Additional scalar bosons

Higgs Hunting 2021, 20–22 September 2021

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on behalf of the CMS Collaboration

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Introduction

- 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^-
- Observation of a charged Higgs boson an unequivocal proof of BSM physics
- 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

Type	u	d	ℓ
I	Φ_2	Φ_2	Φ_2
II	Φ_2	Φ_1	Φ_1
III (X)	Φ_2	Φ_2	Φ_1
IV (Y)	Φ_2	Φ_1	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^{--}
- Extensions with a scalar singlet 2HDM+S lead to 2 additional Higgs bosons
  - h^0, H^0, A^0, $\mathrm{H}^\pm$, h^0_s, $\mathrm{A}^{0\prime}$ ← NMSSM
- Production & decay modes greatly depend on the particles masses

In recent years CMS has increased efforts to cover more phase space & models:

- Resolved & boosted topologies to increase sensitivity at high mass & high p_{T}
- Machine learning techniques for event & object classification (BDTs, DNNs)

Third Generation

- $A^0/H^0 \to t\bar{t}$ — arXiv:1704.07323
- $A^0/H^0 \to b\bar{b}$ — arXiv:1805.12191
- $H^\pm \to tb$ — arXiv:1908.09206, arXiv:2001.07763
- $A^0/H^0 \to \tau\tau$ — arXiv:1803.06553
- $H^\pm \to \tau^\pm\nu_\tau$ — arXiv:1903.04560

Other

- $A^0/H^0 \to \mu\mu$ — arXiv:1907.03152
- $H^\pm \to cs$ — arXiv:2005.08900
- $H^0 \to aa \to \mu\mu\tau\tau$ — arXiv:2005.08694
- $H^0 \to h^0_{125}h^0_s \to \tau\tau bb$ — PAS-HIG-20-014

DiHiggs

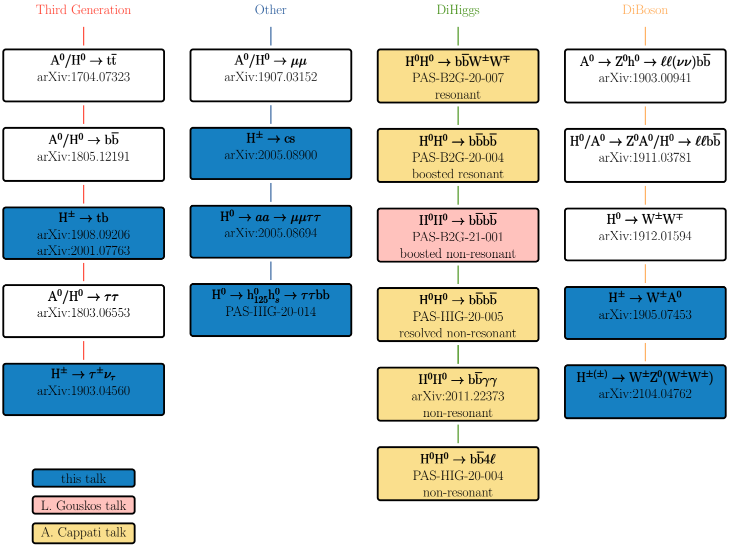
- $H^0H^0 \to b\bar{b}W^\pm W^\mp$ — PAS-B2G-20-007, resonant
- $H^0H^0 \to b\bar{b}b\bar{b}$ — PAS-B2G-20-004, boosted resonant
- $H^0H^0 \to b\bar{b}b\bar{b}$ — PAS-B2G-21-001, boosted non-resonant
- $H^0H^0 \to b\bar{b}b\bar{b}$ — PAS-HIG-20-005, resolved non-resonant
- $H^0H^0 \to b\bar{b}\gamma\gamma$ — arXiv:2011.22373, non-resonant
- $H^0H^0 \to b\bar{b}4\ell$ — PAS-HIG-20-004, non-resonant

DiBoson

- $A^0 \to Z^0h^0 \to \ell\ell(\nu\nu)b\bar{b}$ — arXiv:1903.00941
- $H^0/A^0 \to Z^0A^0/H^0 \to \ell\ell b\bar{b}$ — arXiv:1911.03781
- $H^0 \to W^\pm W^\mp$ — arXiv:1912.01594
- $H^\pm \to W^\pm A^0$ — arXiv:1905.07453
- $H^{\pm(\pm)} \to W^\pm Z^0(W^\pm W^\pm)$ — arXiv:2104.04762

In recent years CMS has increased efforts to cover more phase space & models:

- 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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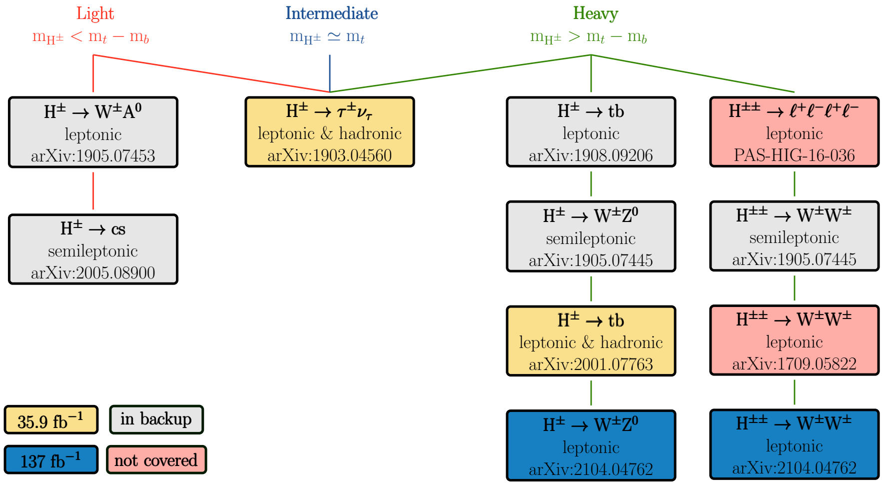
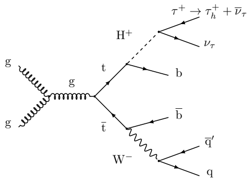


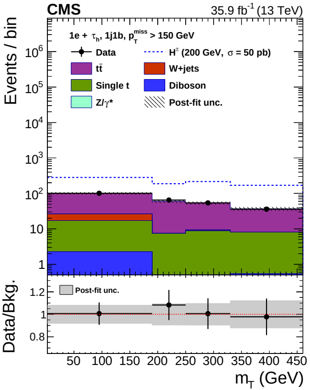
2HDM

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

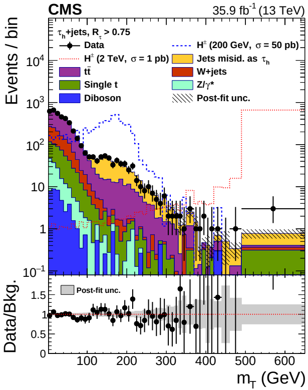
- Three final states; τ_h+jets, $\ell+\tau_h$, ℓ+noτ_h
- Major bkg for τ_h+jets is jet $\to \tau_h$ (data-driven)
- Bkg for $\ell+\tau_h$ and ℓ+noτ_h is $t\bar{t}$ (simulation)
- Simultaneous binned ML fit to $m_T(\tau_h/\ell, p_T^{miss})$



postfit m_T distribution for $\ell+\tau_h$



postfit m_T distribution for τ_h+jets



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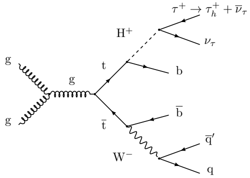
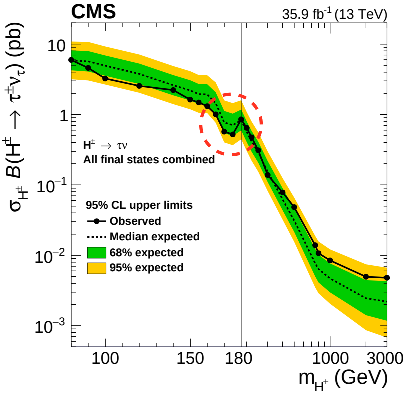
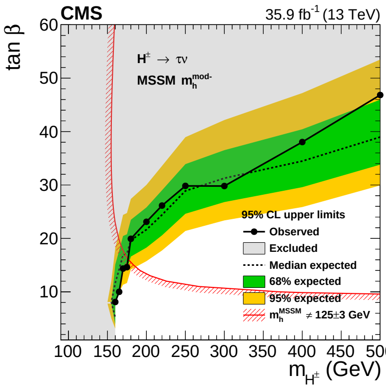


upper limit of 6 pb – 5 fb

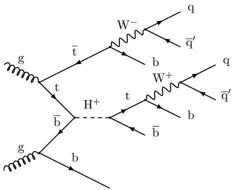


interpretation in m_h^{mod-} scenario

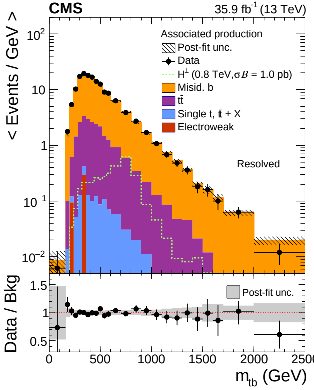


For the heavy $m_{H^{\pm}}$, the decay into top and bottom quarks is dominant:

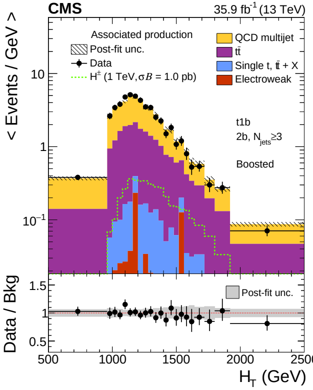
- Fully hadronic $\mathcal{B}$(FH) $\simeq$ 45% $\Rightarrow$ full $m_{H^{\pm}}$ reco
- Resolved t and boosted $W^{\pm}/t$ topologies
- Major bkg are misid. b-jets & QCD multijet
- Fit discriminants are m_{tb} and H_T spectrums



postfit m_{tb} distribution for resolved t



postfit H_T distribution for boosted $W^{\pm}/t$



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

- Fully hadronic $\mathcal{B}$(FH) $\simeq$ 45% $\Rightarrow$ full $m_{H^{\pm}}$ reco
- Resolved t and boosted $W^{\pm}/t$ topologies
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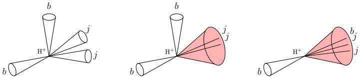
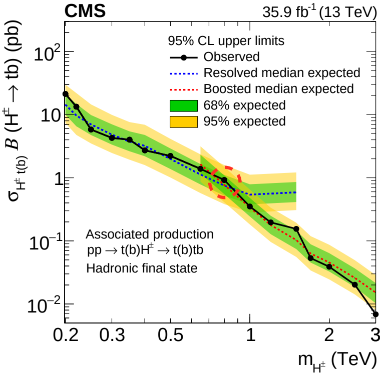
- Fit discriminants are m_{tb} and H_T spectrums

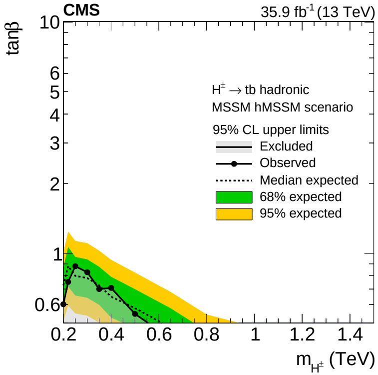
resolved t boosted W boosted t



upper limit of 21 pb – 7 fb



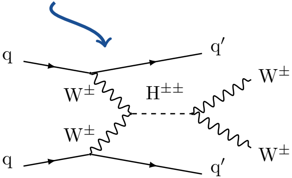
interpretation in hMSSM scenario



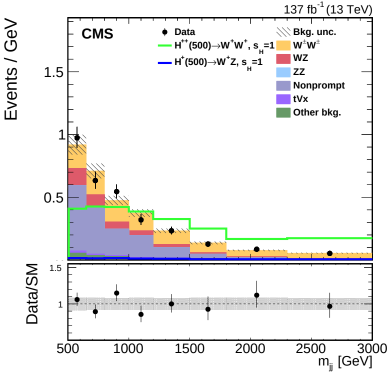
HTM

In GM model H_5 produced via VBF. Simultaneous study of WW and WZ channels:

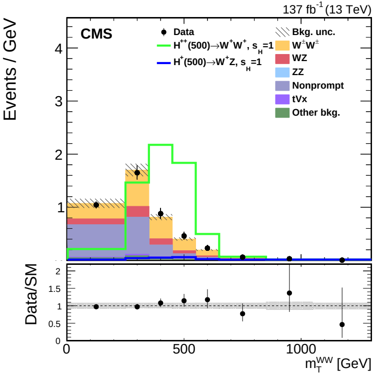
- $2\ell^{SS}$, p_T^{miss}, ≥ 2 jets (large $|\Delta\eta_{jj}|$ & m_{jj})
- Background consists of 3 major types:
  1. Nonprompt from data CR (invert ℓ ID)
  2. WW & WZ from simulation (CR-validated)
  3. Prompt irreducible from MC (tZq & ZZ CRs)



postfit m_{jj} in WW SR (finer binning)

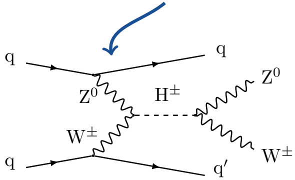


postfit m_T^{WW} in WW SR (finer binning)

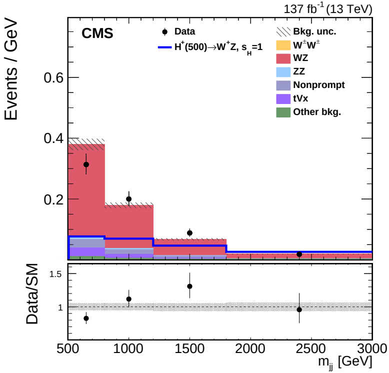


In GM model H_5 produced via VBF. Simultaneous study of WW and WZ channels:

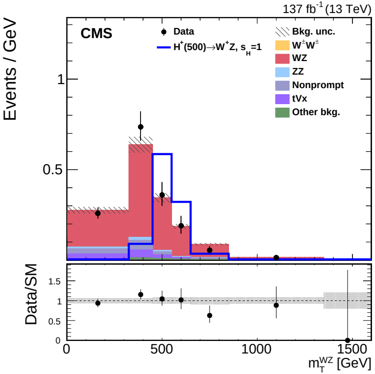
- 3ℓ ($|Q| = 1$), p_T^{miss}, ≥ 2 jets (large $|\Delta\eta_{jj}|$ & m_{jj})
- Background consists of 3 major types:
  1. Nonprompt from data CR (invert ℓ ID)
  2. WW & WZ from simulation (CR-validated)
  3. Prompt irreducible from MC (tZq & ZZ CRs)



postfit m_{jj} in WZ SR

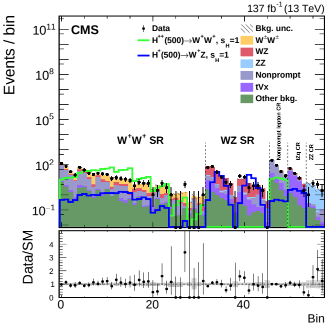


postfit m_T^{WZ} in WZ SR

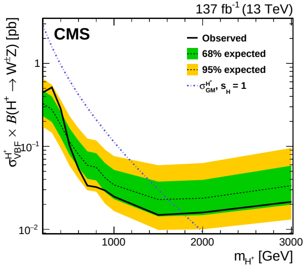


Binned ML fit using m_{jj} and m_{T}^{VV} in 2SRs and 3CRs:

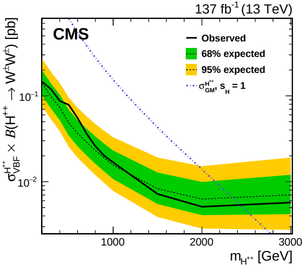
- Ignore H^{++} in $\sigma^{H^+}_{VBF} \cdot \mathcal{B}\left(H^{\pm} \to W^{\pm}Z^{0}\right)$
- Ignore H^{+} in $\sigma^{H^{++}}_{VBF} \cdot \mathcal{B}\left(H^{\pm\pm} \to W^{\pm}W^{\pm}\right)$
- Exclude $s_H > 0.20$–0.35 for $m_{H_5} = 0.2$–1.5 TeV
- Improved limits wrt previous CMS results
- Theoretically inaccessible ($\Gamma_{H_5} > 0.1 m_{H_5}$)



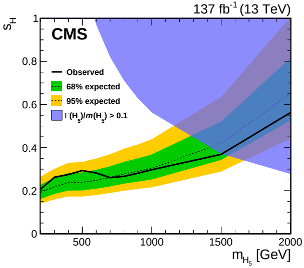
$H^{\pm} \to W^{\pm}Z^{0}$



$H^{\pm\pm} \to W^{\pm}W^{\pm}$

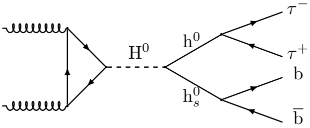


GM model interpretation



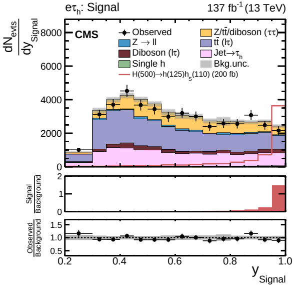
2HDM+S

Search for heavy H^0 decaying into observed h^0 and another Higgs boson h^0_s:

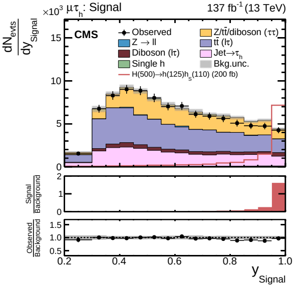


- Categorisation based on $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Require $1\ell 1\tau_h$ ($2\tau_h$), ≥ 2 jets, ≥ 1 b jets
- Three different background estimation methods:
  1. Genuine tau pairs ($\tau\tau$) with τ-embedding
  2. Misidentified τ_h (jet $\to \tau_h$) with misidentification rates
  3. Events with $Z/t\bar{t}$/Diboson decaying into prompt $\ell = e, \mu$ from simulation
- Up to 94% of background events estimated from data
- NN multiclassification with s+4b categories; Returns p-like score/category

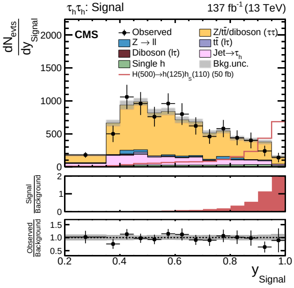
postfit NN in $e\tau_h$ SR



postfit NN in $\mu\tau_h$ SR



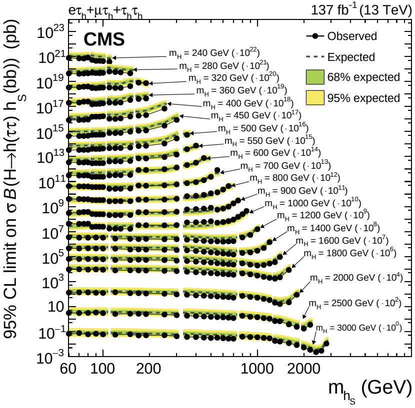
postfit NN in $\tau_h\tau_h$ SR



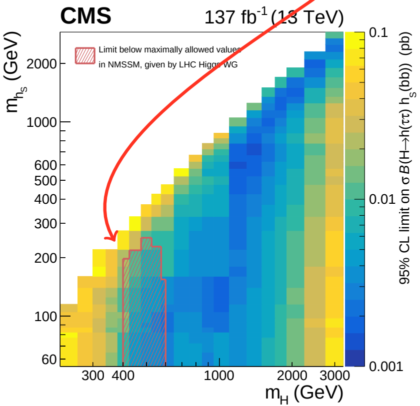
Due to 2 unknown signal masses, limits are derived as a function of m_{H^0} and m_{h_s}:

- For each set of mass points, fit discriminant is NN score — **68 trainings**
- All upper limits shown in a single figure by scaling values by orders of 10
- Upper limits of 125–2.7 fb for $m_{H^0} = 240$–1000 GeV ($m_{h_s} = 85$–250 GeV)
- NMSSM costrained for $400 \leq m_{H^0} \lesssim 600$ GeV and $60 \leq m_{h_s} \lesssim 200$ GeV

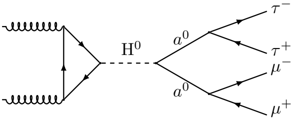
upper limits of 125–2.7 fb



summary of observed limits

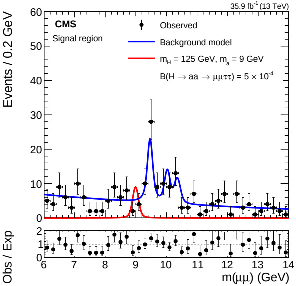


Search for light pseudoscalar a in VBF and ggF production of H^0:

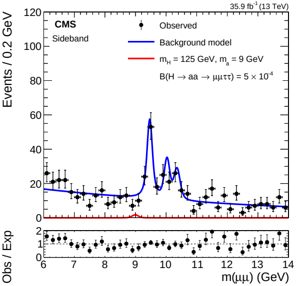


- Focus on $m_a \in [3.6, 21]$ GeV
- $\mathcal{B}(a \to \tau\tau)$ dominates — $m_a < 2m_b$
- Target $\mu\mu\tau_h\tau_\mu$ & exploit Lorentz boost — $m_{H^0} \gg m_a$
- Require 2μ & boosted τ-lepton pair $\tau_h\tau_\mu$
- Fit discriminants are $m_{\mu\mu}$ and $m_{\mu\mu\tau_h\tau_\mu}$
- Simult. unbinned fit in SR, CR & Sideband — **constrain norm & shape**

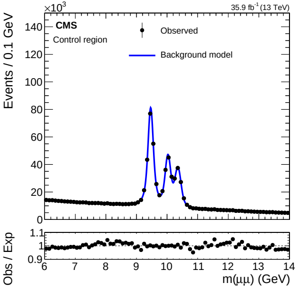
postfit $m_{\mu\mu}$ in SR



postfit $m_{\mu\mu}$ in Sideband



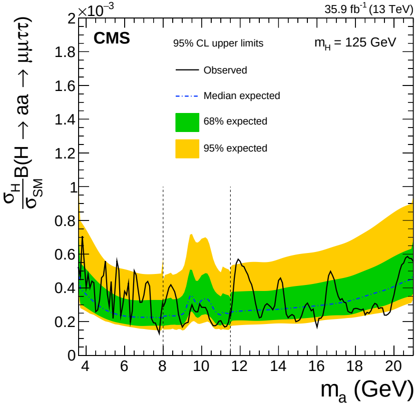
postfit $m_{\mu\mu}$ in CR



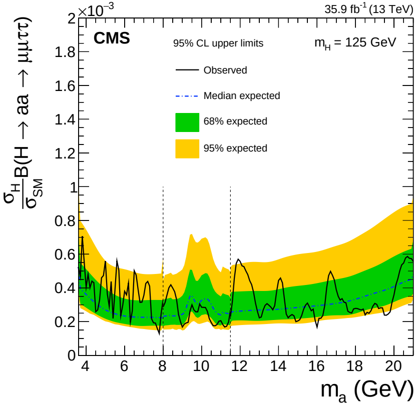
The 2D fit of $m_{\mu\mu}$ vs. $m_{\mu\mu\tau_h\tau_\mu}$ is performed in 3 ranges of the $m_{\mu\mu}$ spectrum:

- Signal modeled as Voigtian×split normal distribution $(m_{\mu\mu} \times m_{\mu\mu\tau_h\tau_\mu})$
- Bkg model accounts for exp. continuum & SM $\mu\mu$ resonances ← $J/\psi, \psi', \Upsilon$
- Model-independent limits on $\sigma_H \mathcal{B}(H^0 \to aa \to \mu\mu\tau\tau)$ for two values of m_{H^0}
- Model-specific limits on $\mathcal{B}(H^0 \to aa)$ also set ← types I–IV

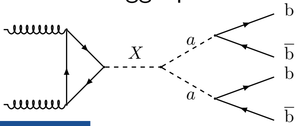
upper limits for $m_{H^0} = 125$ GeV



upper limits for $m_{H^0} = 300$ GeV

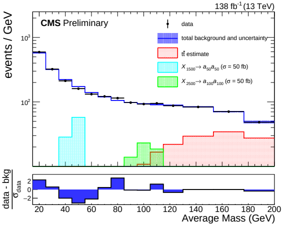


Search for massive resonance X decaying to two light scalars a in ggF production:

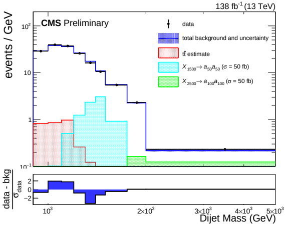


- Focus on $m_a \in [25, 100]$ GeV ; $m_X \in [1, 3]$ TeV
- $\mathcal{B}\left(a \to \mathrm{b}\overline{\mathrm{b}}\right)$ dominates ◀ $m_a > 2m_b$
- Target boosted topologies with overlapping b's ◀ $m_X \gg m_a$
- Large $\mathrm{H_T}$, 2 AK8 jets with double-b tagger
- Define SRs and CRs with 3 quantities:
  - Mass asymmetry $m_{\mathrm{asym}} = \frac{(\mathrm{m}_{j_1} - \mathrm{m}_{j_2})}{(\mathrm{m}_{j_1} + \mathrm{m}_{j_2})}$
  - Double-b tagging score of leading jet D^{bb}_{j1}
  - $\Delta\eta$ between the two AK8 jets

postfit $\mathrm{m}_{\bar{m}} = \frac{m_{j_1} + m_{j_2}}{2}$ in SRs



postfit $\mathrm{m}_{j_1 j_2}$ in SRs

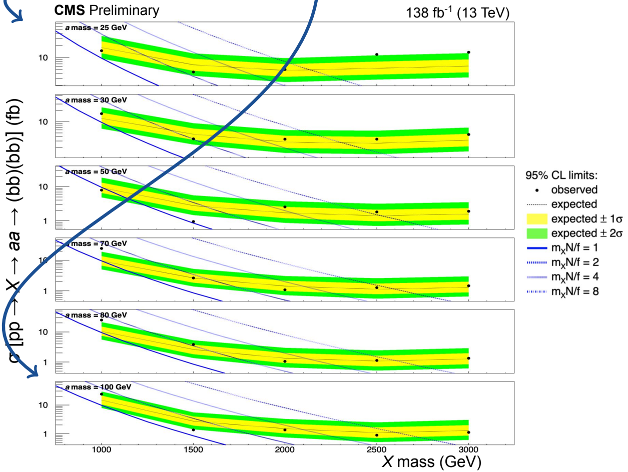


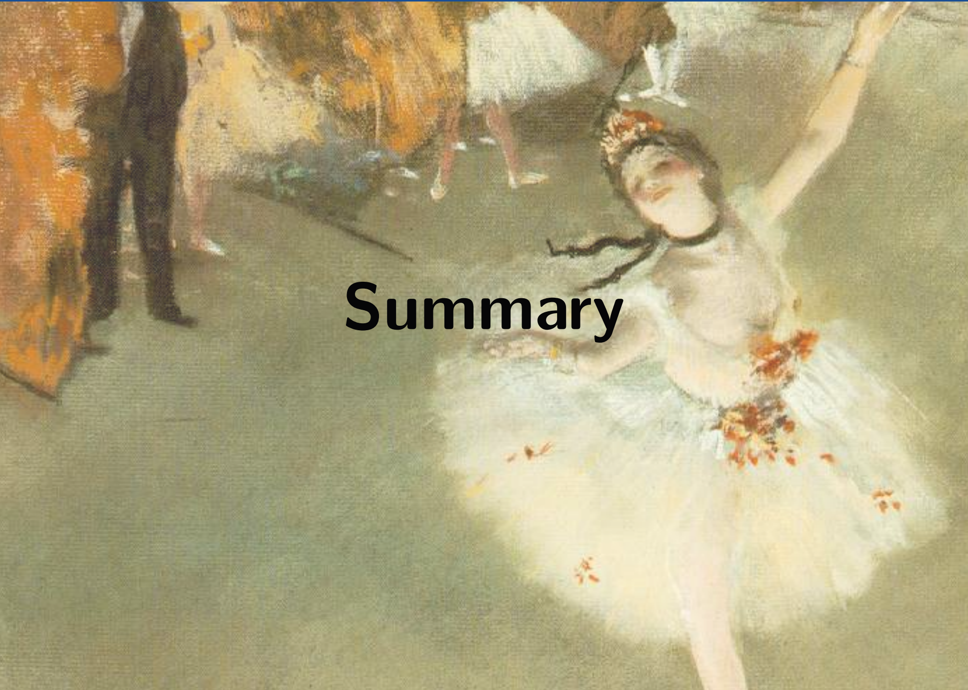
SRs and CRs used

	m_{asym}	$\Delta\eta$	D^{bb}_{j1}
tight search region	< 0.1	< 1.5	> 0.8
loose search region	$\in [0.1, 0.25]$	< 1.5	> 0.8
tight $\Delta\eta$ sideband	< 0.1	> 1.5	> 0.8
loose $\Delta\eta$ sideband	$\in [0.1, 0.25]$	> 1.5	> 0.8
tight double-b sideband	< 0.1	< 1.5	$[-0.8, 0.3]$
loose double-b sideband	$\in [0.1, 0.25]$	< 1.5	$[-0.8, 0.3]$

A 2D mass spectrum of $\mathrm{m}_{\bar{m}} = \frac{m_{j_1}+m_{j_2}}{2}$ and $\mathrm{m}_{j_1 j_2}$ is examined for localised excesses:

- Model-specific limits on $\sigma(\mathrm{pp} \to X) \propto \frac{m_X N}{f}$ ◀ **2HDM, NMSSM, Higgs Doublet**
- Assuming $\mathcal{B}(X \to aa) = \mathcal{B}\left(a \to \mathrm{b\bar{b}}\right) = 100\%$
- Upper limits of 1–30 fb for m_a = 25–100 GeV and m_X = 1–3 TeV ◀ **first limits**

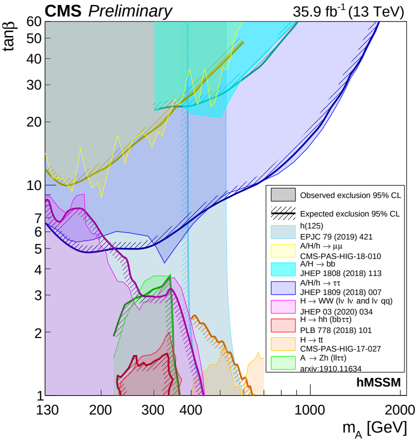


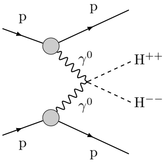


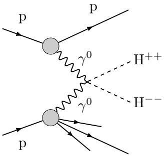
Summary

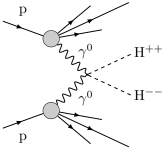
Presented latest searches for additional scalar bosons with CMS:

- New techniques complement $\times 4$ data
  - Improved ML methods
  - More categorisation
- No evidence for BSM physics observed
- Large part of parameter space excluded
- New results soon with full Run II data:
  - Direct searches above & below 125 GeV
  - Study of SM coupling modifications
  - Even more exotic searches . . . ?
- Stay tuned . . .









thank you.

Acknowledgements

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

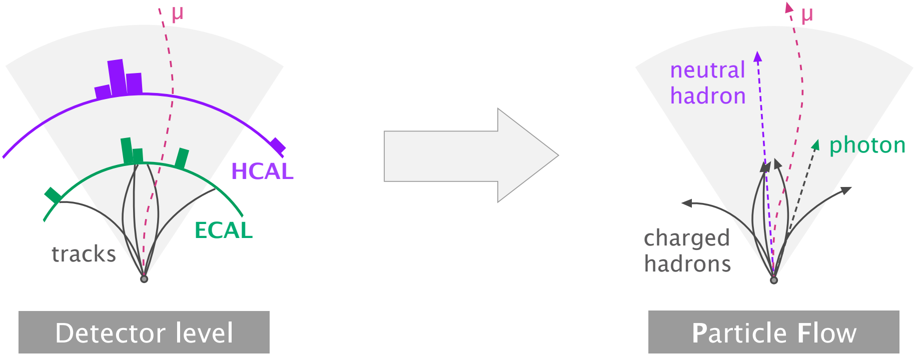
Different *benchmark scenarios* correspond to different sets of MSSM parameters:

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} ($X_t = A_t - \mu\cot\beta$)

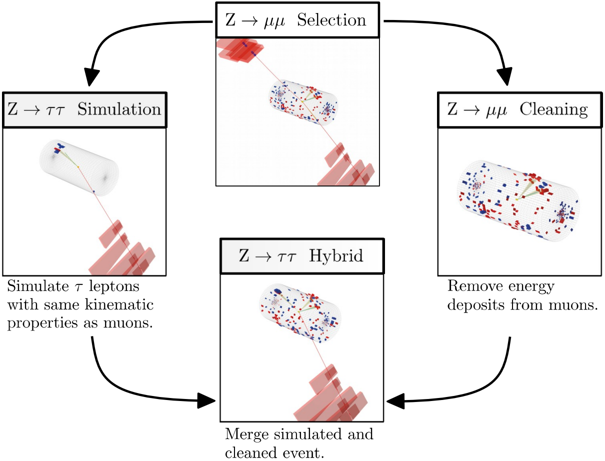
The PF algorithm aims to reco & id each particle in an event: arXiv:1706.04965

- Optimised combination of all subdetectors information
- The γ energy is obtained from the ECAL
- The e energy is determined from Tracker + ECAL
- The μ energy is obtained from its track curvature from Tracker + ECAL
- The $\pi^{\pm}$ energy is determined from Tracker + ECAL + HCAL
- The π^{0} energy is obtained from corrected ECAL + HCAL energy
- All higher-level objects (jets, b-jets, $p_{\mathrm{T}}^{\mathrm{miss}}$) are constructed from PF particles



Create hybrid event comprised of info from both observed and simulated events:

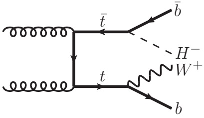
- Select $Z \to \mu\mu$ events in observed data
- Remove all μ-related energy deposits
- Simulate $\tau\tau$ events with same kinematic properties
- Merged μ-cleaned $Z \to \mu\mu$ with simulated $Z \to \tau\tau$ to get hybdrid



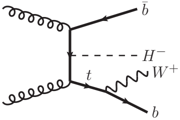
Three mass categories are commonly used in $\mathrm{H}^{\pm}$ searches:

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

double-resonant *t*



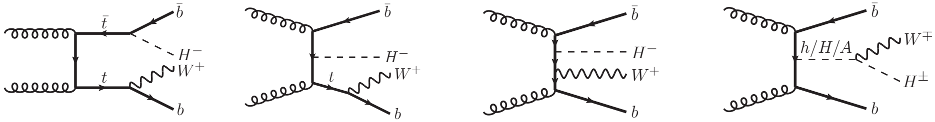
single-resonant *t*



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

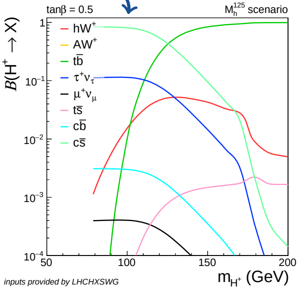
- Light $m_{\mathrm{H}^{\pm}} < m_{\mathrm{t}} - m_{\mathrm{b}}$, heavy $m_{\mathrm{H}^{\pm}} > m_{\mathrm{t}}$, intermediate $m_{\mathrm{H}^{\pm}} \sim m_{\mathrm{t}}$

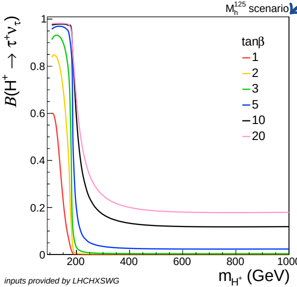
double-resonant t | single-resonant t | non-resonant t | neutral scalars

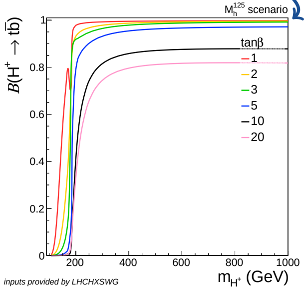


$\mathrm{H}^{\pm}$ decay BRs model-dependent $\Rightarrow$ different searches constrain different scenarios:

- Coupling to 3rd-gen fermions is strongest in type II $\Rightarrow$ Sensitive to $\tau\nu$ and tb
- The cs channel dominates at low $\tan\beta$ and low masses





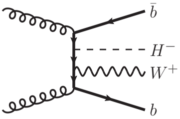


For intermediate H^+ a more involved computation is required due to:

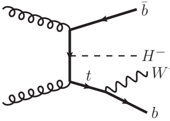
- Finite top-width effects
- Interference between resonant and non-resonant diagrams

The full process $\mathrm{pp} \to \mathrm{bW}^-\overline{\mathrm{b}}\mathrm{H}^+$ is required for reliable calculation: arXiv:1607.05291

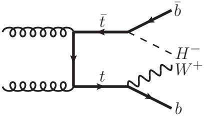
non-resonant *t*



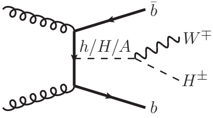
single-resonant *t*



double-resonant *t*



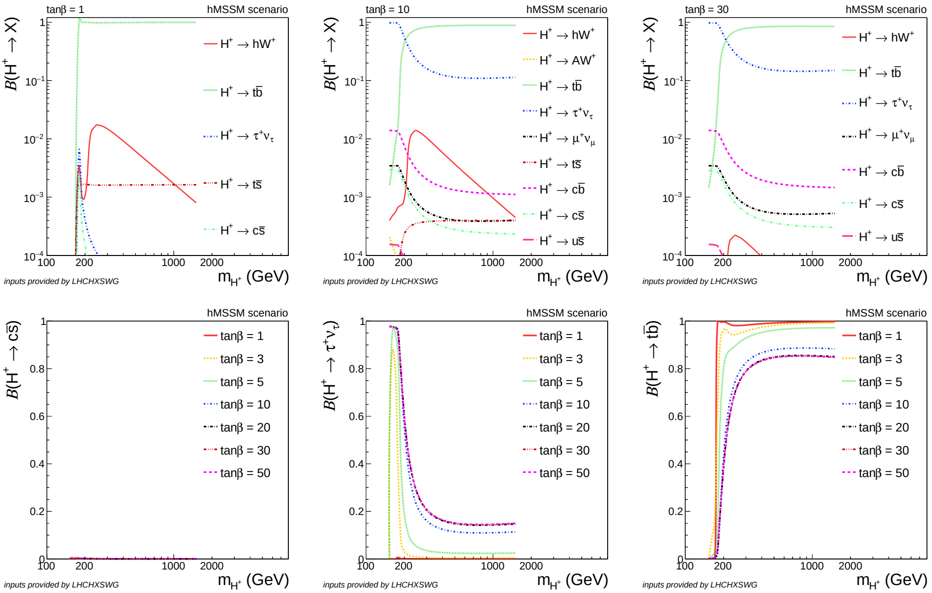
neutral scalars



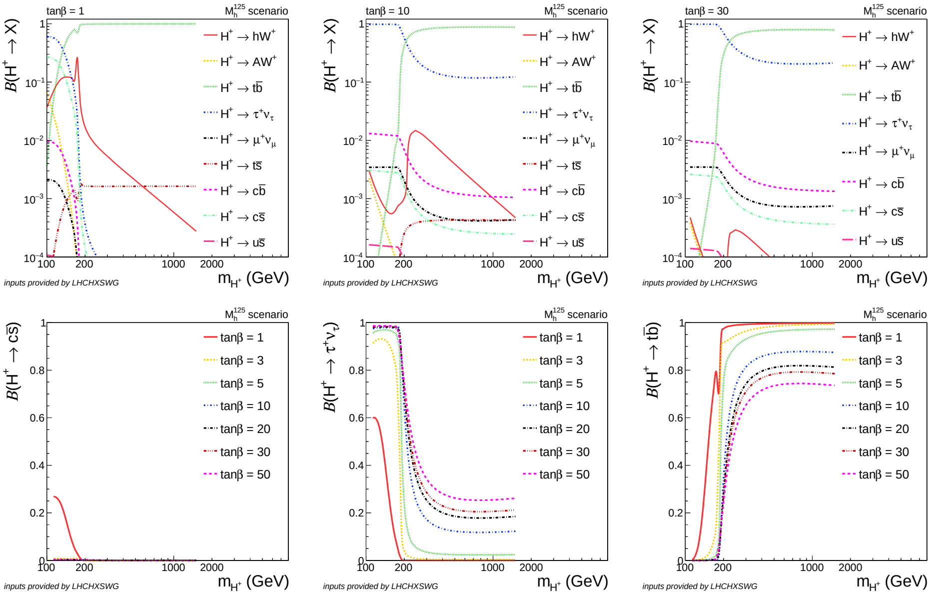
Recent predictions for the NLO cross section of $\mathrm{pp} \to \mathrm{bW}^-\overline{\mathrm{b}}\mathrm{H}^+$ at the LHC:

- Focus on Type II 2HDM
- Increase cross section by roughly 50% (wrt LO)
- Reduce uncertainties by more than factor of 2 (scale variations)

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

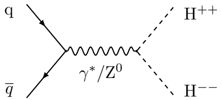


The $\mathrm{H}^{\pm}$ decay BRs in the M_h^{125} benchmark scenario are shown below:

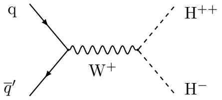


The doubly-charged Higgs boson can be produced via 3 main processes:

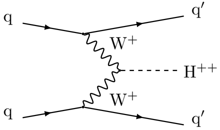
pair production (PP)



associated production (AP)

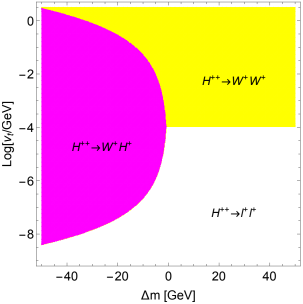


vector boson fusion (VBF)

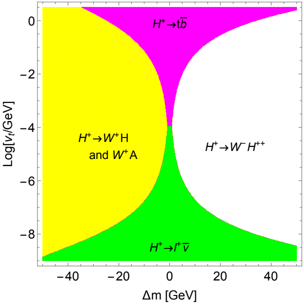


$H^{\pm\pm}$ decays have unique signatures which can be utilised in direct searches:

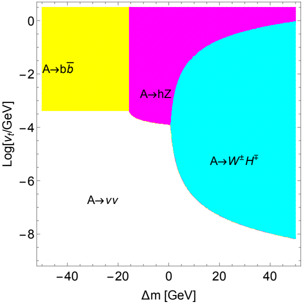
type II seesaw model



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

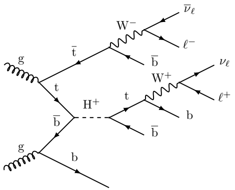


arXiv:1903.02493

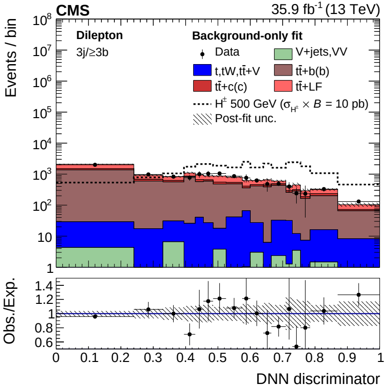


For the heavy $m_{H^{\pm}}$, the decay into top and bottom quarks is dominant:

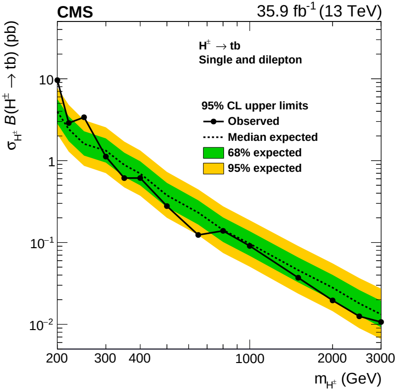
- Single lepton (ℓ) & OS dilepton ($\ell^{\pm}\ell^{\mp}$)
- Categorisation with jet & b-jets multiplicity
- Major bkg is leptonic decay of $W^{\pm}$ in $t\bar{t}$
- MVA techniques to enhance $\frac{S}{B}$ (BDT & DNN)



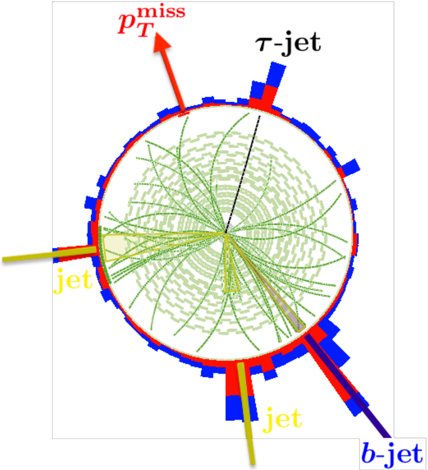
postfit DNN distribution for $\ell^{\pm}\ell^{\mp}$



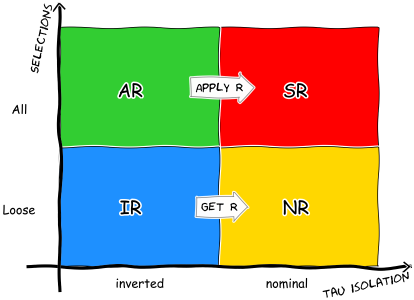
upper limit of 9.6 pb – 0.01 pb



1. Signal trigger ($\tau_h + p_T^{miss}$)
2. At least 1 **τ-jet** (trigger-matched):
   - $p_T^{\tau_h} > 50$ GeV, $|\eta|^{\tau_h} < 2.1$
   - $p_T^{ldg,tk} > 30$ GeV
   - 1-prong decays
   - Discriminators against e/μ
3. Isolated electron/muon veto:
   - $p_T^{e} > 15$ GeV, $|\eta|^{e} < 2.5$
   - $p_T^{\mu} > 10$ GeV, $|\eta|^{\mu} < 2.5$
4. At least 3 PF hadronic jets:
   - $p_T^{j} > 30$ GeV, $|\eta|^{j} < 4.7$
   - Separated from τ_h with $\Delta R > 0.5$
5. From selected jets, at least 1 **b-jet**:
   - $p_T^{b} > 30$ GeV, $|\eta|^{b} < 2.5$
   - Tagged with CSV algorithm (medium)
6. $p_T^{miss} > 90$ GeV
7. Angular selection $R_{bb}^{min} > 40°$
8. $R_\tau = p_T^{ldg,tk} / p_T^{\tau_h}$ categories (≤ 0.75, > 0.75)



Backgrounds with genuine τ_h and $e/\mu \to \tau_h$ events estimated from simulations.
Misidentified τ_h background is measured with fake rate method:



- signal region (SR)
- application region (AR)
- inverted region (IR)
- normalisation region (NR)

- Use samples enriched in misidentified taus by inverting τ_h isolation
- Calculate transfer factors (R) from IR to NR (jet $\to \tau_\mathrm{h}$ enriched regions):

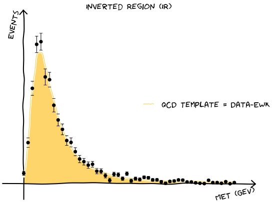
$$R_{\mathrm{IR}\to\mathrm{NR}} = \frac{N_{NR}}{N_{IR}} \simeq R_{\mathrm{AR}\to\mathrm{SR}} \quad (1)$$

- Apply $R_{\mathrm{IR}\to\mathrm{NR}}$ to the AR to estimate jet $\to \tau_\mathrm{h}$ in the SR

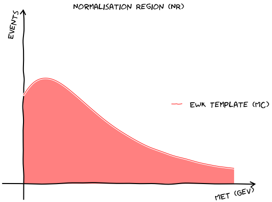
The transfer factors are calculated separately (different q/g content):

- For EWK (includes $\mathrm{t\bar{t}}$) from simulation as $R^{\mathrm{EWK}}_{\mathrm{IR}\rightarrow\mathrm{NR}} = \frac{N^{\mathrm{EWK\ MC}}_{\mathrm{NR}}}{N^{\mathrm{EWK\ MC}}_{\mathrm{IR}}}$
- For QCD from binned ML fit of $p_{\mathrm{T}}^{\mathrm{miss}}$ templates to data as:
  - $R^{\mathrm{QCD}}_{\mathrm{IR}\rightarrow\mathrm{NR}} = \frac{f^{\mathrm{fit}}_{\mathrm{QCD}} \cdot N^{\mathrm{Data\ Fit}}_{\mathrm{NR}}}{N^{\mathrm{QCD\ Fit}}_{\mathrm{IR}}}$
  - The fraction of QCD events, $f^{\mathrm{fit}}_{\mathrm{QCD}}$, is a fit parameter.

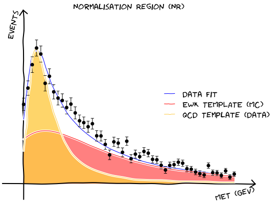
QCD Fit



EWK Fit



Final Fit



The combined transfer factor is defined as a weighted average:

- $R_{\mathrm{IR}\rightarrow\mathrm{NR}} = w^{QCD}_{AR} \cdot R^{\mathrm{QCD}}_{\mathrm{IR}\rightarrow\mathrm{NR}} + (1 - w^{QCD}_{AR}) \cdot R^{\mathrm{EWK}}_{\mathrm{IR}\rightarrow\mathrm{NR}}$

with w^{QCD}_{AR} being the QCD purity in AR.

The measurement is performed in p_{T} and $|\eta|$ bins of the τ_h to:

- Minimise correlations of the $p_{\mathrm{T}}^{\tau_h}$ - $p_{\mathrm{T}}^{\mathrm{miss}}$ variables
- Mitimage geometrical differences in detector response

$\therefore$ The jet $\rightarrow \tau_{\mathrm{h}}$ background measurement in the SR is thus given by:

$$N_{\mathrm{SR}}^{\mathrm{jet} \rightarrow \tau_{\mathrm{h}}} = \sum_{i}^{\tau_h \ \mathrm{bins}} (N_{\mathrm{AR,\ i}}^{\mathrm{Data}} - N_{\mathrm{AR,\ i}}^{\mathrm{EWK\ genuine}\ \tau_h} - N_{\mathrm{AR,\ i}}^{\mathrm{EWK}\ \mathrm{e}/\mu \rightarrow \tau_h}) \times R_{\mathrm{IR} \rightarrow \mathrm{NR}} \tag{2}$$

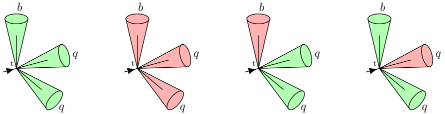
The systematics uncertainties accounted for include:

- The $R_{\mathrm{IR} \rightarrow \mathrm{NR}}$ stat. uncertainties (normalisation uncertainty)
- Difference in the m_{T} shape in SR and AR (shape uncertainty)
- All uncertainties related to the simulated samples

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

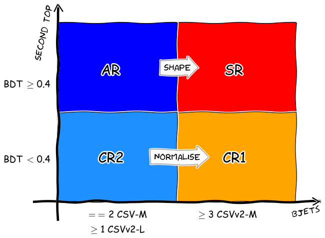
Boosted $W^\pm$	Boosted t
$\tau_{21}^{W} < 0.6$	$\tau_{32}^{top} < 0.67$
$m_{SD}^{W} \in [65, 105]$	$m_{SD}^{top} \in [135, 220]$
0 b-subjets	0 or 1 b-subjets

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

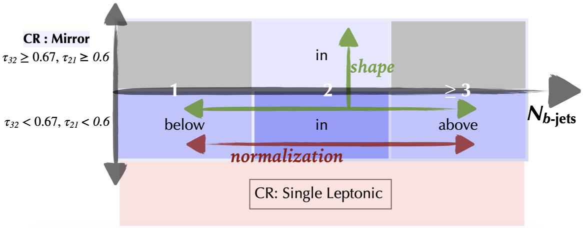


- Minor Genuine-b estimated from simulation
- Main Fake-b measured from data by inverting top- & b-tagging selections

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

i runs over p_{T} and η bins

Boosted $\mathrm{W}^{\pm}/t$



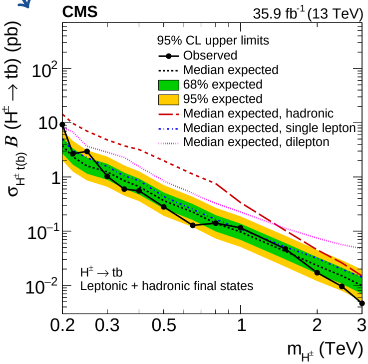
- Dominant QCD multijet ($\sim 90\%$)
  - Shape from **CR: Mirror** (invert τ_{21}^{W} and τ_{32}^{top})
  - Norm from below/above $\Delta m_{\mathrm{H}^{\pm}}$ (sidebands)
- $\mathrm{t\bar{t}}$ with **CR: Single Leptonic**
  - 1ℓ with $10 < p_{\mathrm{T}} < 35$ GeV
- The CRs and SRs are simultaneously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

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

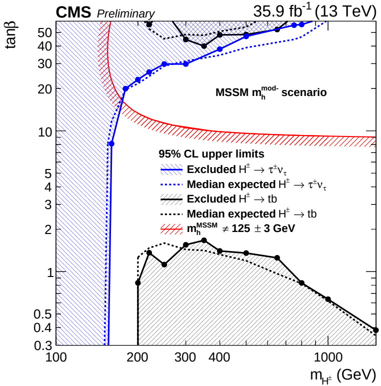
- Single lepton dominates entire $m_{H^\pm}$ spectrum
- Dilepton sensitive at low $m_{H^\pm}$ region ($\sim 20\%$ gain)
- Hadronic $\sim$comparable to dilepton at low $m_{H^\pm}$
- Hadronic competes with Single lepton at 3 TeV ($\sim 30\%$ gain)

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

upper limit of 9.25 pb – 5 fb

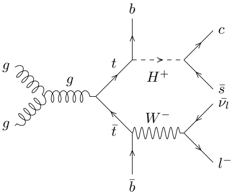


interpretation in m_h^{mod-} scenario

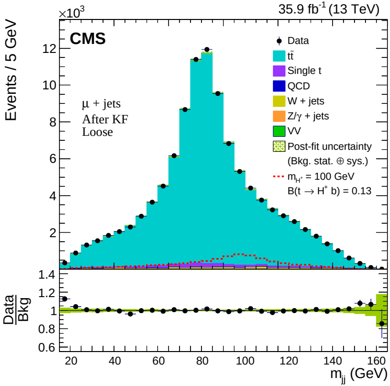


In type II 2HDMs a light $m_{H^{\pm}}$ decays predominantly to cs for low $\tan\beta$ values:

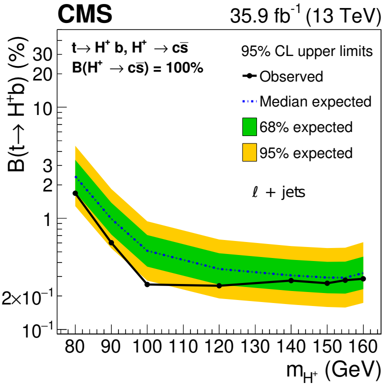
- Require 1ℓ, ≥ 4 jets (≥ 2 b-tagged), p_T^{miss}
- Top kinematic fit (KF) with m_t constraints
- Categorisation based on c-tagging (L,M,T)
- Fit discriminant is m_{jj} of 2 non-b jets



postfit dijet mass after KF on objects (T)

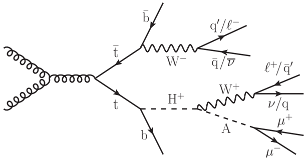


upper limit of 1.68-0.25% on $\mathcal{B}\left(t \to bH^{+}\right)$

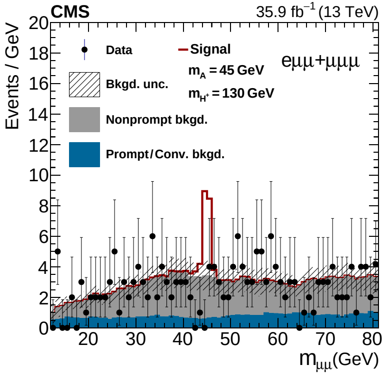


First LHC search for light $m_{H^\pm}$ decaying to *WA* in any range of $m_{H^\pm}$:

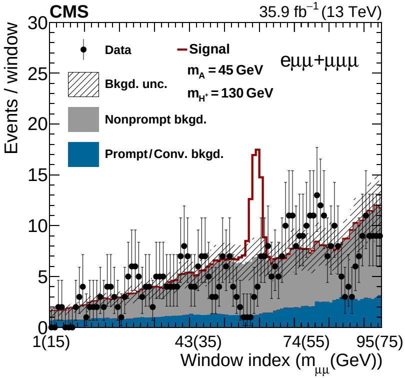
- Target $e\mu\mu$ or $\mu\mu\mu$ with $A^0 \to \mu^+\mu^-$
- $\mathcal{B}\left(A^0 \to \mu^+\mu^-\right)$ small but high $\varepsilon^\mu_{\text{ID}}$ and $\frac{\sigma(p^\mu_T)}{p^\mu_T}$
- Major bkg is $t\bar{t}$ with nonprompt leptons
- Excess search in mass windows *w* of $m_{\mu^+\mu^-}$



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

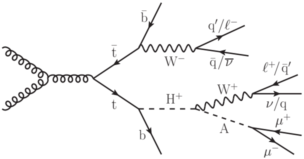


w optimised to maximise median significance

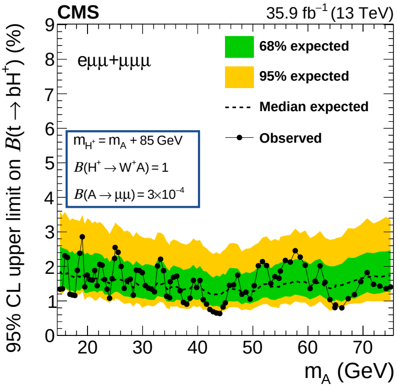


Upper limits at 95% CL on $\mathcal{B}(t \to bH^+) \cdot \mathcal{B}(H^\pm \to W^\pm A^0) \cdot \mathcal{B}(A^0 \to \mu^+\mu^-)$:

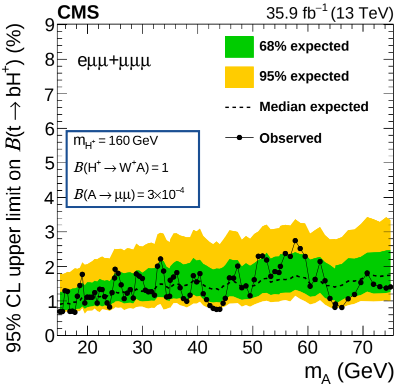
- Based event yields in w from $e\mu\mu$ & $\mu\mu\mu$
- Upper limit between 0.63 – 2.9%
- Sensitivity dominated by stat. uncertainty
- Limit difference smaller than uncertainties



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

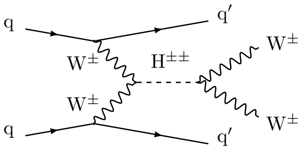


$m_{H^\pm} = 160$ GeV

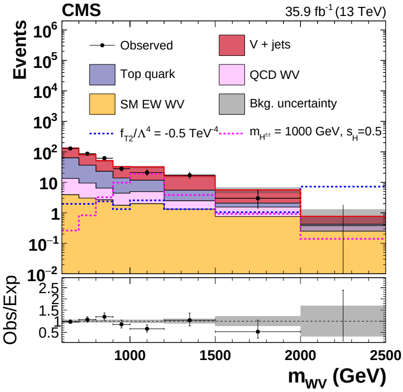


In the GM model $H^{\pm}$ and $H^{\pm\pm}$ are produced via VBF:

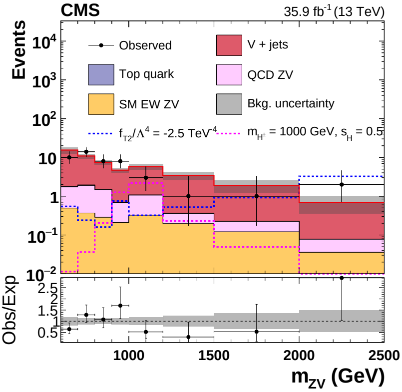
- Semileptonic *WV* (1ℓ) and *ZV* (2ℓ) decays
- Hadronic *V* reconstructed as AK8 ($\tau_{21}^{V} < 0.55$)
- Leptonic *W* reconstructed from solving the p_z^{ν}
- Major bkg is W+jets (WV) and Z+jets (ZV)



Signal extraction with fit to m_{WV}

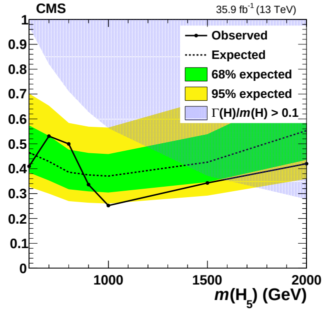


Signal extraction with fit to m_{ZV}

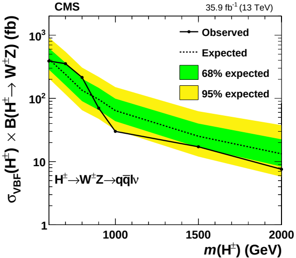


- Use WV & ZV to extract limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}\left(\text{H}^{\pm} \to \text{W}^{\pm}\text{Z}^{0}\right)$
- Use WW channel to extract limits on $\sigma_{\text{VBF}} \cdot \mathcal{B}\left(\text{H}^{\pm\pm} \to \text{W}^{\pm}\text{W}^{\pm}\right)$
- Combine WV, ZV, WW for GM model limits
- Exclude $s_H > 0.53$ for $m_{\text{H}_5} = [0.6, 2]$ TeV
- Theoretically inaccessible

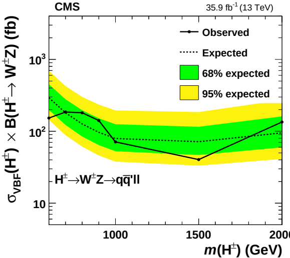
interpretation in GM model



WV channel



ZV channel



WW channel