Searches for charged Higgs bosons at CMS

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on behalf of the CMS Collaboration

EPS, Ghent, Belgium
Jul-12th-2019

Charged Higgs bosons are predicted in many Standard Model (SM) extensions

- Two-Higgs-doublet model (2HDM) — Minimal extension of SM
  - Five physical scalar states: h, H, A, **H^+, H^-**
  - Different types based on the couplings of the fermions to the doublet

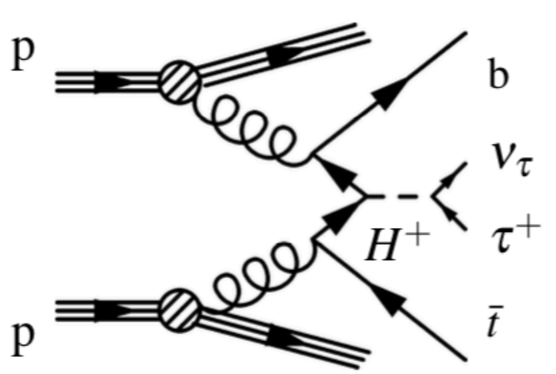
Model	Type I	Type 2	Lepton-Specific	Flipped
Φ_1	–	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

arXiv:1002.4916

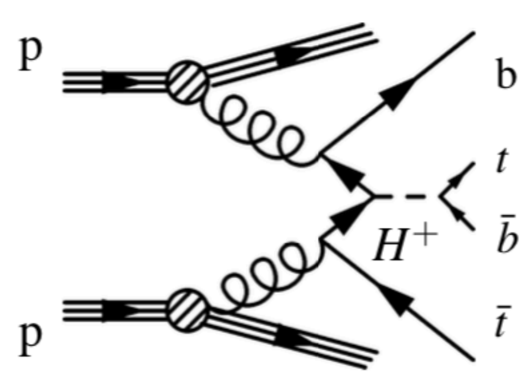
  - Coupling to third generation fermions is the strongest in Type2
    -> Sensitive to searches in ***tb*** and ***τν*** final states

- Higgs triplet models
  - Charged Higgs bosons appear in Higgs sectors extended by a scalar triplet Φ
  - Couplings to **W** and **Z** bosons at tree level
  - Georgi-Machacek model: one real and one complex SU(2) triplet

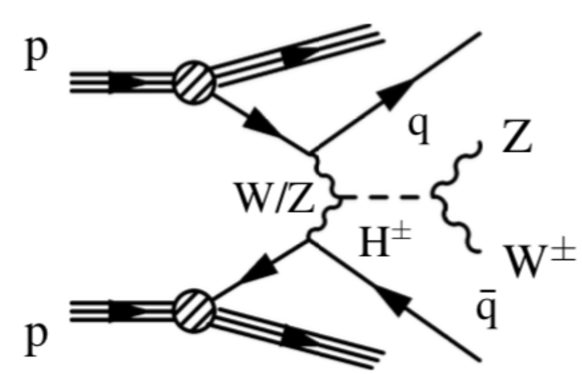
$gg \to H^+$



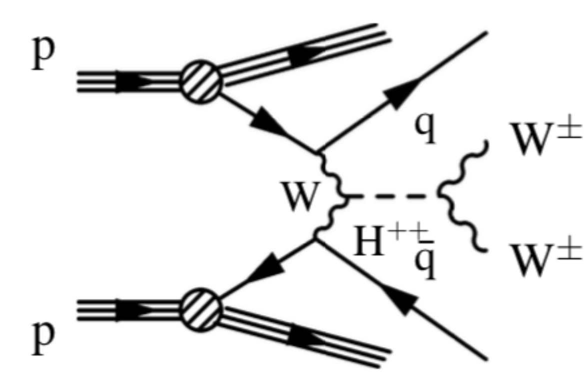
$gg \to H^+$



$q\bar{q} \to H^\pm \to ZW^\pm$



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



Overview of Run II Charged Higgs Searches

80 GeV — 160 GeV — m_{top} — 180 GeV — 3 TeV — $m_{H^\pm}$

Light Mass Regime

- $H^\pm \to \tau^\pm\nu_\tau$ CMS-HIG-18-014 arXiv:1903.04560
  - leptonic + hadronic
  - 80 - 160 GeV
- $H^\pm \to W^\pm A$ CMS-HIG-18-020 arXiv:1905.07453
  - in $e\mu\mu$ or $\mu\mu\mu$ final states
  - 100 - 160 GeV

$W^\pm A$ & tb Covered in this talk

Intermediate Mass Regime

- $H^\pm \to \tau^\pm\nu_\tau$ CMS-HIG-18-014
  - leptonic + hadronic
  - 160 - 180 GeV
  - first to probe intermediate mass regime

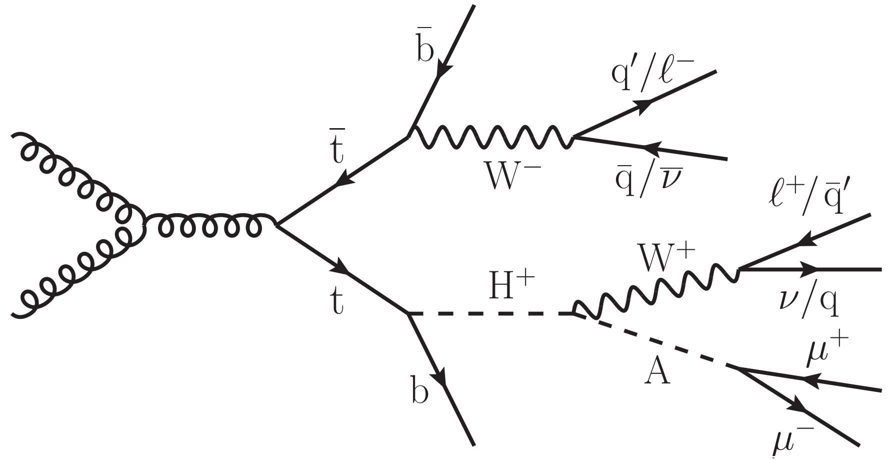
Heavy Mass Regime

- $H^\pm \to \tau^\pm\nu_\tau$ CMS-HIG-18-014
  - leptonic + hadronic
  - 180 GeV - 3 TeV
- $H^\pm \to tb$
  - leptonic (CMS-PAS-HIG-18-004) + hadronic (CMS-PAS-HIG-18-015) NEW
  - 200 GeV - 3 TeV
- $H^\pm \to W^\pm Z$ CMS-HIG-16-027 (15.2 fb^{-1}) arXiv:1705.02942
  - multi-leptonic CMS-SMP-18-001 arXiv:1901.04060
    - 200 GeV - 2 TeV
  - semi-leptonic CMS-SMP-18-006 arXiv:1905.07445
    - 600 GeV - 2 TeV
- $H^{\pm\pm} \to W^\pm W^\pm$
  - multi-leptonic CMS-SMP-17-004 arXiv:1709.05822
    - 200 GeV - 1 TeV
  - semi-leptonic CMS-SMP-18-006
    - 600 GeV - 2 TeV

$H^\pm \rightarrow W^\pm A$: Overview

CMS-HIG-18-020

- Targeted ***eμμ*** or ***μμμ*** final states: $t\bar{t} \rightarrow bH^+\bar{b}W^- \rightarrow b\bar{b}W^+W^-A;\ W^+W^- \rightarrow l\nu q\bar{q}',\ \boldsymbol{A \rightarrow \mu^+\mu^-}\ (\ell = e,\mu)$
  - Advantages at low p_T : efficient identification, better momentum resolution, pileup robustness
  - **First** search **in this process** in any range of $m_A/m_{H^\pm}$ and any $H^\pm$ production mode
- **First model-independent** search in this mass region for any decay of A



m_A:15 - 75 GeV, $m_{H^\pm}$:100 -160 GeV, $m_{H^\pm} > mA + mW$

- Background Estimation
  - Main background: Jet-induced **nonprompt leptons** (~70%)
    - Estimated with data-driven **tight-to-loose ratio method**
      - Apply extrapolation factors on observed ID composition
      - Factors measured in control regions
  - Others: Prompt trilepton (~ 20%), Conversion (< ~10%), …
    - Estimated from simulation

$N_{nonprompt} = N_{2P1N} + N_{1P2N} + N_{3N}$ in SR($N_{3\ \text{tight ID}}$)

(P : Prompt; N: Nonprompt)

$H^\pm \to W^\pm A$: Search Strategy

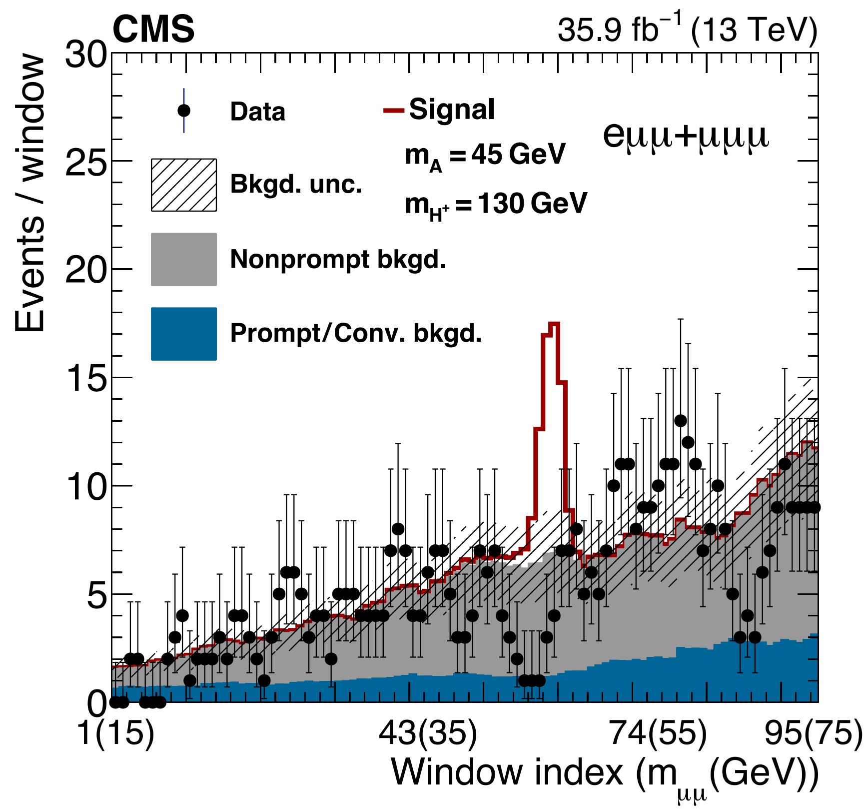
$A \to \mu^+\mu^-$

- Exactly 3 tight leptons (1 opposite-sign muon pair), no additional loose lepton
- Opposite-sign muon pair selection for $\mu^\pm\mu^\pm\mu^\mp$ final state
  - One with different charge $\mu^\mp \to A$
  - The same-sign muon pair $\mu^\pm\mu^\pm$ (backup p16)
    - The one more likely from A
    - Usually the one with lower p_T

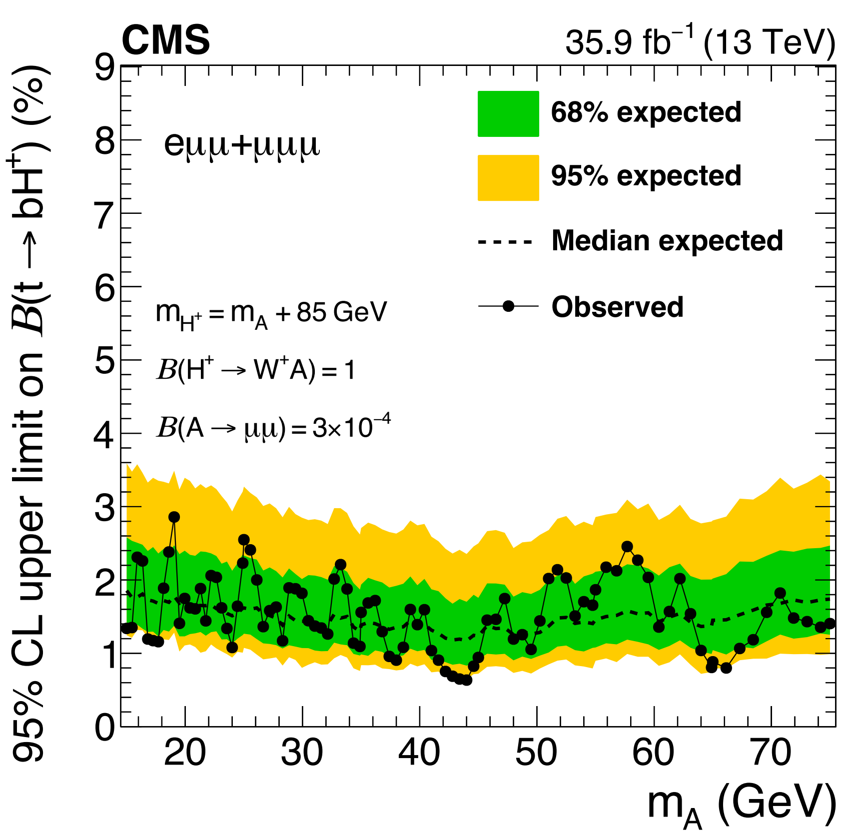
- A narrow resonance in mass windows of $\mathbf{m_{\mu\mu}}$ spectrum is searched
  - Advantage over **poor resolution of $\mathbf{m_{H^\pm}}$**
  - **Width(ω) of windows are optimized**(in 10 GeV step of m_A) to maximize expected significance
    - $\sqrt{2[(n_s + n_b)\ln(1 + n_s/n_b) - n_s]}$ (G. Cowan et al, Ref.[8])
  - Windows are placed in steps of 0.45–1.15 GeV for m_A
    - Yields in those windows obtained by interpolation of the yields of simulated samples

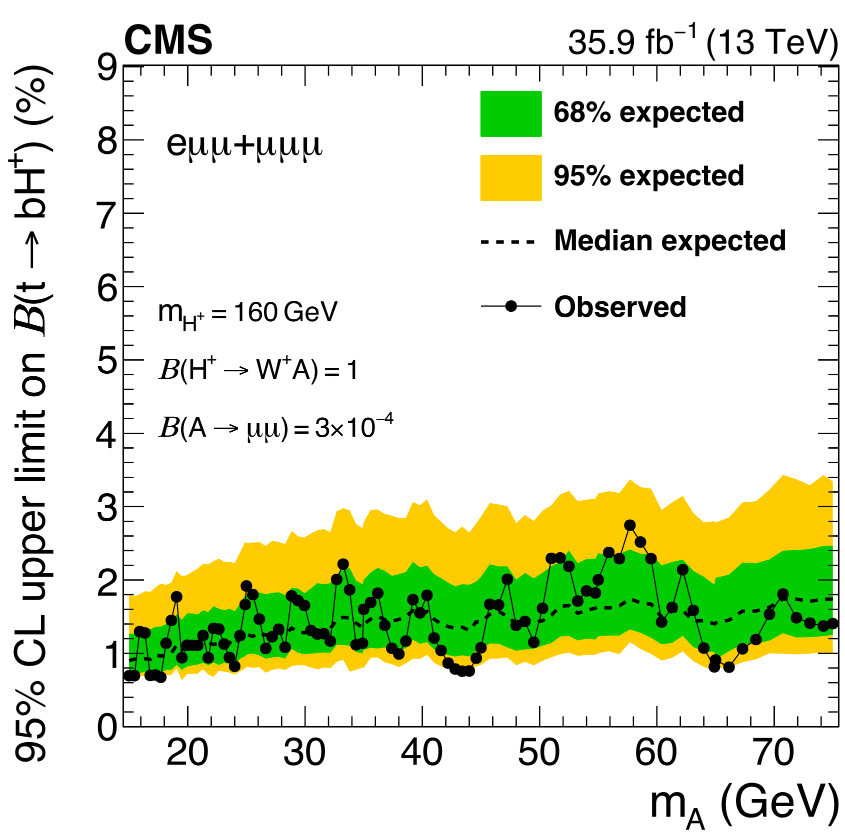
m_A range (GeV)	[15, 25)	[25, 35)	[35, 45)	[45, 55)	[55, 65)	[65, 75)	75
Window index	1–23	24–42	43–59	60–73	74–85	86–94	95
m_A step (GeV)	0.45	0.55	0.6	0.75	0.9	1.15	—
w (GeV)	[0.5, 0.7)	[0.7, 0.8)	[0.8, 1.0)	[1.0, 1.2)	[1.2, 1.5)	[1.5, 1.8)	1.8

95 mass points in total



- $(m_{H^{\pm}}, m_A) = (130,45)$ GeV, assuming $\sigma(t\bar{t}) = 832$ pb, $\mathcal{B}(t\rightarrow bH^{\pm}) = 0.02$, $\mathcal{B}(H^{\pm}\rightarrow W^{\pm}A) = 1$, $\mathcal{B}(A\rightarrow \mu^{+}\mu^{-}) = 3\text{x}10^{-4}$
- Mass window index used (window center in () in GeV unit)
- **No statistically significant excess is found** in any of the signal mass windows





- Left : $m_{H+} = m_A + 85$ GeV
- Right : $m_{H+} = 160$ GeV
- $\mathcal{B}(t\rightarrow bH^{\pm}) > 2.9\%$ is excluded at 95% CL in the entire search region
  - **First** limits on $\mathcal{B}(t\rightarrow bH^{\pm})$ in this decay mode

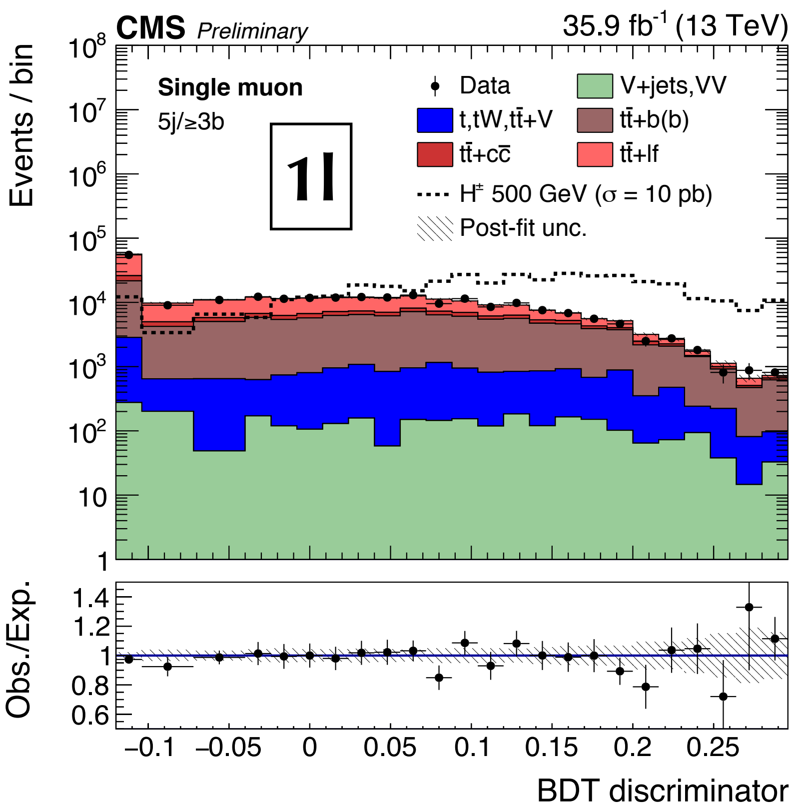
$H^{\pm} \rightarrow tb$ leptonic: Overview

CMS-PAS-HIG-18-004

- Highest branching fraction for a large spectrum of tanβ
- Both **single-lepton**(1l: *e or* μ) and **di-lepton** (2l: *ee*, $\mu\mu$, *e*μ) final states targeted
- Events categorized by **jet** and **b-jet multiplicity**

SR:Signal Region — CR : Control Region

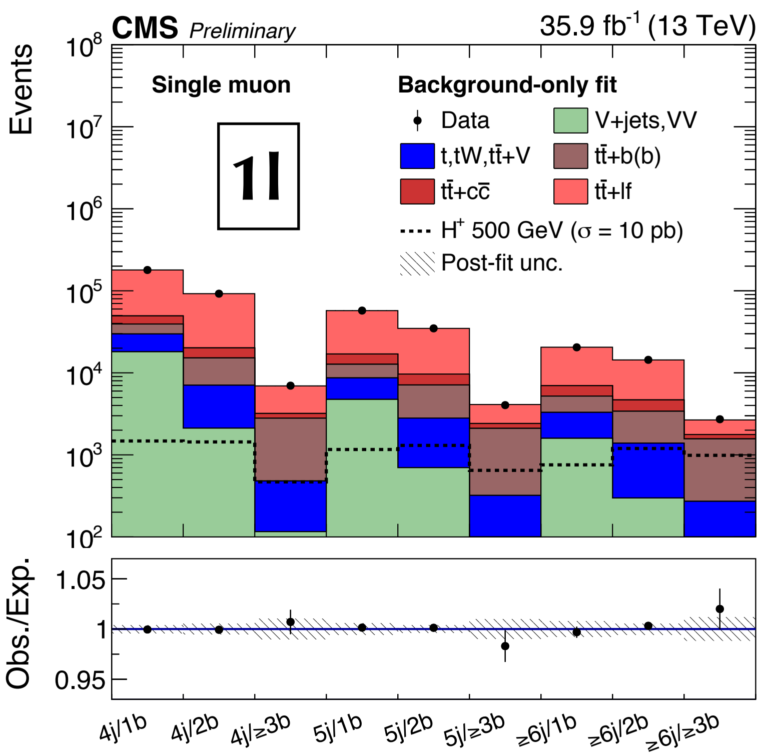
Number of jets (1l)	Number of jets (2l)	1 b-jet	2 b-jets	≥3 b-jets
≥6	≥4	CR	SR	SR
5	3	CR	SR	SR
4	2	CR	CR	SR

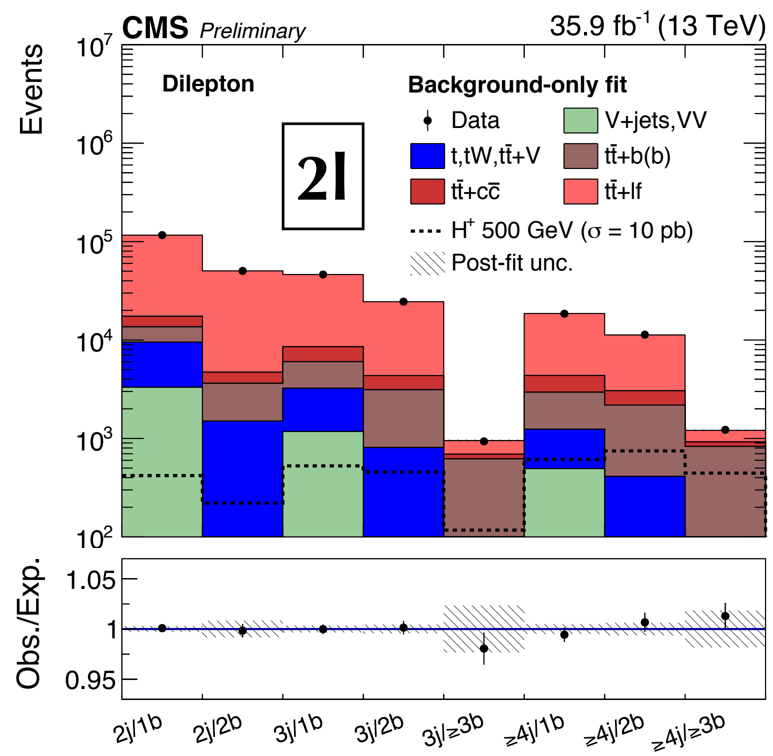


- Multivariate analysis used: trained against $t\bar{t}$
  - Variables sensitive to signal/$t\bar{t}$ separation (backup p17)
  - **1l : BDT** : Trained in inclusive ≥ 5 jets, ≥ 2 b in total 4 SRs
  - **2l : DNN**: Trained in inclusive ≥ 3 jets, ≥ 1 b regions
- Simultaneously fit performed across all regions
  - **1l : SR:** Output BDT discriminator distributions + **CR:** Event yields
  - **2l : SR + CR:** Output DNN discriminator distributions

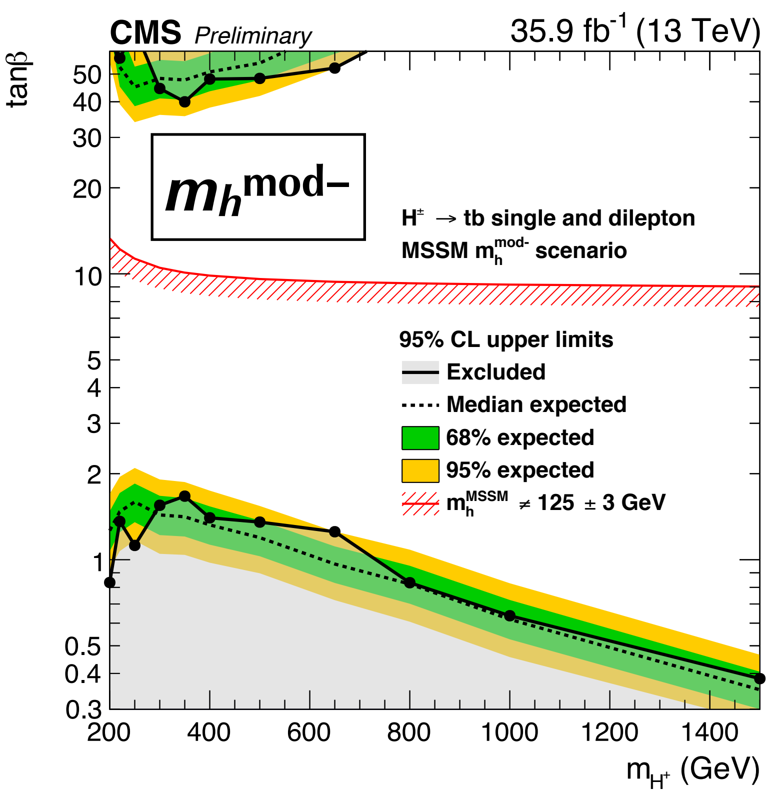
- Background estimation
  - Dominate background : $\mathbf{t\bar{t}}$ (>~80%) : Split in **light ($t\bar{t}$ + LF)** and **heavy flavor ($t\bar{t}$ + b and $t\bar{t}$ + cc)**
    - **Light** : constrained by simultaneous fit with control regions
    - **Heavy** : left freely float in fit
  - Others — electroweak, single-top, … : Estimated from simulation

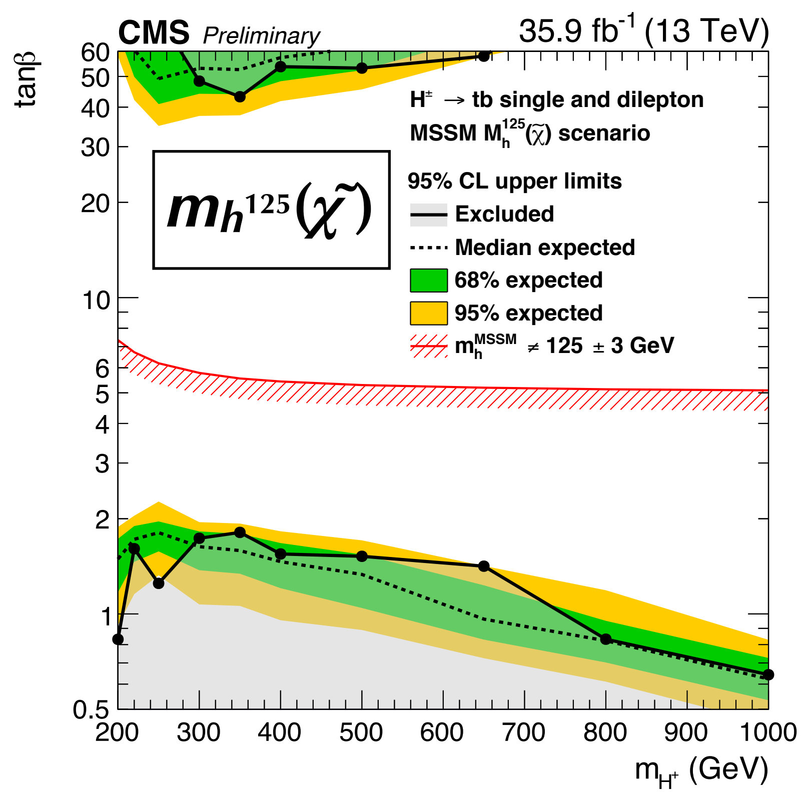
H± → tb leptonic: Results

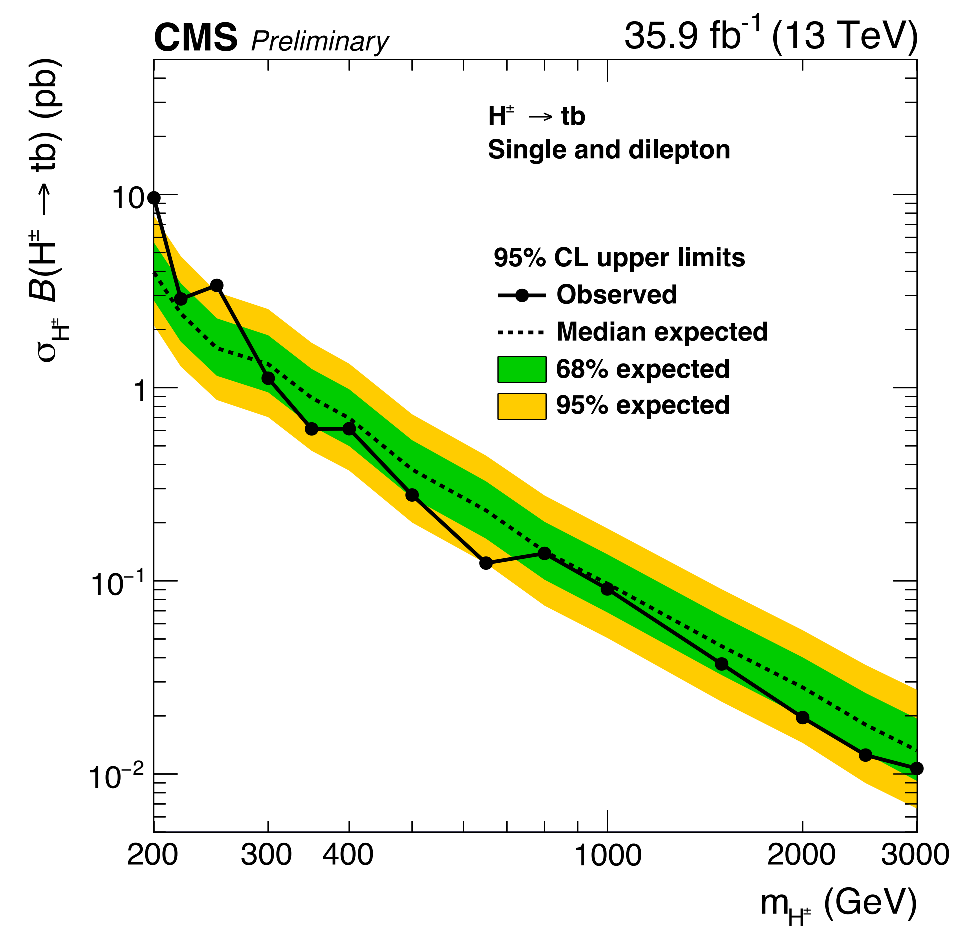




- **No excess observed** in all categories
- Upper limits set with **1l + 2l combined**
- Excluded parameter space shown in $m_h^{\text{mod-}}$ and $m_h^{125}(\tilde{\chi})$ scenario
  - High values of $\tan\beta$ ~ 40–60 is excluded
  - Low values of $\tan\beta$ ~ 0.4–1.5 (0.6–1.5) are excluded in the $m_h^{\text{mod-}}$ ($m_h^{125}(\tilde{\chi})$) scenario







$H^{\pm} \rightarrow tb$ hadronic: Overview

CMS-PAS-HIG-18-015

NEW

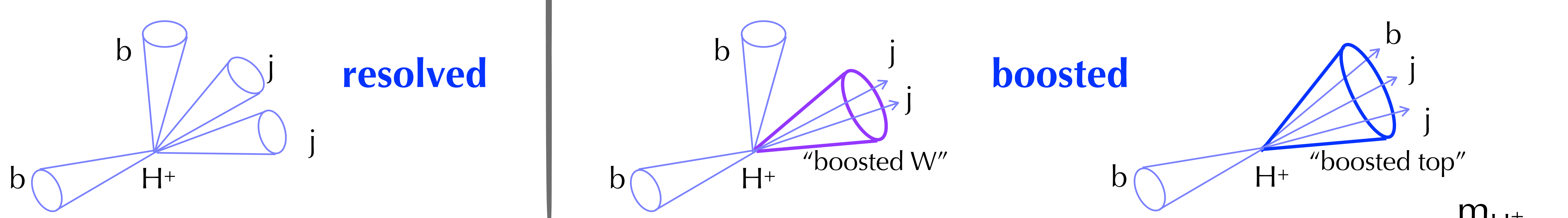
- Large branching ratio + the whole Higgs can be reconstructed
- Lower $m_{H^{\pm}}$ → all the decay products are well separated → **resolved**
- $m_{H^{\pm}}$ increases → decay products become **boosted** → **boosted W**(2 merged jets)/**top**(3 merged jets)

- ≥ 7 jets, ≥ 3 b-tags
- **Custom top-tagger** trained with **BDT**

  arXiv:1707.03316

  - Form trijet combination (1b+2j)
    - Signal : all 3 components match
    - Background : all others
  - Train in $t\bar{t}$ samples
  - 2 tops with BDT score ≥ 0.40

- ≥ 1 AK8jet, ≥ 1 b-tag
- **Jet substructure** used for **top/W identification**
  - N-subjettiness : τ_{21} (W) & τ_{32} (top)
  - Soft drop mass (SDMass)
  - Number of b-subjet
    - W : none
    - top : separate into 2 categories: **0 (t0)** and **1(t1)**



H± → tb hadronic: Strategy

CMS-PAS-HIG-18-015

NEW

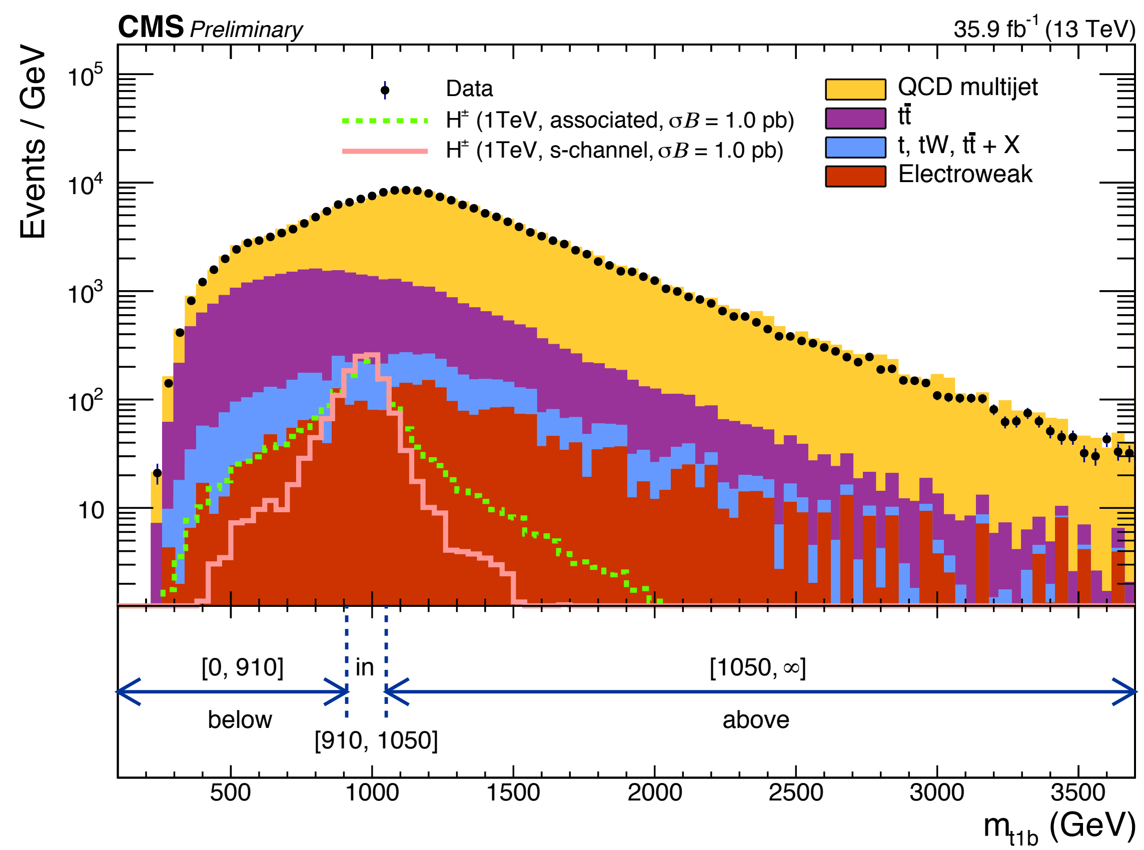
resolved | **boosted** → $m_{H^\pm}$

resolved

- Reconstruct a tetrajet object invariant mass($\mathbf{m_{jjbb}}$)
  - The leading in p_T top
  - The leading in p_T free b-jet
- An excess is searched for in the invariant mass ($\mathbf{m_{jjbb}}$) spectrum

boosted

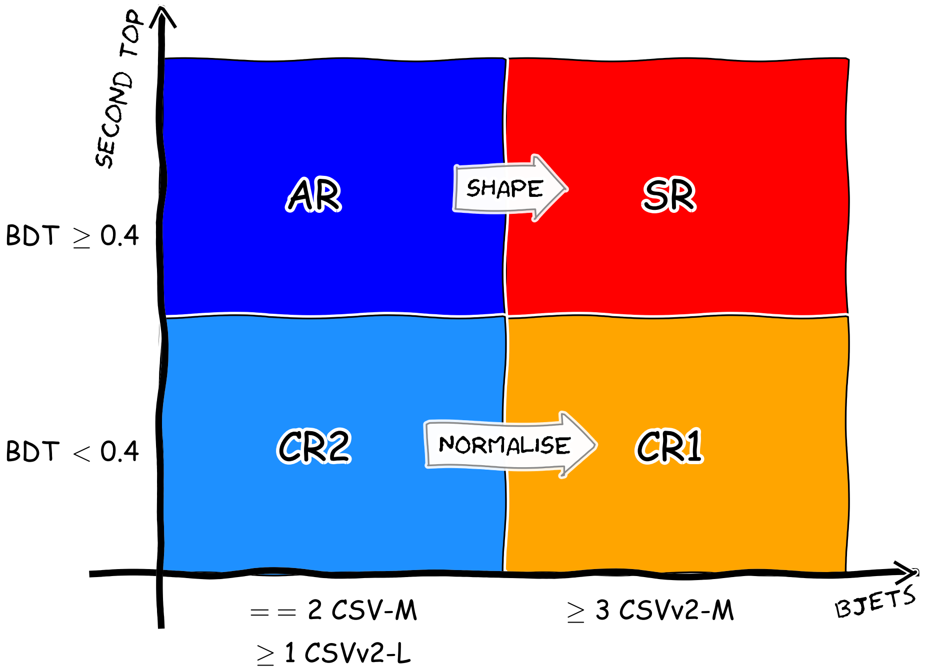
- Reconstructed H± from **top+b** or **W+b+b(jet) :**
  - 4 basic categories
    - 2 top-tagged : **t0b, t1b**
    - 2 W-tagged : **Wbb, Wbj**
- Further categorized by
  - $N_{\text{b-jets}}$ (= 1, =2, ≥3)
  - $N_{\text{extra jets}}$ (≤ 2, >2)
  - Mass window — FWHM of signal (below/in/above)
- An excess is searched for in the $\mathbf{H_T}$ distribution **in mass window**

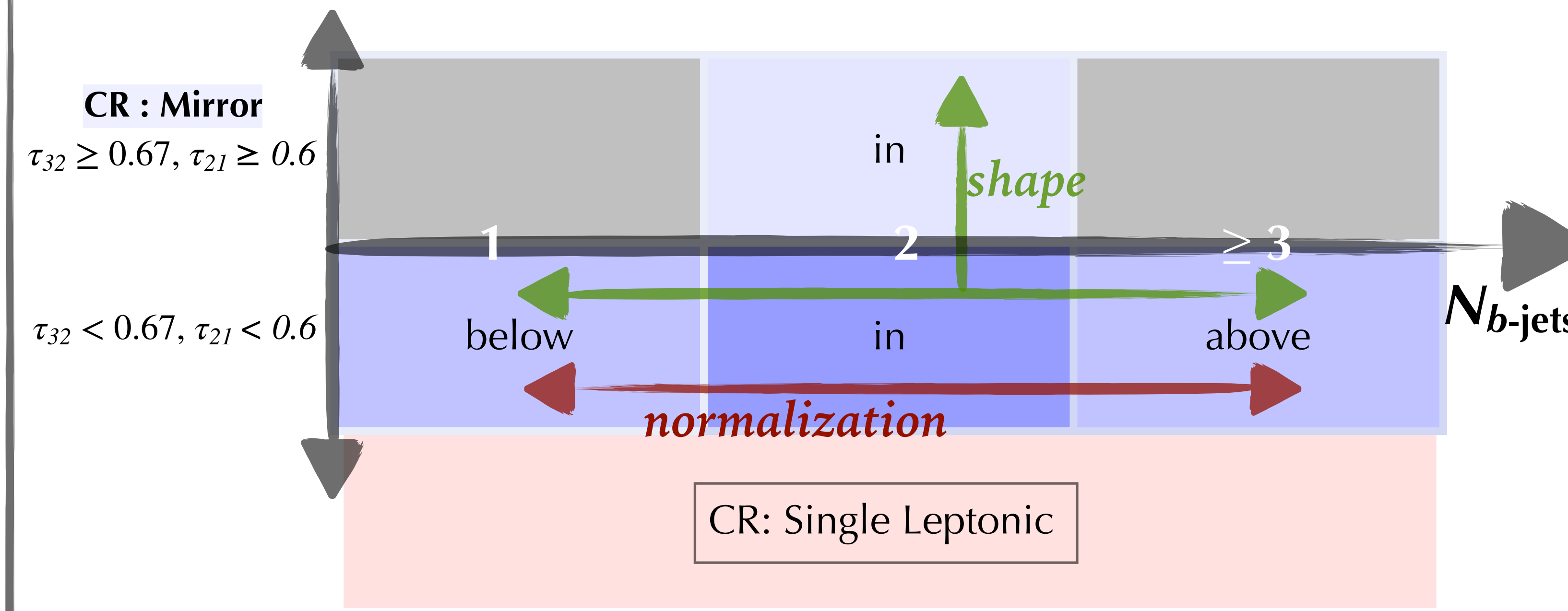


H± → tb hadronic: Background Estimation NEW

CMS-PAS-HIG-18-015

resolved | **boosted** | $m_{H^\pm}$





- Main background: **Fake b-jets**
  - Measured from data by inverting top- & b- tagging requirement

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

(i runs over p_T and η-bins)

- Others: Genuine-b
  - Estimated from simulation

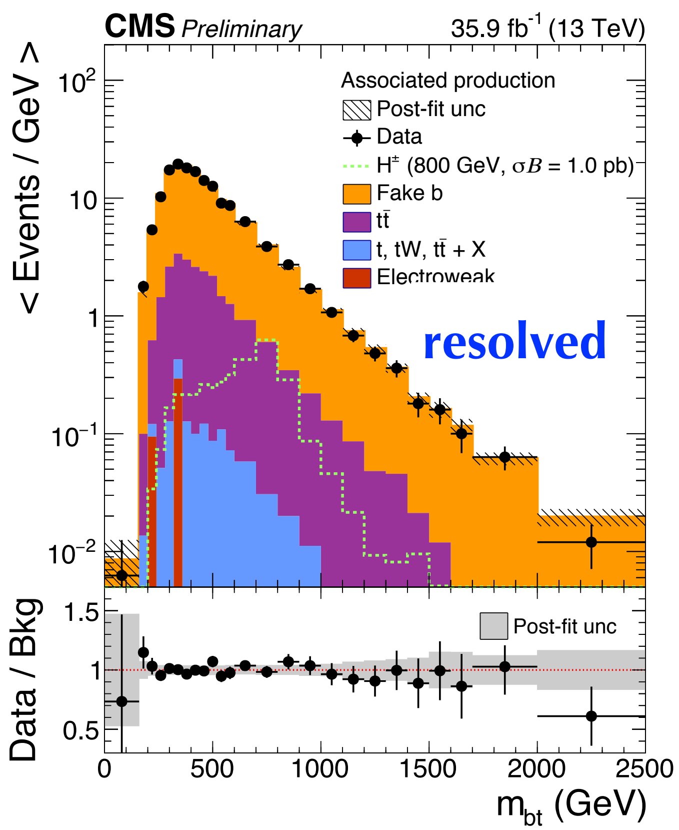
- Main background: **QCD multijet** (~90%) & **$t\bar{t}$** (~8%)
  - **QCD multijet**
    - **CR : Mirror** : invert $\tau_{32}(\tau_{21})$ cut
      - control QCD shape
    - Sidebands (**below/above**)
      - control QCD normalization
  - **$t\bar{t}$** : **CR: Single Leptonic** : 1 e/μ with $10 < p_T < 35$ GeV

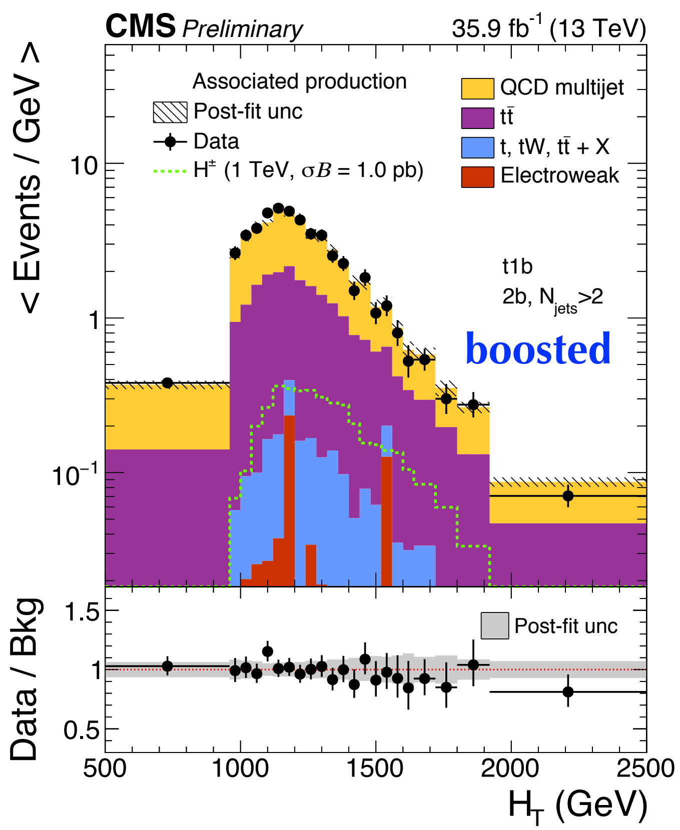
- **SR - in** + **below** + **above** + **CR : mirror - in** + **CR : single leptonic** used for simultaneously fit

H± → tb hadronic: Results

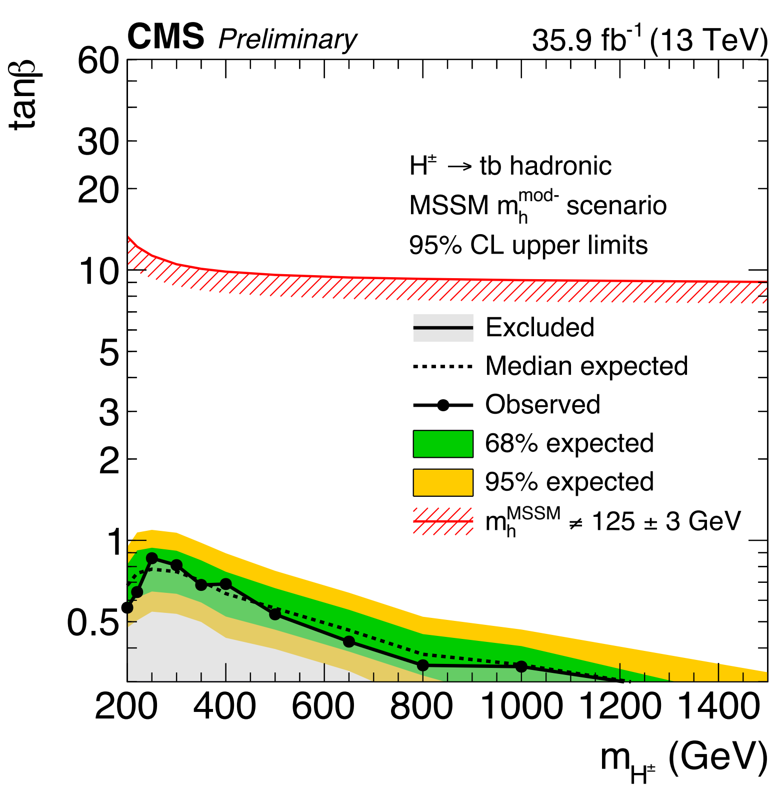
CMS-PAS-HIG-18-015

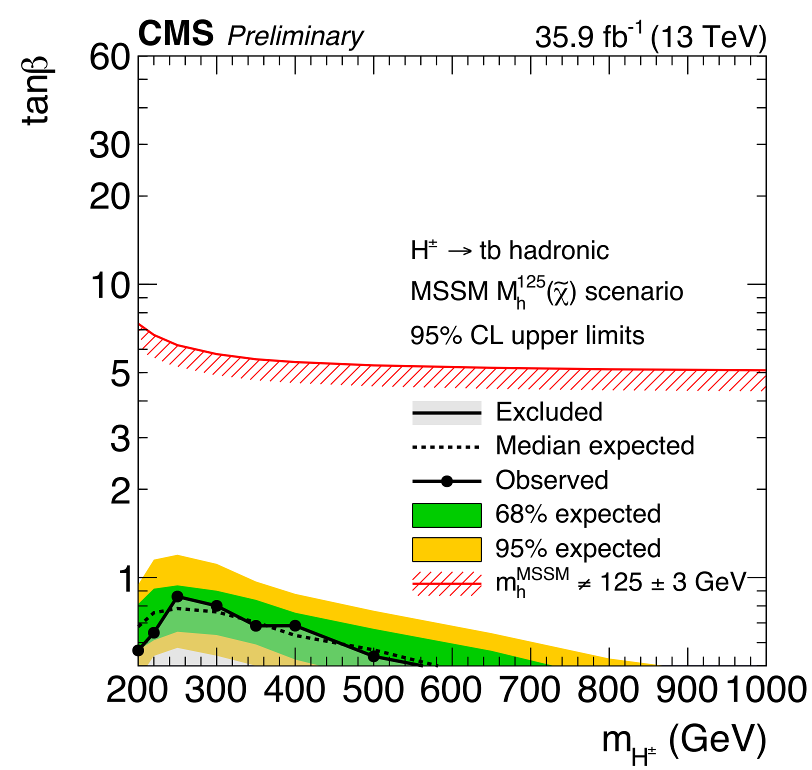
NEW

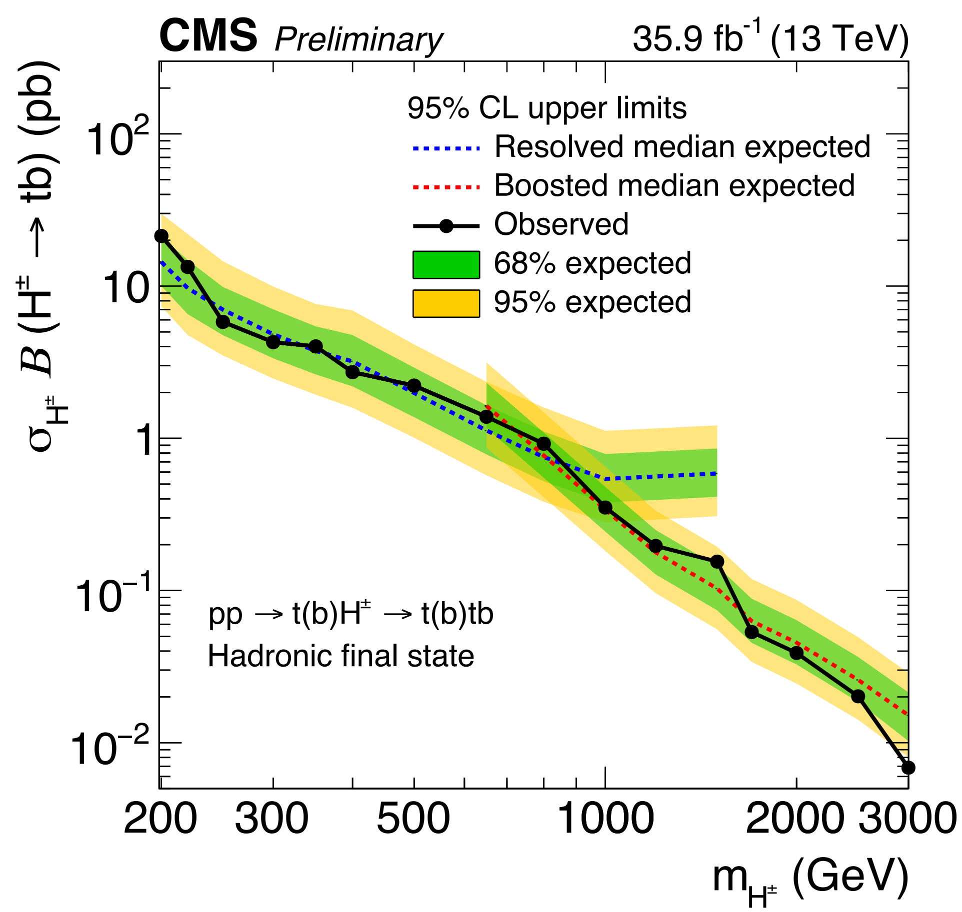




- Better limits are chosen between the two
  - $m_{H\pm} \leq 800$GeV : **resolved**
  - $m_{H\pm} > 800$GeV : **boosted**
- **No excess observed** across all mass region
- Excluded parameter space shown
  - m_h^{mod-} scenario : tanβ values from 0.25 to 0.86 are excluded
  - $m_h^{125}(\tilde{\chi})$ scenario : tanβ values from 0.45 to 0.86 are excluded



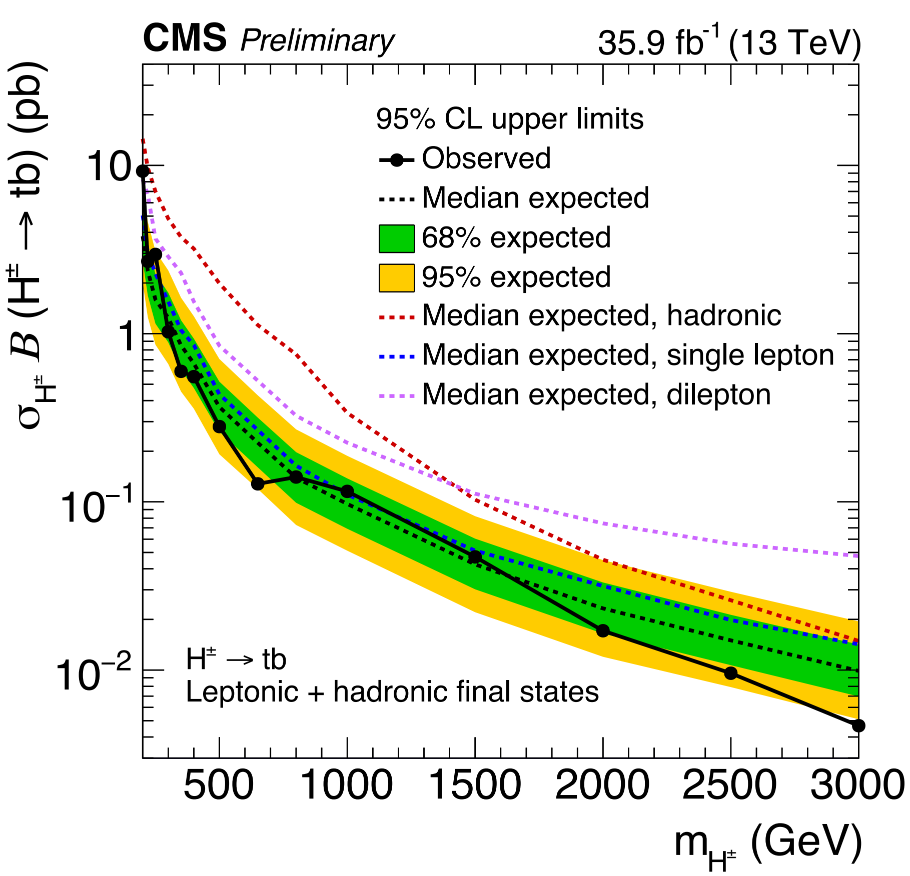


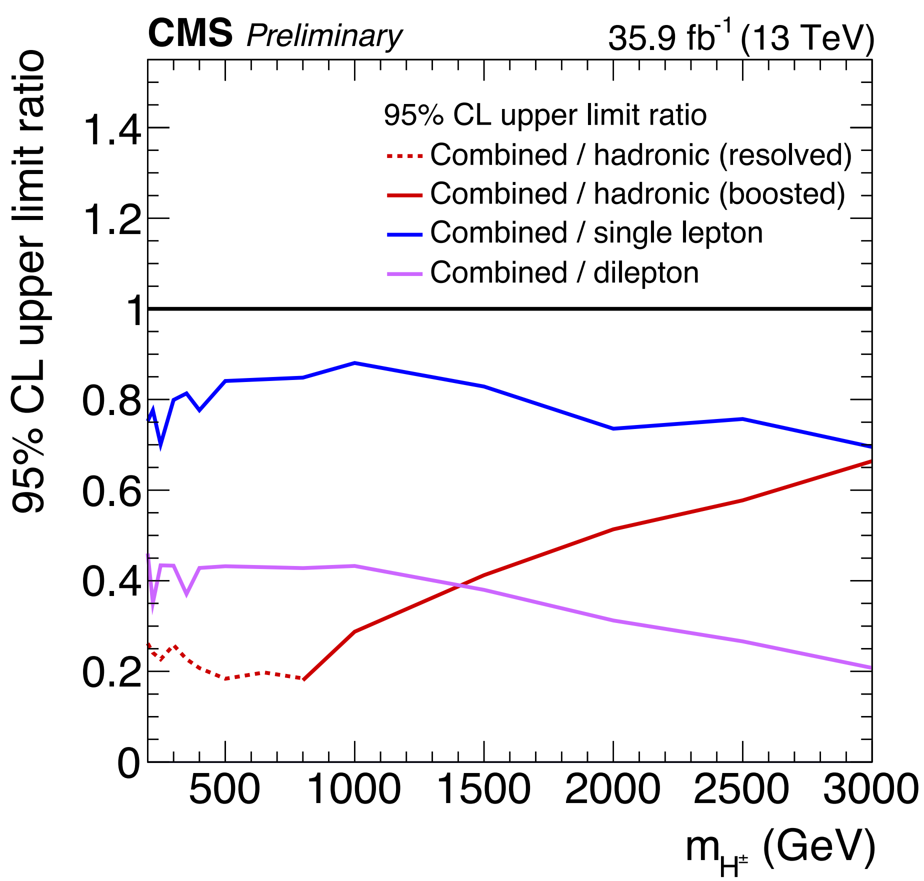


Charged Higgs Combination

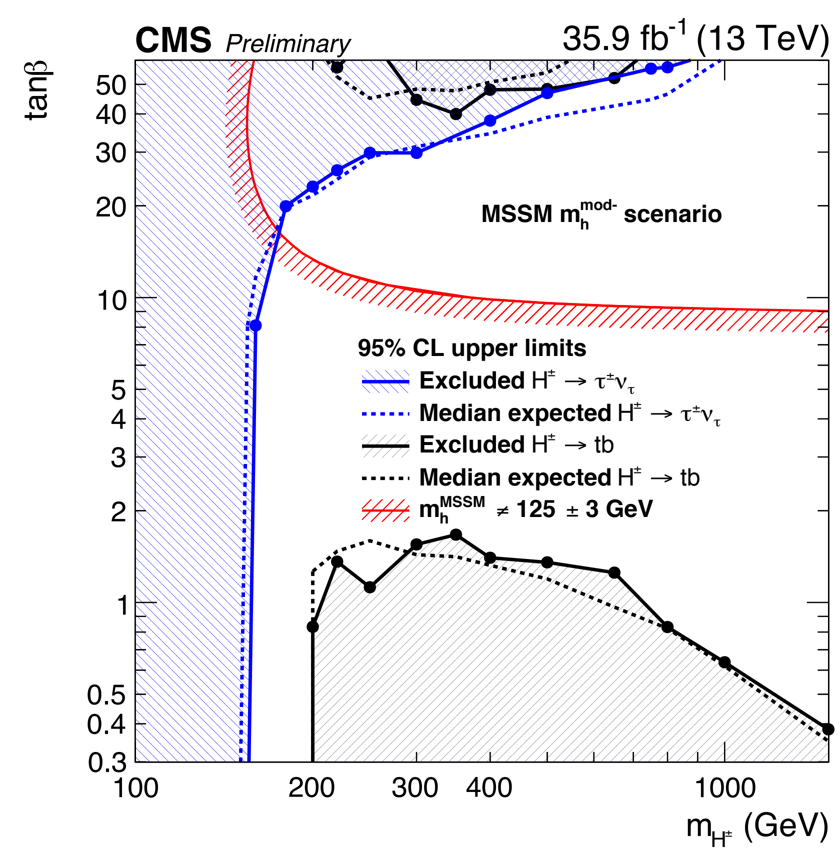
- Combination of **H± → tb leptonic** and **hadronic**
  - **1l** final state dominants across entire mass range
  - **2l** final state is sensitive at **lower mass region**, ~ 20% gain
  - **Hadronic** final state is comparable as 1l at **higher mass region**, ~30% gain
- Excluded parameter space of both **H± → tb** and **H± → $\tau^{\pm}\nu_{\tau}$** displayed is also shown

H± → tb leptonic + hadronic





H± → tb + H± → $\tau^{\pm}\nu_{\tau}$



Summary

- **CMS has a comprehensive charged Higgs boson searches program**
  - Latest analyses in 2HDM are presented in details
    - $H^{\pm} \rightarrow W^{\pm}A$ and $H^{\pm} \rightarrow tb$ leptonic + hadronic
    - No excesses observed in a variety of searches
    - 95% CL upper limits are set
    - Interpretation and exclusion in MSSM scenarios are shown
  - Also fresh results in Higgs triplet models
    - $H^{\pm} \rightarrow W^{\pm}Z$ and $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ semi-leptonic (backup p18,19)
      - Model independent limits are set
      - First model dependent limits in s_H-$m(H_5)$ plane above 1 TeV

- Currently all analyses are done on 2016 dataset (35.9 fb^{-1})
- More to come with a luminosity of 137.1 fb^{-1} in total from the full Run2 dataset

Thanks!

BACK UP

$H^\pm \rightarrow W^\pm A$: Opposite-sign muon pair selection

- Opposite-sign muon pair selection
  - $m_{\mu\mu} > 12$ GeV, $|m_{\mu\mu} - m_Z| > 10$ GeV
  - Specific for $\mu^\pm\mu^\pm\mu^\mp$
    - One with different charge $\mu^\mp \longrightarrow$ **A**
    - The same-sign muon pair $\mu_1^\pm\mu_2^\pm$
      - When and only when
        - $\Delta p_T(\mu^\pm,\mu^\pm) < 25$GeV
        - only one $\mu_{1(2)}$ with 50 GeV $< m_T(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,miss}) < 120$GeV

        Satisfied: $\mu_{2(1)} \longrightarrow$ **A**
      - Otherwise: $\mu_{lower\ pT} \longrightarrow$ **A**

Input variables for $H^{\pm} \to tb$ leptonic multivariate analysis

1ℓ and 2ℓ	H_{T}	Scalar sum of the jet transverse momenta
	p_{Tb}	Largest transverse momentum among the b-tagged jets
	p_{T}^{miss}	Missing transverse momentum
	$\min m(\ell, b)$	Minimum invariant mass between the lepton and the b-tagged jet
	$\max \Delta\eta(b, b)$	Maximum pseudorapidity separation between b-tagged jet pairs
	$\min \Delta R(b, b)$	Minimum separation between b-tagged jet pairs
	p_{T}-ave CSV	p_{T} weighted average of the combined secondary vertex discriminator of the non-b-tagged jets
	FW_{2}	Second Fox–Wolfram moment
	centrality	Ratio of the sum of the transverse momentum and the total energy of all jets
1ℓ	m_{jjj}	Invariant mass of the jet system composed by the first three jets ranked in p_{T}
	$m_{T}(\ell, \vec{p}_{T}^{miss})$	Transverse mass of the system constituted by the lepton and the $\vec{p}_{T}^{miss}$
	$\Delta R(\ell, bb)$	Distance between b-tagged jet pair with the smallest ΔR separation and the lepton
	$\mathrm{ave}\Delta R(b, b)$	Average separation between b-tagged jet pairs
2ℓ	N_{jets}	Number of selected jets
	$N_{b\,jets}$	Number of selected b-tagged jets
	$\Delta R(\ell, b)$	Distance between the lepton and the b-tagged jet with largest transverse momenta
	$p_{T\ell}$	Largest transverse momentum between the leptons
	$\frac{p_{T\ell 1} - p_{T\ell 2}}{p_{T\ell 1} + p_{T\ell 2}}$	Lepton p_{T} asymmetry
	$m(\ell, b)$	Invariant mass of the lepton and b-tagged jet with the largest transverse momentum (top quark candidate)
	m_{T}^{min}	$\min\left[m_{T}(b, p_{T\ell 1} + \vec{p}_{T}^{miss}), m_{T}(b, p_{T\ell 2} + \vec{p}_{T}^{miss})\right]$. The smallest of the transverse masses constructed with the leading b-tagged jet and each of the two W boson hypotheses

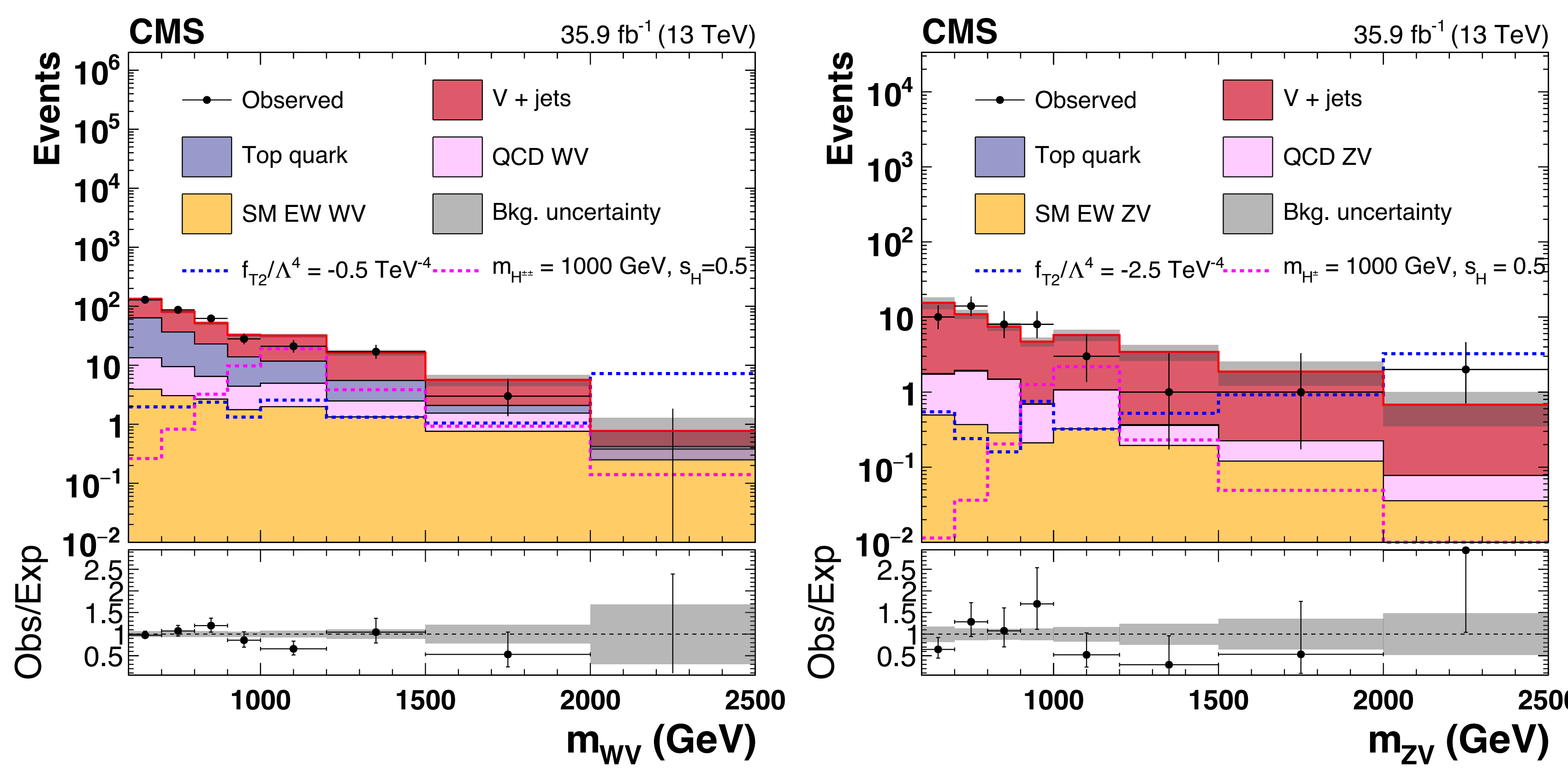
Searches in $W^{\pm}Z(H^{\pm})/W^{\pm}W^{\pm}(H^{\pm\pm})$ final states: semi-leptonic

CMS-SMP-18-006

- In Georgi-Machacek model (Higgs triplet model), singly (doubly) charged Higgs bosons are produced via VBF that decay to W and Z bosons (same-sign W boson pairs)
- Semi-leptonic decay of WV targeted
  - $H^{\pm} \to W^{\pm}Z \to \ell\nu qq$ (or $qq\ell\ell$)
  - $H^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell\nu qq$

- Leptonic W is reconstructed from solving the the p_z^{ν},
  - Solution closest to p_z^{ℓ} is picked
- Hadronic W/Z reconstructed as one large radius jet using jet substructure

- m_{VV} used for signal extraction
- No excess observed



Searches in W±Z(H±)/W±W±(H±±) final states: semi-leptonic

CMS-SMP-18-006

- Place model independent limits on singly and doubly charged Higgs cross section
- Combine the 3 results and produce the model dependent limits in s_H-m plane
  - H± and H±± in the GM model are degenerate in mass ($m(H_5)$) at tree level
  - Coupling depends on $m(H_5)$ and the parameter s_H
    - s^2_H characterizes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplet fields
  - Blue shaded area covers the theoretically disallowed parameter space
  - The first limits above 1 TeV