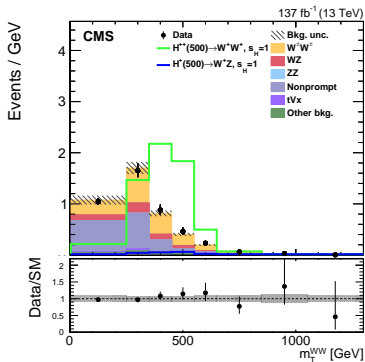
- Final discriminant: 2D distribution  $m_T^{VV}$  VS.  $m_{jj}$

$$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}, \text{ where } i \text{ runs over all } \ell \text{ \& } p_T^{\text{miss}}$$

$m_{jj}$  in  $W^{\pm}W^{\pm}$  SR



$m_T^{WW}$  in  $W^{\pm}W^{\pm}$  SR

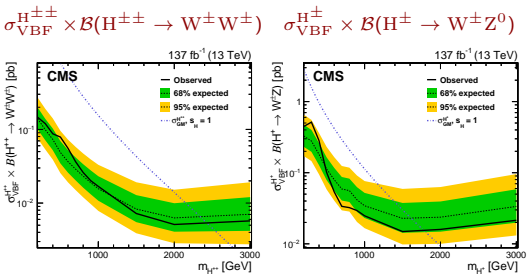


- Simultaneous binned ML fit of  $W^{\pm}W^{\pm}$ ,  $W^{\pm}Z^0$  SRs and tZq, ZZ and non-prompt  $\ell$  CRs
- No significant excess above the SM background prediction

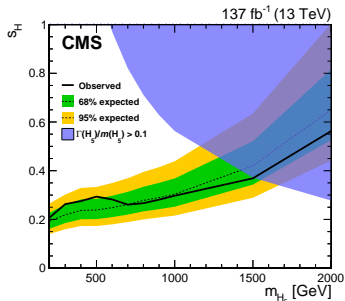
# DOUBLY-CHARGED HIGGS $H^{\pm\pm} \rightarrow W^{\pm}Z^0$ & $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

- ▶ Model independent upper limits at 95% CL
- ▶ Results interpreted also in the Georgi-Machacek model

model-independent



interpretation in GM model

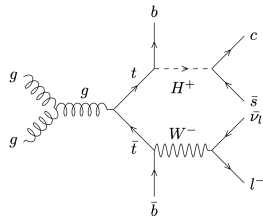


- ▶ Assuming narrow intrinsic widths:
  - ▶  $\Gamma_{H^{\pm}(H^{\pm\pm})} \lesssim 0.05 m_{H^{\pm}(H^{\pm\pm})}$

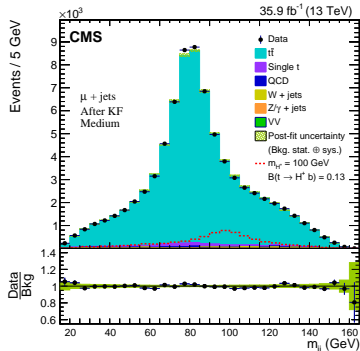
- ▶  $s_H > 0.20 - 0.30$  excluded for  $m_{H_5}$  range from 200 – 1500 GeV
- ▶ Theoretically inaccessible region
- ✓ improved sensitivity wrt. previous CMS results

# SINGLY-CHARGED HIGGS $H^\pm \rightarrow cs$

- ▶ Search for **light**  $H^\pm$ :  $80 < m_{H^\pm} < 160$  GeV
- ▶  $BR(H^\pm \rightarrow cs)$  dominant for low  $\tan\beta < 1$  in Type-II 2HDM
- ▶ Signal event candidate:
  - ▶  $1\ell$  ( $e, \mu$ ), 2 b-jets, 1 c-jet & 1 light-jet,  $p_T^{\text{miss}}$
- ▶ Main backgrounds:
  - ▶ SM  $t\bar{t}$  +jets, single-t, W+jets,  $Z/\gamma^*$ +jets, VV (from simulation)
  - ▶ QCD multijet (data-driven)
- ▶ Final discriminant is  $m_{jj}$  of 2 non-b jets
- ▶ Kinematic fit (KF):
  - ▶  $m_{jj}$  close to  $m_W$
  - ▶ constraints on  $m_{bcq}^{\text{inv}} = m_{bl\nu}^{\text{inv}} = m_{\text{top}}$
- ▶ Categorization based on c-tagging (3 WPs)



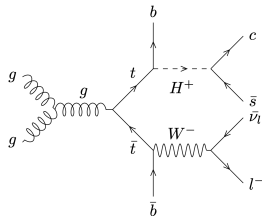
## $\mu$ +jets, Medium c-tagging



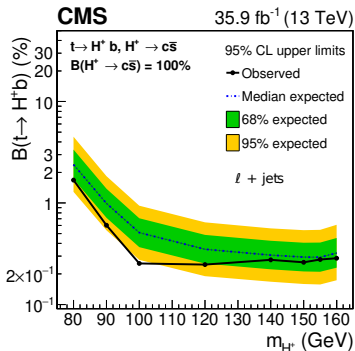


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1.68-0.25% on  $B(t \rightarrow H^+ b)$



# SINGLY-CHARGED HIGGS $H^\pm \rightarrow \tau^\pm \nu_\tau$ hadronic + leptonic

- ▶ Type-II 2HDM:  $\mathcal{BR}(H^\pm \rightarrow \tau^\pm \nu_\tau)$  dominant for light  $H^\pm$ , sizeable for heavy  $H^\pm$
- ▶ Search for  $80 < m_{H^\pm} < 3000$  in three exclusive final states:  $\tau_h + \text{jets}$ ,  $\ell + \tau_h$  and  $\ell + \text{no } \tau_h$

## ▶ $\tau_h + \text{jets}$ :

- ▶ 1-prong  $\tau_h$ ,  $p_T^{\text{miss}} \geq 3$  jets ( $\geq 1$  b jet),  $\ell$ -veto
- ▶ Angular cut to suppress  $j \rightarrow \tau_h$  background
- ▶ Categorization based on  $\tau$  polarization:  

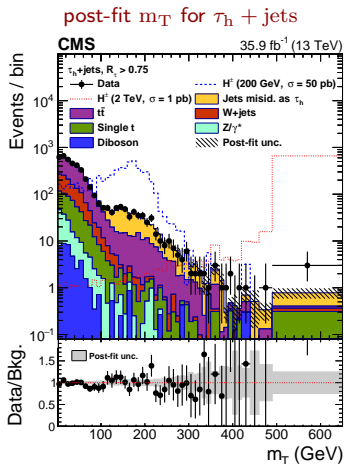
$$R_\tau = p_T^{\text{track}} / p_T^{\tau_h}$$
- ▶  $j \rightarrow \tau_h$  is the main background (data-driven)

## ▶ $\ell + \tau_h$ ( $\ell + \text{no } \tau_h$ ):

- ▶  $1\ell$ ,  $1$  (veto on)  $\tau_h$ ,  $p_T^{\text{miss}} \geq 1$  b jet
- ▶ Categorization based on  $\ell = (\mu, e)$ , jet and b jet multiplicities & binned in  $p_T^{\text{miss}}$
- ▶ Main background is  $t\bar{t}$  (simulation)

- ▶ Final discriminant is transverse mass

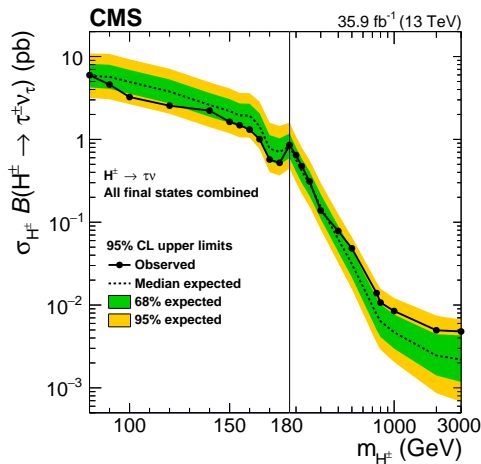
$$m_T(\tau_h/\ell) = \sqrt{2p_T(\tau_h/\ell)p_T^{\text{miss}}[1 - \cos\Delta\phi(\vec{p}_T(\tau_h/\ell), \vec{p}_T^{\text{miss}})]}$$



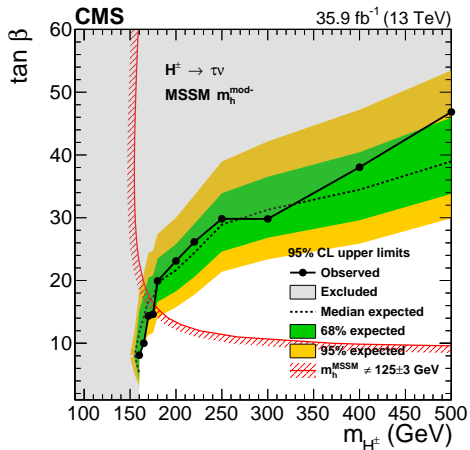
# SINGLY-CHARGED HIGGS $H^\pm \rightarrow \tau^\pm \nu_\tau$ hadronic + leptonic

- ▶ Simultaneous ML fit on 36  $m_T$  distributions
- ▶ 95% CL upper limits are set on  $\sigma_{H^\pm} \times \mathcal{B}(H^\pm \rightarrow \tau^\pm \nu_\tau)$
- ▶ Results interpreted in  $m_h^{\text{mod-}}$  benchmark scenario

6 pb – 5 fb for 80 GeV-3 TeV



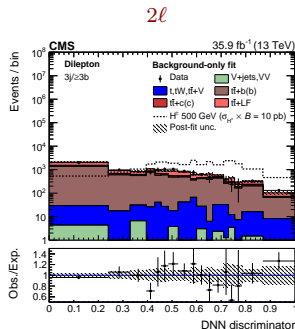
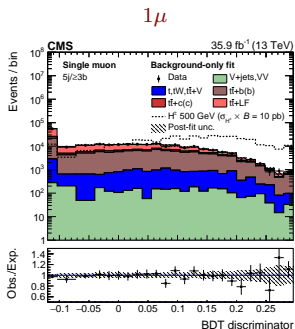
$\tan \beta$  range 1-60 excluded for  $m_{H^\pm}$  up to 160 GeV



# SINGLY-CHARGED HIGGS $H^\pm \rightarrow tb$ leptonic

- ▶  $\mathcal{B}(H^\pm \rightarrow tb)$  of heavy  $H^\pm$  dominant for large range of  $\tan\beta$
- ▶ Search for  $200 < m_{H^\pm} < 3000$  GeV in final states with  $1\ell$  ( $e, \mu$ ) &  $2\ell$  ( $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$ )
- ▶ Signal selections:
  - $1\ell$  :  $=1\ell$  with tight ID,  $p_T^{\text{miss}}, \geq 4$  jets
  - $2\ell$  :  $=2\ell$  OS, no events with  $m_{\ell\ell}^{\text{OSSF}} < 12$  GeV &  $76 < m_{\ell\ell}^{\text{OSSF}} < 106$  GeV,  $p_T^{\text{miss}}, \geq 2$  jets
- ▶ Categorization based on jet and b-jet multiplicities
- ▶ Dominant background is  $t\bar{t}$ ; separated into  $t\bar{t} + \text{LF}$ ,  $t\bar{t} + b(b)$  and  $t\bar{t} + c(c)$  processes

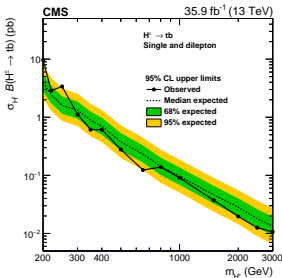
- ▶ MVA techniques utilizing kinematic and topological shapes for signal vs. background discrimination
- ▶ Simultaneous ML fit on the MVA output discriminator



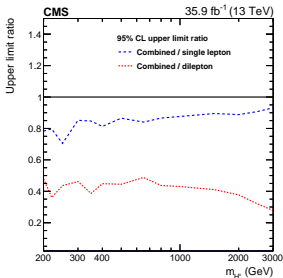
# SINGLY-CHARGED HIGGS $H^\pm \rightarrow tb$ leptonic

- ▶ 95% CL upper limit on  $\sigma_{H^\pm} \mathcal{B}(H^\pm \rightarrow tb)$
- ▶ Combined limit driven by  $1\ell$  category
- ▶ Results interpreted in MSSM  $m_h^{\text{mod-}}$ :
  - ▶ Observed exclusion of high  $\tan\beta$  in the range 40 - 60 for  $m_{H^\pm}$  range 200 - 700 GeV and of low  $\tan\beta$  in the range 0.4-1.5 for  $m_{H^\pm}$  range of 200 GeV-1 TeV

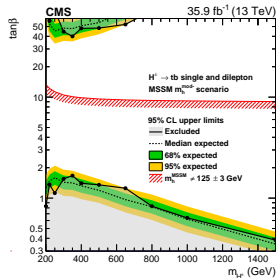
9.6 pb - 11 fb



Contribution of each final state



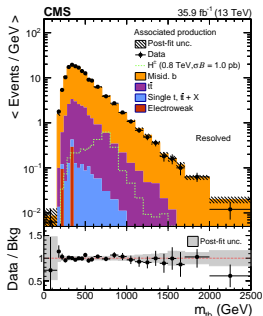
Interpretation in  $m_h^{\text{mod-}}$



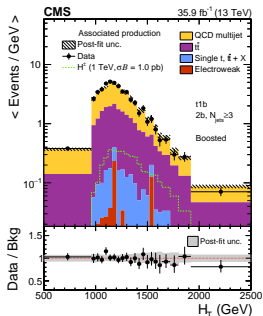
# SINGLY-CHARGED HIGGS $H^\pm \rightarrow tb$ fully hadronic

- ▶ Resolved  $t$  and Lorentz-boosted  $W^\pm$ ,  $t$  topologies
- ▶ Signal selection for resolved  $t$ :
  - ▶  $\geq 7$  jets ( $\geq 3$  b-tagged), high  $H_T$ , 2 resolved  $t$  tagged with custom BD TG
  - ▶  $m_{H^\pm}$  reconstruction from  $ldg$  in  $p_T$  resolved  $t$  +  $ldg$  in  $p_T$  free b-jet
- ▶ Signal selection for boosted  $W^\pm$ ,  $t$ :
  - ▶  $\geq 1$  AK8 jet,  $\geq 1$  b-jets, boosted  $W^\pm$  &  $t$  tagged with jet substructure techniques
  - ▶  $m_{H^\pm}$  reconstruction from boosted  $W^\pm + b + j(b)$  or boosted  $t + b$
  - ▶ Categorization based on jets, b-jets and  $\Delta m_{H^\pm}$
- ▶ Dominant background is misidentified b-jets & QCD multijet events (data-driven)

post-fit  $m_{H^\pm}$  for resolved  $t$



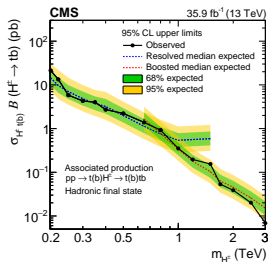
post-fit  $H_T$  for boosted  $W^\pm$ ,  $t$



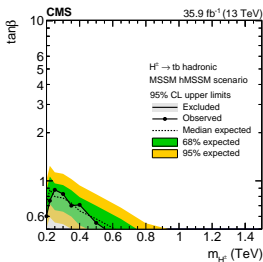
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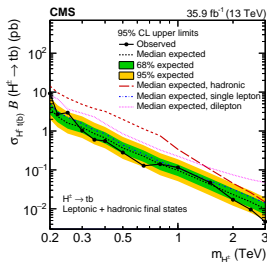
21.3 pb - 7 fb



interpretation in hMSSM



leptonic + hadronic



- ▶ Presented latest results on searches for  $H^\pm$  and  $H^{\pm\pm}$  at CMS:
  - ✓ Covered previously unexplored phase space & models
  - ✓ Improved analysis techniques (MVAs, categorization)
  - ▶ No evidence for BSM physics observed
  
- ✓ New results coming soon with Full Run 2 Legacy data
  - ▶  $\times 4$  more statistics
  - ▶ New search channels!

Thank you!





Ευρωπαϊκή Ένωση

Ευρωπαϊκά Διαρθρωτικά και  
Επενδυτικά Ταμεία



Κυπριακή Δημοκρατία



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# Backup

- Summary of the selection requirements of  $W^\pm W^\pm$  and  $W^\pm Z^0$  events

Variable	$W^\pm W^\pm$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
$p_T^j$	$>50/30$ GeV	$>50/30$ GeV
$ m_{\ell\ell} - m_Z $	$>15$ GeV (ee)	$<15$ GeV
$m_{\ell\ell}$	$>20$ GeV	—
$m_{\ell\ell\ell}$	—	$>100$ GeV
$p_T^{\text{miss}}$	$>30$ GeV	$>30$ GeV
b jet veto	Required	Required
$\tau_h$ veto	Required	Required
$\max(z_\ell^*)$	$<0.75$	$<1.0$
$m_{jj}$	$>500$ GeV	$>500$ GeV
$ \Delta\eta_{jj} $	$>2.5$	$>2.5$

- Zeppenfeld variable,  $z_\ell^*$ :

10.1103/PHYSREVD.54.6680

$$z_\ell^* = \frac{|\eta^\ell - \frac{1}{2}(\eta^{j1} + \eta^{j2})|}{|\Delta\eta_{jj}|}$$

# BACKUP Singly-charged Higgs to WA

- ▶ First search for  $H^\pm \rightarrow W^\pm A^0$  in the  $A^0 \rightarrow \mu^+ \mu^-$  decay channel
- ▶  $100 < m_{H^\pm} < 160$  GeV &  $15 < m_A < 75$  GeV

▶ Final states:  $e\mu\mu$  and  $\mu\mu\mu$

▶ Signal selection:

- ▶ exactly 3 $\ell$  with tight ID (1 OS  $\mu$  pair)
- ▶  $m_{\mu\mu} > 12$  GeV,  $|m_{\mu\mu} - m_Z| > 10$  GeV
- ▶ at least 2 jets (1 b-tagged)

▶ Main background:  $t\bar{t}$  + non-prompt  $\ell$

- ▶ data-driven, *tight-to-loose* method

▶ Excess searched in mass windows of  $m_{\mu^+ \mu^-}$

