Charged Higgs bosons at ATLAS and CMS

Higgs 2020, 26-30 October 2020

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on behalf of the ATLAS and CMS Collaborations

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- In most extensions of the SM, the Higgs sector must also be extended
- Minimal extensions known as two-Higgs-doublet models (2HDMs) predict:
  - $\mathcal{CP}$-even h^0 and H^0, $\mathcal{CP}$-odd A^0
  - Singly-charged H^+ and H^-
- Four ways to couple SM fermions to two Higgs doublets (no FCNCs):

type I All quarks & leptons couple to Φ_2

type II All *u*-type to Φ_2 and all *d*-type & ℓ to Φ_1

type X Both *u* & *d* types couple to Φ_2, all ℓ to Φ_1

type Y Roles of two doublets reversed wrt type II

Model	*d*	*u*	ℓ
I	Φ_2	Φ_2	Φ_2
II	Φ_1	Φ_2	Φ_1
X	Φ_2	Φ_2	Φ_1
Y	Φ_1	Φ_2	Φ_2

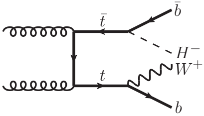
MSSM (type II)

- Higgs triplet models (HTMs) extend the sector by addition of scalar triplet(s):
  - Georgi-Machacek (GM) model adds one real & one complex SU(2) triplet
  - Appearance of the $\mathrm{H}^\pm\ \mathrm{W}^\pm\ \mathrm{Z}^0$ coupling at tree-level
  - Presence of doubly-charged Higgs bosons H^{++} and H^{--}
- Observation of a charged Higgs boson an unequivocal proof of BSM physics
- Production & decay modes greatly depend on the particles masses . . .

Three mass categories are commonly used in $\mathrm{H}^{\pm}$ searches:

- Light $m_{\mathrm{H}^{\pm}} < m_{\mathrm{t}} - m_{\mathrm{b}}$

double-resonant *t*



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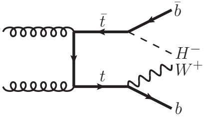
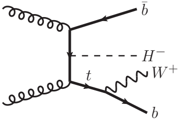


single-resonant t



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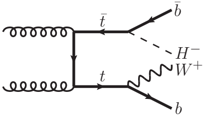
- Light $m_{\mathrm{H}^{\pm}} < m_{\mathrm{t}} - m_{\mathrm{b}}$, heavy $m_{\mathrm{H}^{\pm}} > m_{\mathrm{t}}$, intermediate $m_{\mathrm{H}^{\pm}} \sim m_{\mathrm{t}}$

double-resonant t



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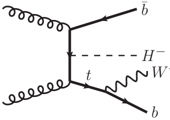
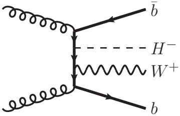
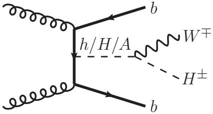


non-resonant t



neutral scalars



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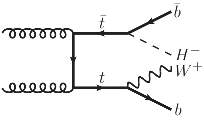

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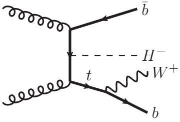

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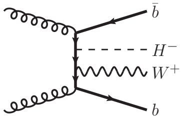

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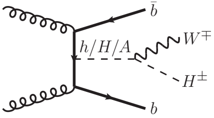
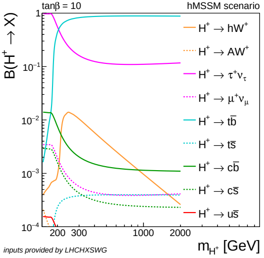
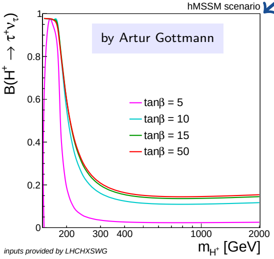
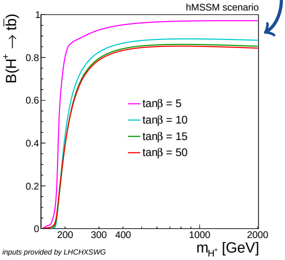


$\mathrm{H}^{\pm}$ decay BRs model-dependent $\Rightarrow$ different searches constrain different scenarios:

- In MSSM the *cs* decay channel is dominant at low $m_{\mathrm{H}^{\pm}}$ and small $\tan\beta$
- Coupling to 3rd-gen fermions is strongest in type II $\Rightarrow$ Sensitive to $\tau\nu$ and *tb*

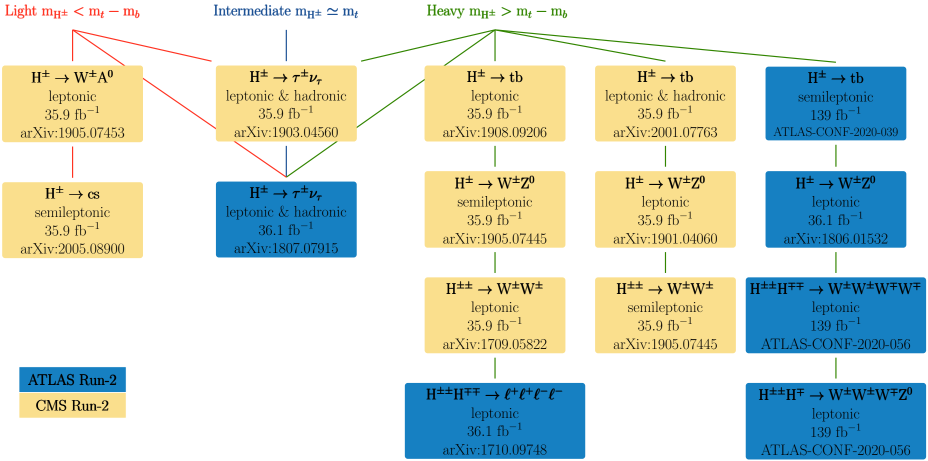






Both ATLAS and CMS have increased efforts to cover more phase space & models:

- Closed the $m_{\mathrm{H}^\pm} \sim \mathrm{m}_{top}$ window ($\sigma_{\mathrm{NLO}^{\mathrm{pp}\to\mathrm{bW}^-\bar{\mathrm{b}}\mathrm{H}^+}}$ in 2016) arXiv:1607.05291
- Resolved & boosted topologies to increase sensitivity at high mass & high p_{T}
- Machine learning techniques for event & object classification (BDTs, DNNs)



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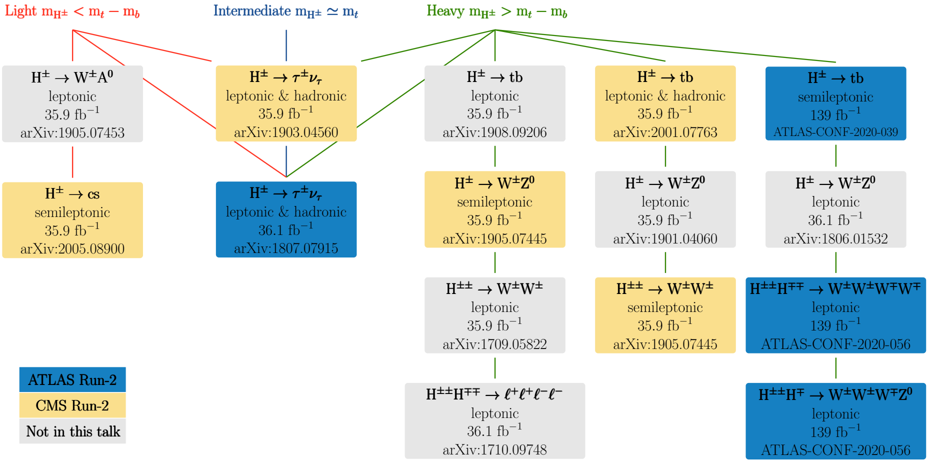
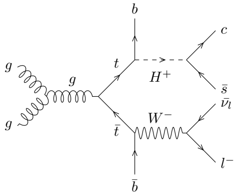
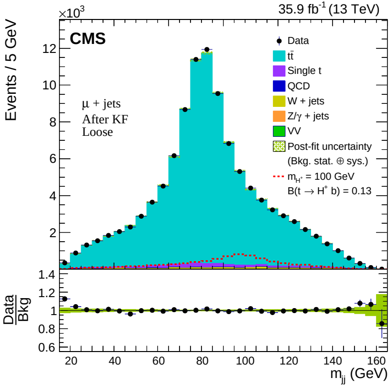


In type II 2HDMs a light $m_{H^{\pm}}$ decays predominantly to cs for low $\tan\beta$ values:

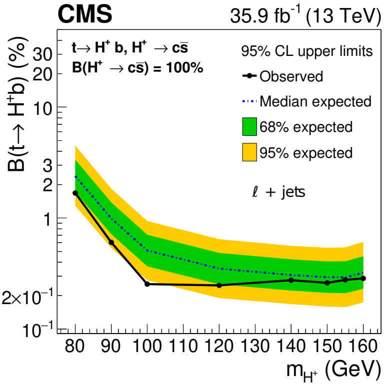
- Require ℓ, p_T^{miss}, and ≥ 4 jets (≥ 2 b-tagged)
- Top kinematic fit (KF) with m_{top} constraints
- Categorisation based on c-tagging (L,M,T)
- Discriminant is m_{jj} of 2 non-b jets



post-fit dijet mass after KF on objects (T)

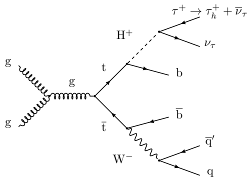


upper limit of 1.68-0.25% on $\mathcal{B}\left(t \to bH^{+}\right)$

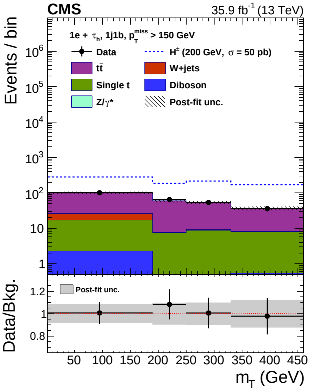


In type II 2HDMs a light $m_{H^{\pm}}$ decays ~exclusively to $\tau\nu$, is sizeable at heavy $m_{H^{\pm}}$:

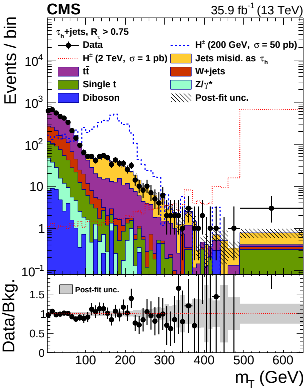
- Three final states; τ_h+jets, $\ell+\tau_h$, ℓ+noτ_h
- Major bkg for τ_h+jets is $j \to \tau_h$ (data-driven)
- Bkg for $\ell+\tau_h$ and ℓ+noτ_h is $t\bar{t}$ (simulation)
- Simultaneous binned ML fit to $m_T(\tau_h/\ell, p_T^{miss})$



post-fit m_T distribution for ℓ+noτ_h



post-fit m_T distribution for τ_h+jets



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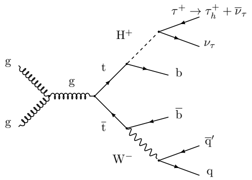
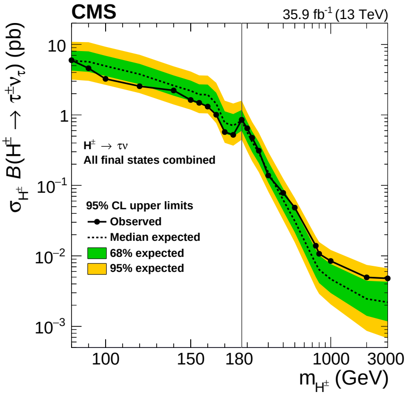
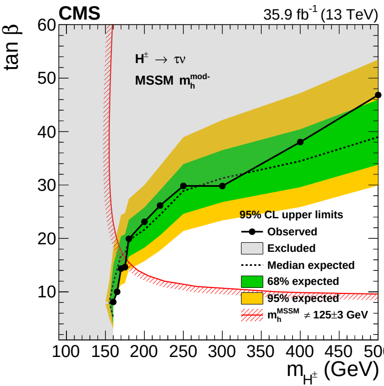


upper limit of 6 pb – 5 fb

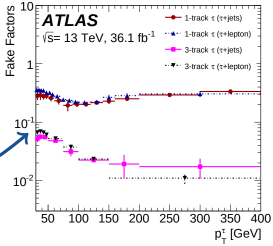


interpretation in m_h^{mod-} scenario

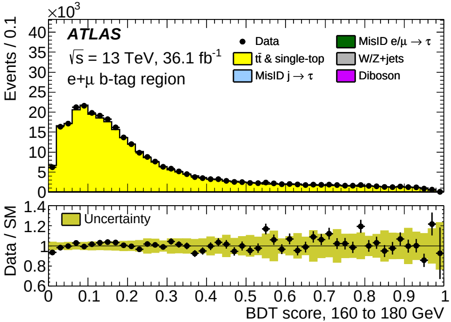


Search targets $\tau_{\rm h}$+jets, $\tau_{\rm h} + e$, $\tau_{\rm h} + \mu$ final states with MVA using BDTs:

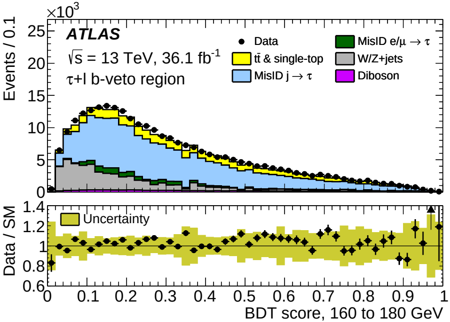
- Signal binned in 3 final states & 5 $m_{H^\pm}$ ranges
- Each final state trained vs dominant SM $t\bar{t}$
- Validation of SM $t\bar{t}$ modelling in $e\mu$ CR
- Other major bkg is $\tau_{\rm h}$-misid with $j \to \tau_{\rm h}$ fakes
  - fake-factors from data ($p_{\rm T}^{\tau_{\rm h}}$, n-prongs)
  - validated in b-tag-veto CR



BDT distribution in $e\mu$ $t\bar{t}$ CR

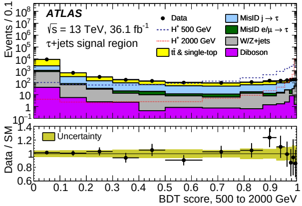


BDT distribution in b-tag-veto CR



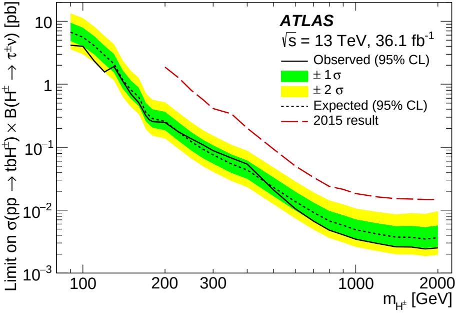
The BDT scores are used as discriminating variables for the fitted regions:

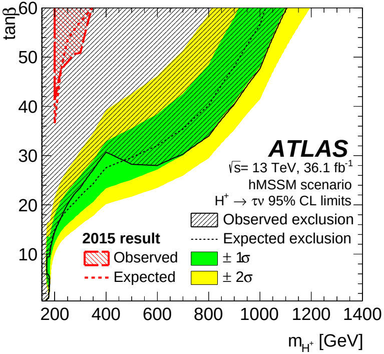
- Upper limit of 4.2 pb – 2.5 fb
- Exclusion 5 – 7 times better than with 3.2 fb^{-1}
- Interpretation in hMSSM scenario:
  - All $\tan\beta$ values excluded for $m_{H^{\pm}} < 160$ GeV
  - For $\tan\beta = 60$ $m_{H^{\pm}} \leq 1.1$ TeV is excluded



0.25% and 0.031% for $m_{H^{\pm}}$ =[90,160] GeV

interpretation in hMSSM scenario

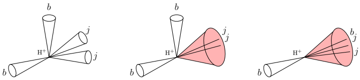




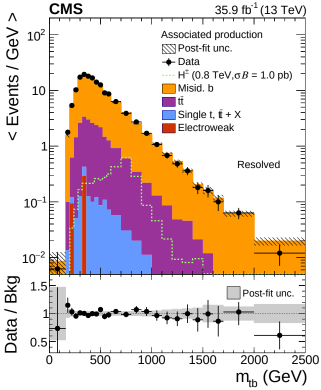
For the heavy $m_{\mathrm{H}^{\pm}}$, the decay into top and bottom quarks is dominant:

- Fully hadronic $\mathcal{B}\,(\mathrm{FH}) \simeq 45\%$ ⇒ full $m_{\mathrm{H}^{\pm}}$ reco
- Resolved t and boosted $\mathrm{W}^{\pm}/t$ topologies
- Major bkg are misid. b-jets & QCD multijet
- Discriminants are m_{tb} and $\mathrm{H_T}$ spectrums

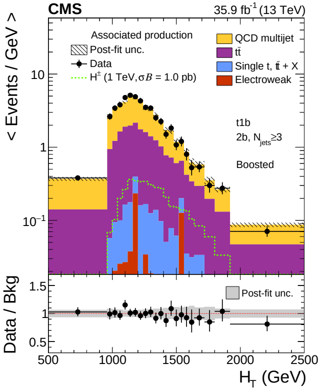
resolved t boosted W boosted t



post-fit m_{tb} distribution for resolved t



post-fit $\mathrm{H_T}$ distribution for boosted $\mathrm{W}^{\pm}/t$



For the heavy $m_{H^{\pm}}$, the decay into top and bottom quarks is dominant:

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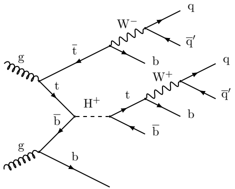
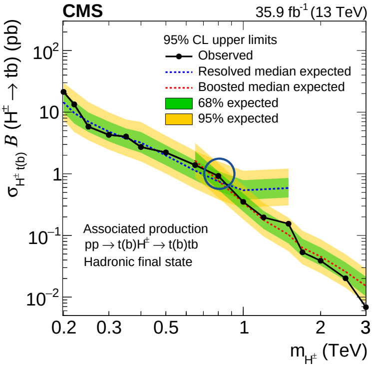
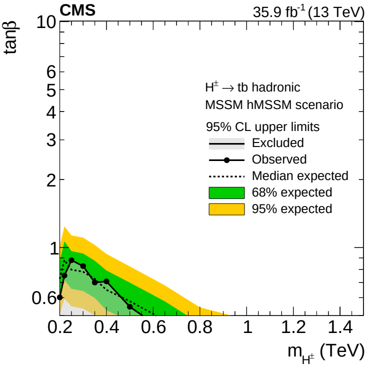


upper limit of 21 pb – 7 fb

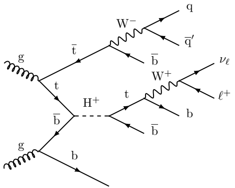


interpretation in hMSSM scenario

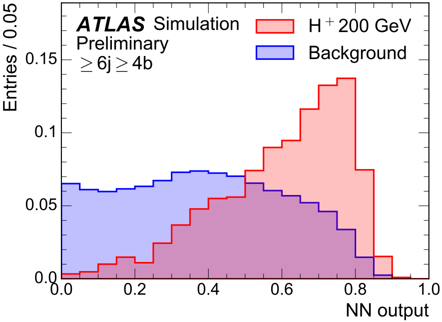


Full Run 2 analysis (139 fb^{-1}) focused on single lepton channel (best significance):

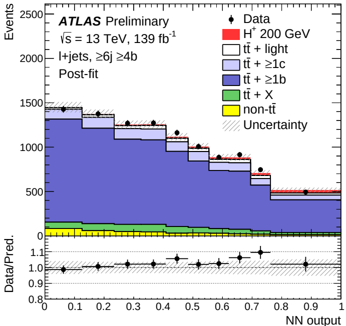
- Require $1\ell^{\pm} = e^{\pm}, \mu^{\pm}$, ≥ 5 jets (≥ 2 *b*-tagged)
- Event classification with jet/*b* jet multiplicity
- Mass-parametrised NN trained with all $m_{H^{\pm}}$
- Main bkg is $t\bar{t}$+jets (data/MC corrections)
  1. Correct the jet multiplicity distribution
  2. Correct the H_T distribution (for each N_j)



trained all SRs using 15 variables

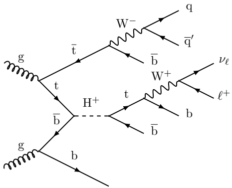


post-fit NN distribution for $\geq 6j \geq 4b$ SR

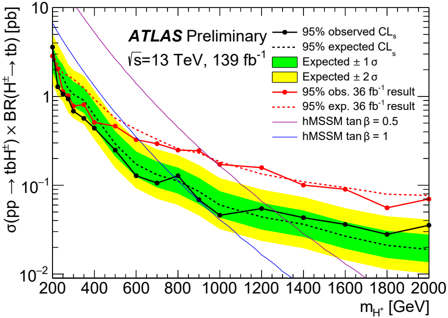


Model-independent limits on $\sigma_{H^{\pm}} \cdot \mathcal{B}(H^{\pm} \rightarrow tb)$ using the CL_S method:

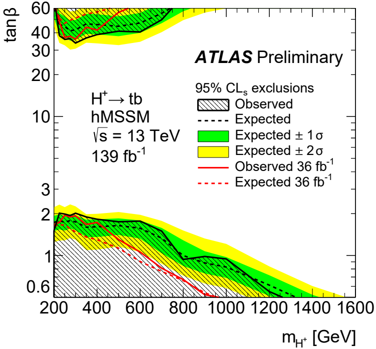
- Simultaneous binned ML fit to 4 NN outputs
  - 5j3b, 5j≥4b, ≥6j≥3b, ≥6j≥4b
- One fit for each masspoint $m_{H^{\pm}}$
- Improvement wrt 36.1 fb^{-1} results (high $m_{H^{\pm}}$)
- Systematics-limited at low $m_{H^{\pm}}$



upper limit of 3.6 pb – 0.035 pb

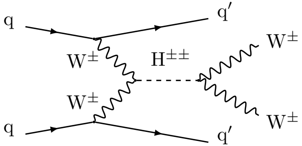


interpretation in hMSSM scenario

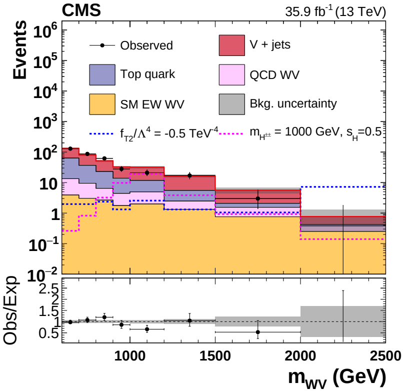


In the GM model $H^\pm$ and $H^{\pm\pm}$ are produced via VBF:

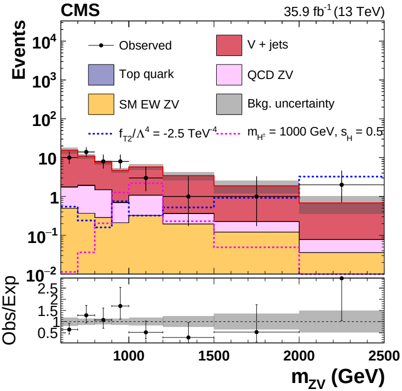
- Semileptonic *WV* (1ℓ) and *ZV* (2ℓ) decays
- Hadronic *V* reconstructed as AK8 ($\tau_{21}^V < 0.55$)
- Leptonic *W* reconstructed from solving the p_z^ν
- Major bkg is W+jets (WV) and Z+jets (ZV)



Signal extraction with fit to m_{WV}

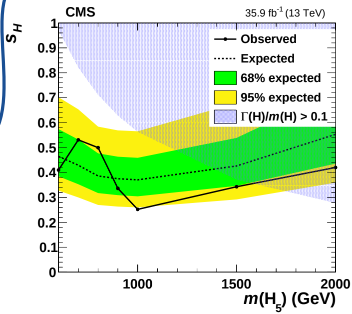


Signal extraction with fit to m_{ZV}

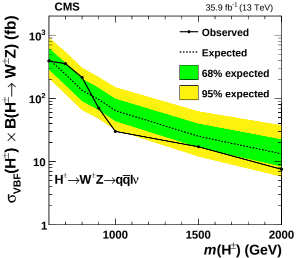


- Use *WV* & *ZV* to extract limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}\left(H^{\pm} \to W^{\pm}Z^{0}\right)$
- Use *WW* channel to extract limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$
- Combine *WV*, *ZV*, *WW* for GM model limits
- Exclude $s_H > 0.53$ for $m_{H_5} = [0.6, 2]$ TeV
- Theoretically inaccessible

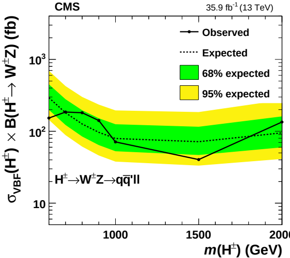
interpretation in GM model



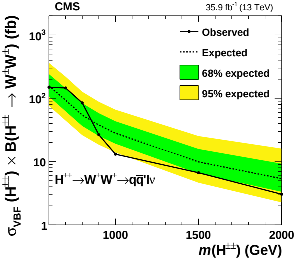
WV channel



ZV channel



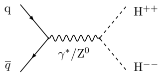
WW channel



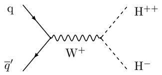
Search motivated by the rich scalar phenomenology in type II seesaw model: **NEW**

- 6 SRs for each $m_{H^{\pm}}$ hypothesis
  - $2\ell^{SC}$ ee, $\mu\mu$, eμ (SC=same-charge)
  - 3ℓ same-flavour opposite-sign ℓ pairs (0, 1 || 2)
  - 4ℓ treated globally
- SM WZ dominant (MC with norm. from data)
- Non-prompt ℓ & charge-flip e (data-based)
  - b-/c-hadron decays, $\pi^{\pm} \to e^{\pm}$
  - e-interactions $e^{\pm} \to e^{\pm}\gamma \to e^{\pm}e^{\pm}e^{\mp}$

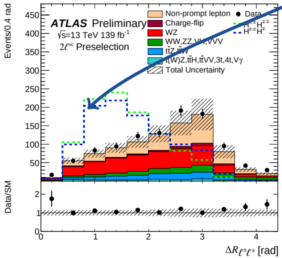
pair production



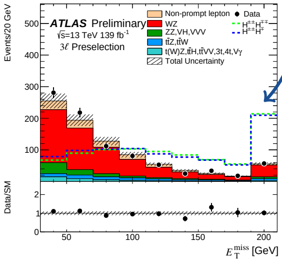
associated production **NEW**



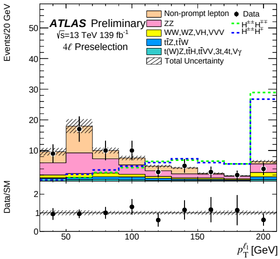
boosted $W^{\pm}$'s for low $m_{H^{\pm\pm}}$



significant E_T^{miss} in all SRs



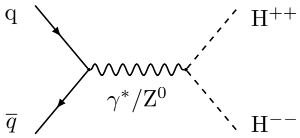
leading lepton p_T used in 4ℓ



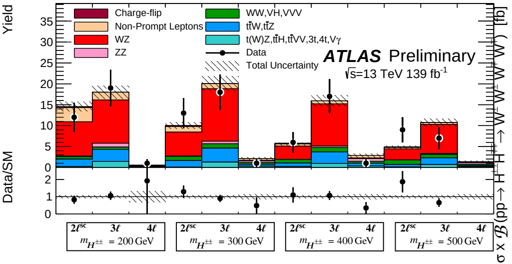
Upper limits on $\sigma_{PP} \cdot \mathcal{B}\,(H^{\pm\pm}H^{\mp\mp} \to W^{\pm}W^{\pm}W^{\mp}W^{\mp})$ at 95% CL: NEW

- By combination of $2\ell^{SS}$, 3ℓ, 4ℓ channels
- A type II seesaw model with $v_t = \mathcal{O}\,(100)$ MeV
- Observed lower limit on $m_{H^{\pm\pm}}$ is 350 GeV
- Uncertainties range from 10–30%. Sources:
  - non-prompt ℓ (statistical)
  - theory (PS model, higher order corr., PDF)

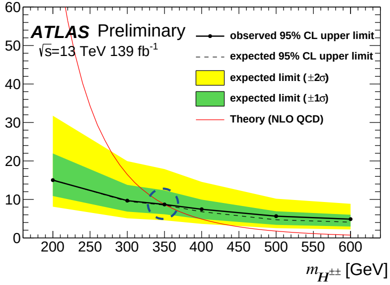
pair production (PP)



Event yields for combination of $2\ell^{SS}$, 3ℓ, 4ℓ



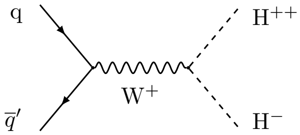
$2\ell^{SS}$, 3ℓ, 4ℓ combination



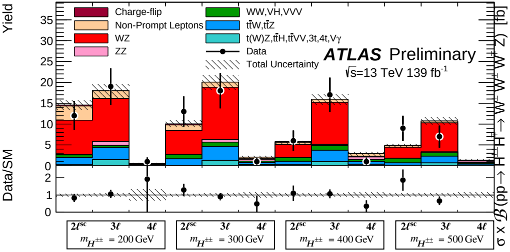
Upper limits on $\sigma_{AP} \cdot \mathcal{B}\left(H^{\pm\pm}H^{\mp} \rightarrow W^{\pm}W^{\pm}W^{\mp}Z^{0}\right)$ at 95% CL: NEW

- By combination of $2\ell^{SS}$, 3ℓ, 4ℓ channels
- A type II seesaw model with $v_t = \mathcal{O}(100)$ MeV
- Observed lower limit on $m_{H^{\pm\pm}}$ is 220 GeV
- Limit in AP mode weaker than in PP mode:
  - Different BRs for channels (16% vs. 26%)
  - SRs optimised to maximise sensitivity for PP

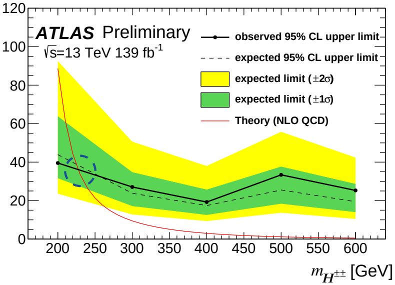
associated production (AP)



Event yields for combination of $2\ell^{SS}$, 3ℓ, 4ℓ

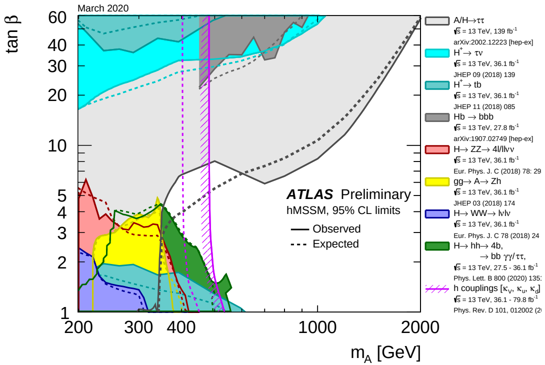


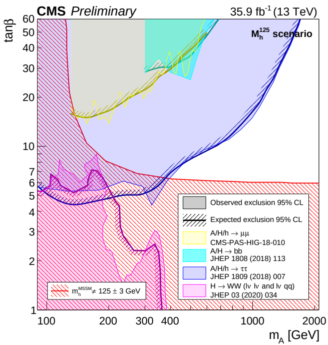
$2\ell^{SS}$, 3ℓ, 4ℓ combination



Presented latest results on searches for $\mathrm{H}^{\pm}$ and $\mathrm{H}^{\pm\pm}$ at ATLAS & CMS:

- No evidence for BSM physics observed
- Large regions of 2HDMs & HTMs parameter space are now excluded
- New results coming soon with full Run 2 Legacy data:
  - Almost $\times 4$ more statistics for both experiments
  - Improved machine learning methods for event & object classification
  - More categorisation to increase sensitivity
  - New search channels with sensitivity to unexplored regions





thank you.

This work was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research Promotion Foundation under the projects

POST-DOC/0718/0169 and **EXCELLENCE/1918/0379**

Ευρωπαϊκή Ένωση
Ευρωπαϊκά Διαρθρωτικά και Επενδυτικά Ταμεία

Κυπριακή Δημοκρατία

Διαρθρωτικά Ταμεία
της Ευρωπαϊκής Ένωσης στην Κύπρο

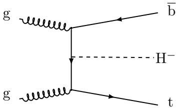
- Santander matching *on page 19*
- MSSM benchmark scenarios *on page 20*
- Single-charged Higgs boson decay *on page 21*
- Doubly-charged Higgs boson production *on page 23*
- CMS $\mathrm{H}^{\pm} \to \mathrm{tb}$ arXiv:2001.07763 *on page 24*
- CMS $\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{A}^{0}$ arXiv:1905.07453 *on page 27*
- CMS $\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}^{0}$ arXiv:1901.04060 *on page 29*
- ATLAS $\mathrm{H}^{\pm\pm} \to \mathrm{W}^{\pm}\mathrm{W}^{\pm}$ arXiv:1808.01899 *on page 32*
- ATLAS $\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}^{0}$ arXiv:1806.01532 *on page 34*

The predictions of 4FS and 5FS calculated at NLO can be combined using the *Santander matching* scheme arXiv:1112.3478.

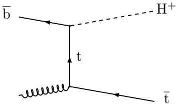
$$\sigma^{\mathrm{matched}} = \frac{\sigma^{\mathrm{4FS}} + w \cdot \sigma^{\mathrm{5FS}}}{1+w}$$

$$w = \ln\left(\frac{\mathrm{m}_{\mathrm{H}^+}}{\mathrm{m}_{\mathrm{b}}}\right) - 2$$

4FS

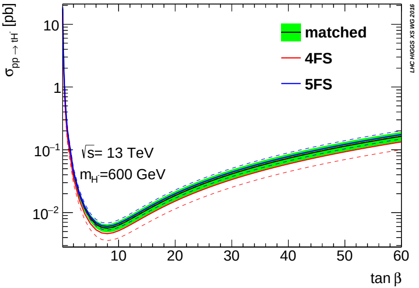


5FS

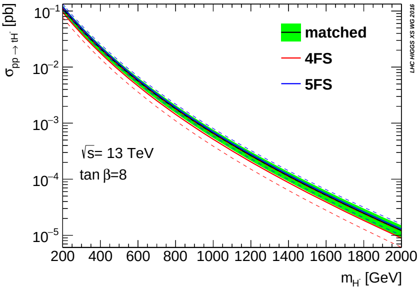


where σ^{4FS} and σ^{5FS} denote the respecitve total inclusive cross sections.

LHC Higgs Cross Section WG



LHC Higgs Cross Section WG

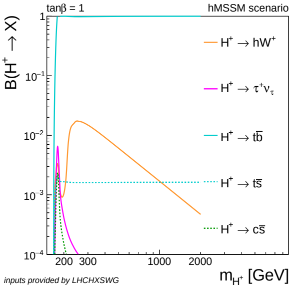


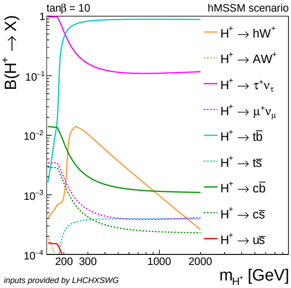
Different *benchmark scenarios* correspond to different sets of MSSM parameters:

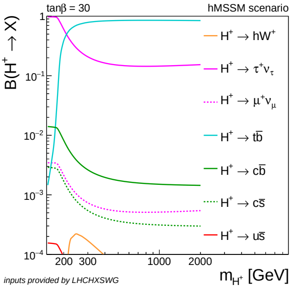
Scenario	M_{SUSY} (GeV)	μ (GeV)	M_2 (GeV)	X_t^{os} (GeV)	$X_t^{\overline{\mathrm{MS}}}$ (GeV)	$M_{\tilde{l}_3}$ (GeV)
$m_{\mathrm{h}}^{\mathrm{max}}$	1000	200	200	$2M_{\mathrm{SUSY}}$	$\sqrt{6}M_{\mathrm{SUSY}}$	1000
$m_{\mathrm{h}}^{\mathrm{mod}+}$	1000	200	200	$1.5M_{\mathrm{SUSY}}$	$1.6M_{\mathrm{SUSY}}$	1000
$m_{\mathrm{h}}^{\mathrm{mod}-}$	1000	200	200	$-1.9M_{\mathrm{SUSY}}$	$-2.2M_{\mathrm{SUSY}}$	1000
Light stop	500	350	350	$2M_{\mathrm{SUSY}}$	$2.2M_{\mathrm{SUSY}}$	1000
Light stau	1000	500	200	$1.6M_{\mathrm{SUSY}}$	$1.7M_{\mathrm{SUSY}}$	245
Light stau ($\Delta\tau$ corr.)	1000	450	400	$1.6M_{\mathrm{SUSY}}$	$1.7M_{\mathrm{SUSY}}$	250
τ-phobic Higgs	1500	2000	200	$2.45M_{\mathrm{SUSY}}$	$2.9M_{\mathrm{SUSY}}$	500
Low-M_{h}	1500	free	200	$2.45M_{\mathrm{SUSY}}$	$2.9M_{\mathrm{SUSY}}$	1000

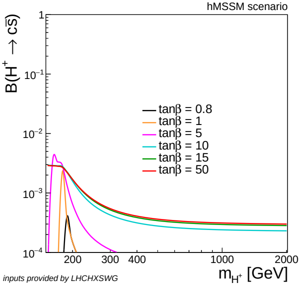
- hMSSM: $\mathrm{h}^0 = \mathrm{H}^0_{125}$, $M_{\mathrm{SUSY}} \sim 1$ TeV, Higgs sector described by $\{\tan\beta, m_{\mathrm{A}^0}\}$ and h^0 phenomenology by couplings to V, t, b
- M_h^{125}: Heavy superparticles⇒production & decay of MSSM Higgs bosons only slightly affected by them
- $m_{\mathrm{h}}^{\mathrm{max}}$: maximal stop mixing, gives maximal light m_{h^0} for fixed $\{\tan\beta, m_{\mathrm{A}^0}\}$
- $m_{\mathrm{h}}^{\mathrm{mod}}$: modified $m_{\mathrm{h}}^{\mathrm{max}}$, X_t/M_{SUSY} reduced to give $m_{\mathrm{h}^0} = 125$ GeV for larger parameter space. +/- according to sign of X_t/M_{SUSY} ($X_t = A_t - \mu\cot\beta$)

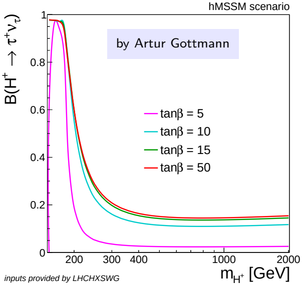
The $\mathrm{H}^{\pm}$ decay BRs in the hMSSM benchmark scenario are shown below:

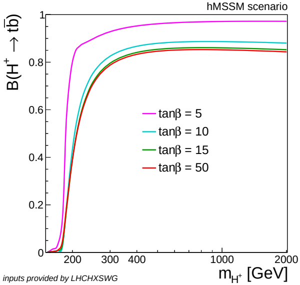




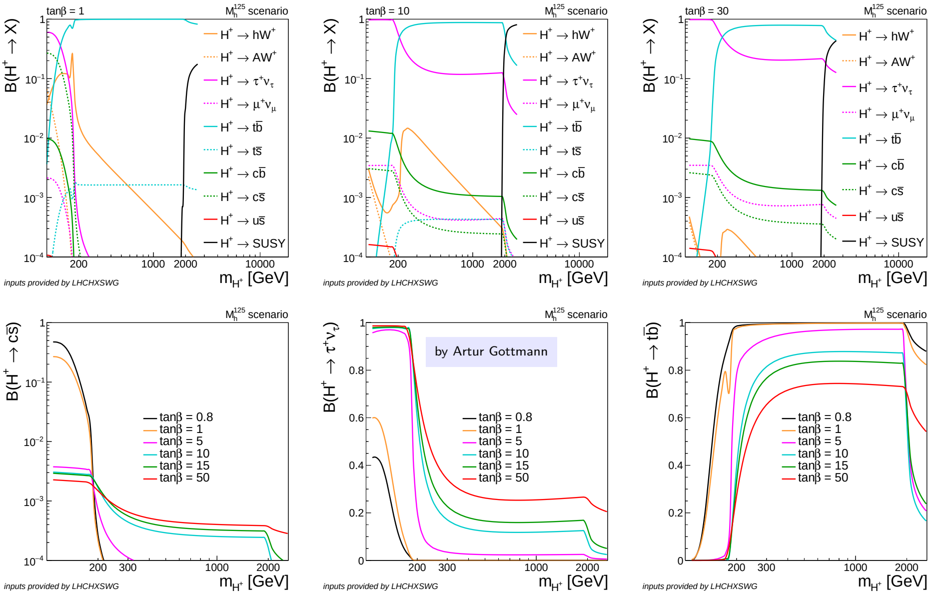






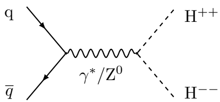


The $\mathrm{H}^{\pm}$ decay BRs in the M_h^{125} benchmark scenario are shown below:

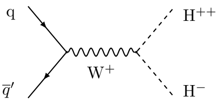


The doubly-charged Higgs boson can be produced via 3 main processes:

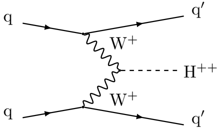
pair production (PP)



associated production (AP)

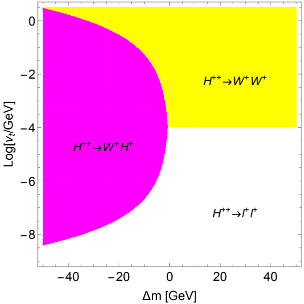


vector boson fusion (VBF)

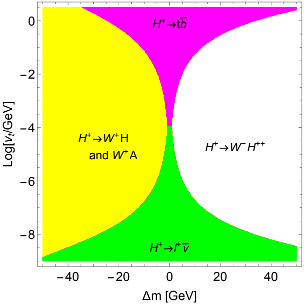


$H^{\pm\pm}$ decays have unique signatures which can be utilised in direct searches:

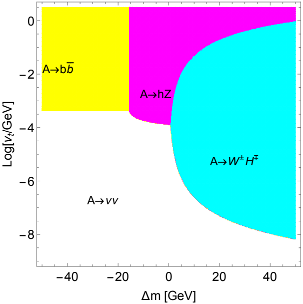
type II seesaw model



$m_{H^{\pm\pm}} = 250$ GeV



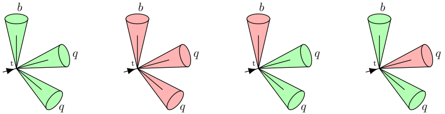
arXiv:1903.02493



Both analyses selected fully-hadronic final states by enforcing lepton vetoes:

Resolved t

1. ≥ 7 AK4 jets, ≥ 3 b-tags
2. $H_T > 500$ GeV
3. 2 resolved tops with BDTG ≥ 0.4
   custom tagger trained in $t\bar{t}$ sample



4. Reconstruct $m_{H^{\pm}}$ using tetrajet from:
   - leading in p_T resolved top
   - leading in p_T free b jet
5. Search for excess in the m_{tb} spectrum

Boosted $W^{\pm}/t$

1. ≥ 1 AK8 jets, ≥ 1 b-jets
2. Jet substructure used for $W^{\pm}/t$ tag

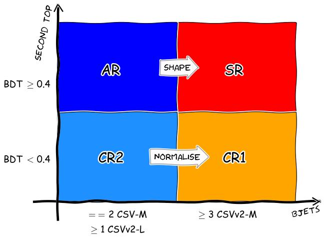
Boosted $W^{\pm}$	Boosted t
$\tau_{21}^{W} < 0.6$	$\tau_{32}^{top} < 0.67$
$m_{SD}^{W} \in [65, 105]$	$m_{SD}^{top} \in [135, 220]$
0 b-subjets	0 or 1 b-subjets

3. Reconstruct $m_{H^{\pm}}$ from AK8+AK4

Boosted $W^{\pm}$	Boosted t
W+b+b	t_{0b}+b
W+b+j	t_{1b}+b

4. N_j, N_b, $\Delta m_{H^{\pm}}$ categorisation
5. Search for excess in H_T of $\Delta m_{H^{\pm}}$

Resolved t

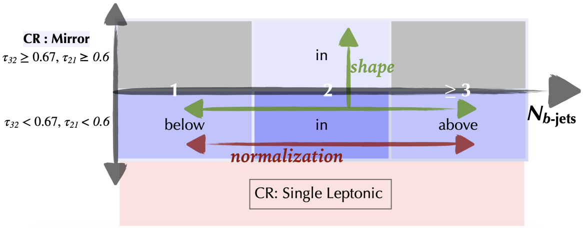


- Minor Genuine-b estimated from simulation
- Main Fake-b measured from data by inverting top- & b-tagging selections

$$N_i^{SR} = \sum_i N_i^{AR} \cdot \left(\frac{N_i^{CR1}}{N_i^{CR2}} \right)$$

i runs over p_T and η bins

Boosted $W^\pm/t$



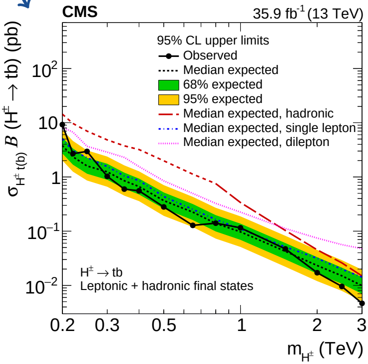
- Dominant QCD multijet ($\sim 90\%$)
  - Shape from **CR: Mirror** (invert τ_{21}^{W} and τ_{32}^{top})
  - Norm from below/above $\Delta m_{H^\pm}$ (sidebands)
- $t\bar{t}$ with **CR: Single Leptonic**
  - 1ℓ with $10 < p_T < 35$ GeV
- The CRs and SRs are simultaneously fitted to:
  - determine normalisation
  - determine shape of the bkg distributions

Combination of $H^\pm \to tb$ leptonic & $H^\pm \to tb$ hadronic final states:

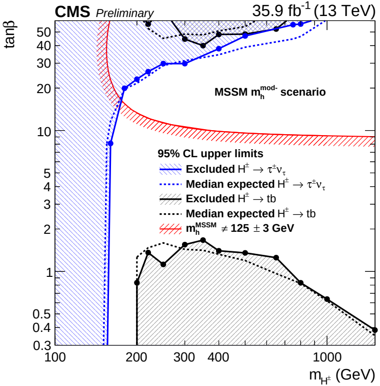
- Single lepton dominates entire $m_{H^\pm}$ spectrum
- Dilepton sensitive at low $m_{H^\pm}$ region ($\sim$ 20% gain)
- Hadronic $\sim$comparable to dilepton at low $m_{H^\pm}$
- Hadronic competes with Single lepton at 3 TeV ($\sim$ 30% gain)

Combination $H^\pm \to \tau^\pm\nu_\tau$ + $H^\pm \to tb$ leptonic is also shown

upper limit of 9.25 pb – 5 fb

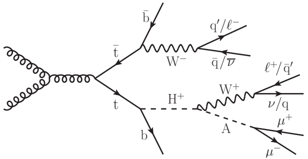


interpretation in m_h^{mod-} scenario

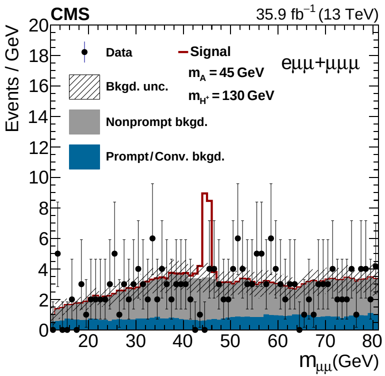


First LHC search for light $m_{H^\pm}$ decaying to WA in any range of $m_{H^\pm}$:

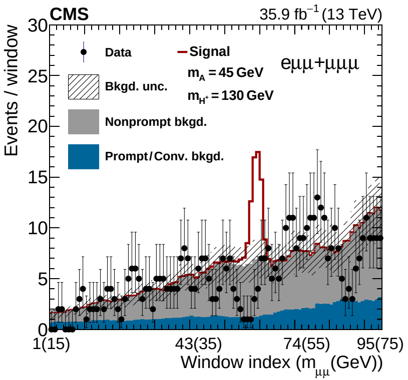
- Target $e\mu\mu$ or $\mu\mu\mu$ with $A^0 \to \mu^+\mu^-$
- $\mathcal{B}\left(A^0 \to \mu^+\mu^-\right)$ small but high ε^{μ}_{ID} and $\frac{\sigma(p^{\mu}_{T})}{p^{\mu}_{T}}$
- Major bkg is $t\bar{t}$ with nonprompt leptons
- Excess search in mass windows w of $m_{\mu^+\mu^-}$



$m_{\mu^+\mu^-}$ of $A^0 \to \mu^+\mu^-$ candidates

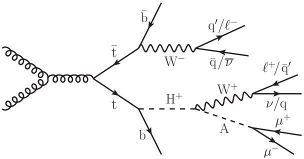


w optimised to maximise median significance



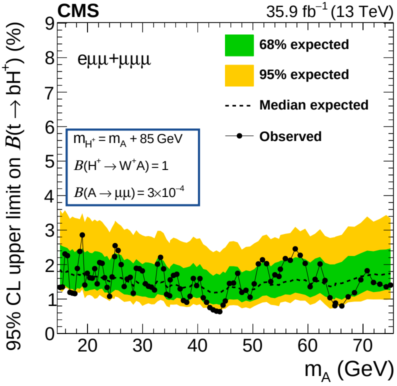
Upper limits at 95% CL on $\mathcal{B}(\mathrm{t} \to \mathrm{bH}^{+}) \cdot \mathcal{B}(\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{A}^{0}) \cdot \mathcal{B}(\mathrm{A}^{0} \to \mu^{+}\mu^{-})$:

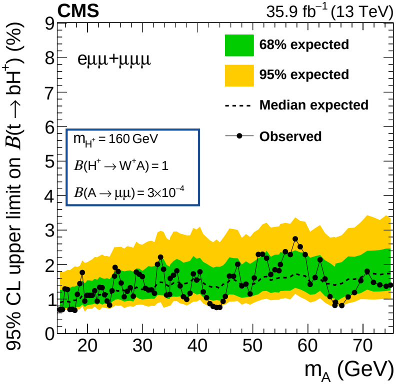
- Based event yields in w from $e\mu\mu$ & $\mu\mu\mu$
- Upper limit between 0.63 – 2.9%
- Sensitivity dominated by stat. uncertainty
- Limit difference smaller than uncertainties



$m_{\mathrm{H}^{\pm}} = m_{\mathrm{A}^{0}} + 85$ GeV

$m_{\mathrm{H}^{\pm}} = 160$ GeV



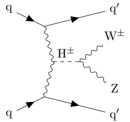


Additional Material CMS $\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}^{0}$ arXiv:1901.04060

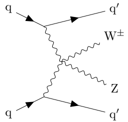
Event selection with 3 lepton candidates:

- OSSF dilepton ($\ell^{\pm}\ell^{\mp}$) with $p_{\mathrm{T}} > 25\,(15)$ GeV and $|\mathrm{m}_{\ell^{\pm}\ell^{\mp}} - m_{\mathrm{Z}^0}^{\mathrm{PDG}}| < 15$ GeV
- 3rd isolated lepton ℓ' with $p_{\mathrm{T}} > 20$ GeV
- $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- ≥ 2 AK4 jets with $p_{\mathrm{T}} > 50$ GeV, $|\eta| < 4.7$, $\mathrm{m}_{j1j2} > 500$ GeV, $\Delta\eta(j_1, j_2) > 2.5$
- Shifted pseudorapidity cut $|\eta^{*}_{3\ell}| = |\eta_{3\ell} - \frac{1}{2}(\eta_{j1} + \eta_{j2})| < 2.5$ arXiv:9605444

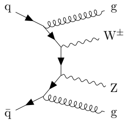
Signal



EW bkg



QCD bkg



Additional selections for background suppression:

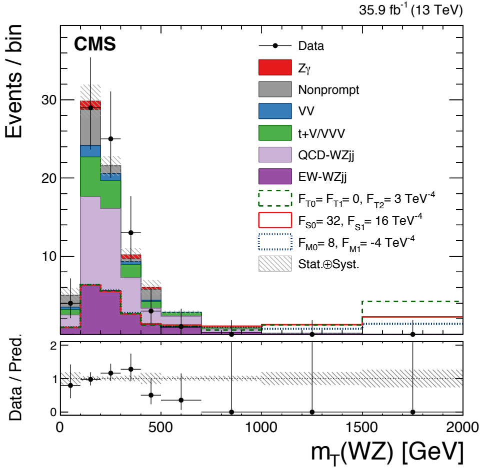
- 4th lepton veto with $p_{\mathrm{T}} > 10$ GeV
- *b* jet veto with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.7$ (suppress $\mathrm{t\bar{t}}$)
- $\mathrm{m}_{\ell^{\pm}\ell^{\mp}} > 4$ GeV (against collinear emission & low mass resonances)
- $\mathrm{m}_{3\ell} > 100$ GeV (suppress Z^0 production with FSR)

ML fit to the transverse mass to extract limits on $H^{\pm}$ production cross section:

- $m_{\mathrm{T}}\,(WZ) = \sqrt{\left(E_{\mathrm{T}}^{W} + E_{\mathrm{T}}^{Z}\right)^2 - \left(\vec{p}_T^{\,W} + \vec{p}_T^{\,Z}\right)^2}$
- W is constructed from $p_{\mathrm{T}}^{\mathrm{miss}}$ and ℓ' not associated with $\mathrm{m}_{\ell^{\pm}\ell^{\mp}}$

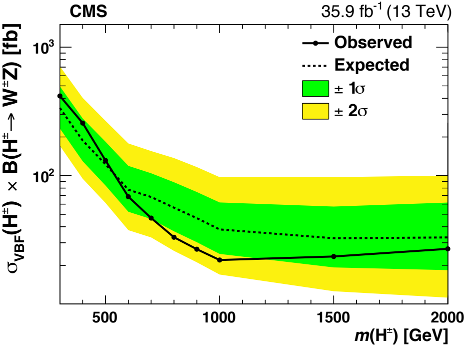
Background estimation:

- Prompt ℓ backgrounds ($Z\gamma$, VV, top, EW-WZjj) estimated from simulation
- QCD-WZjj normalisation from a control region
- Nonprompt ℓ background estimated from data ("tight-to-loose method")

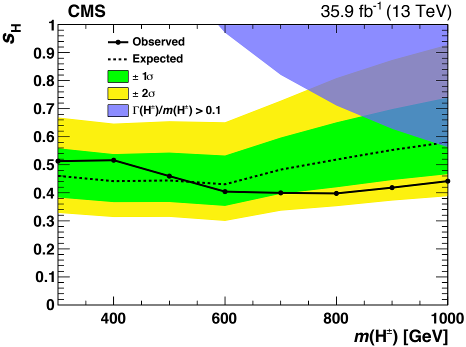


95% upper limits on $\sigma_{\mathsf{VBF}} \cdot \mathcal{B}\left(\mathrm{H}^\pm \to \mathrm{W}^\pm \mathrm{Z}^0\right)$ and s_H using CL$_S$ criterion:

model-independent limits



interpretation in GM model



- Assuming intrinsic $\Gamma_{\mathrm{H}^\pm}$ is narrow

- Upper limit of 0.52 pb – 0.44 fb on s_H
- Assuming $\mathcal{B}\left(\mathrm{H}^\pm \to \mathrm{W}^\pm \mathrm{Z}^0\right) = 1$
- Theoretically inaccessible

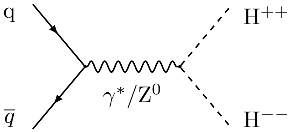
A search motivated by the rich scalar phenomenology in type II seesaw model:

- Three final states; $2\ell^{SS}$, 3ℓ, 4ℓ
- 6 SRs for each $m_{H^\pm}$ hypothesis

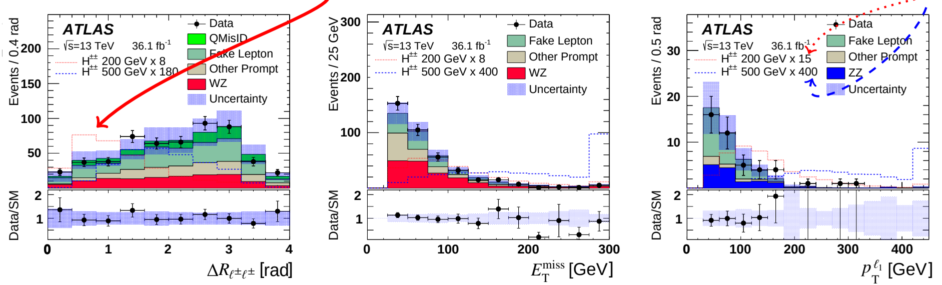
$2\ell^{SS}$	ee, $\mu\mu$, eμ
3ℓ	SFOS ℓ pairs (0, 1 || 2)
4ℓ	treated globally

- Major bkgs: q-misid (brem) & fake ℓ's
- Mass- & channel-dependent optimisation

PP suppressed at large $m_{H^{\pm\pm}}$



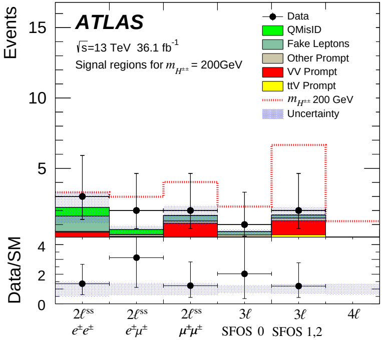
boosted $W^\pm$'s for low $m_{H^{\pm\pm}}$ — significant p_T^{miss} in all SRs — σ_{VBF} falls rapidly with $m_{H^{\pm\pm}}$



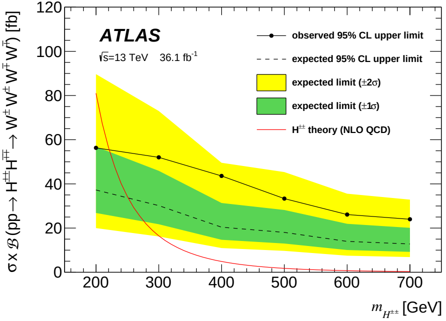
Upper limits on $\sigma_{\text{DY PP}} \cdot \mathcal{B}\,(H^{\pm\pm}H^{\mp\mp} \to W^{\pm}W^{\pm}W^{\mp}W^{\mp})$ at 95% CL:

- Obtained from the combination of $2\ell^{SS}$, 3ℓ, 4ℓ channels
- Observed lower limit on $m_{H^{\pm\pm}}$ is 220 GeV (linear interp. of sensitivity)
- Dominant systematic uncertainties are q-misid and fake ℓ's
- Search sensitivity dominated by stat. uncertainty of event yields in SRs

Event yields in SRs for $m_{H^{\pm\pm}} = 200$ GeV

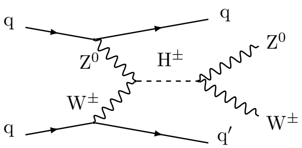


$2\ell^{SS}$, 3ℓ, 4ℓ combination

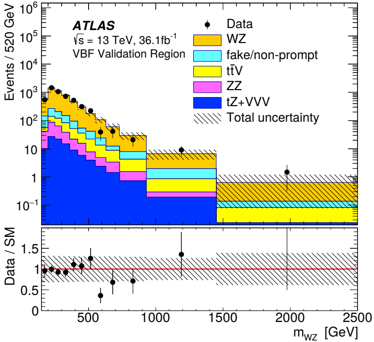


In the GM model $H^\pm$ are produced via the VBF process $pp \to W^\pm Z^0 jj$:

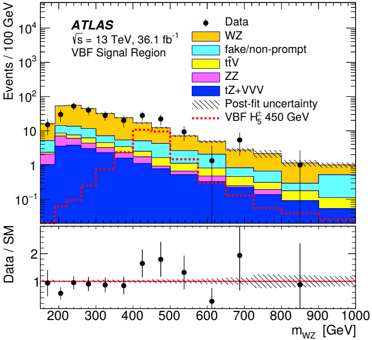
- Search targets fully leptonic channel with 3ℓ
- $2\ell^{OSSF}$, $|m_{\ell\ell} - m_{Z^0}| < 20$ GeV
- W reco from solving the p_z^ν ($m_{W^\pm}$ constraint)
- $|\Delta\eta_{jj}| > 3.5$, $m_{jj} > 500$ GeV
- Bkg is SM WZ bkg (norm. & shape from MC)



validation CR by inverting $|\Delta\eta_{jj}|$ & m_{jj} cuts

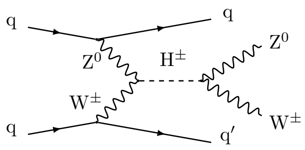


postfit m_{WZ} distribution in SR

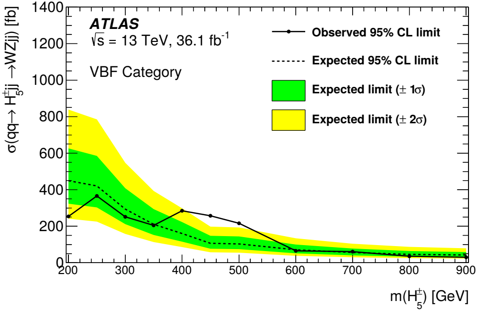


Exclusion limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}\left(H^{\pm} \rightarrow W^{\pm}Z^{0}\right)$ and the GM model parameter $\sin\theta_H$:

- $2.9\sigma_{\text{local}}$ $(1.6\sigma_{\text{global}})$ excess at $m_{H^{\pm}} \simeq 450$ GeV
- Dominant syst. uncert. is *WZ* modelling
- Sensitivity dominated by stat. uncertainty
- Theoretical intrinsic $\Gamma_{H^{\pm}} > 5\,(10)\%$ of $m_{H^{\pm}}$



upper limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}\left(H^{\pm} \rightarrow W^{\pm}Z^{0}\right)$



upper limits on GM mixing parameter $\sin\theta_H$