Search for Additional Higgs Boson at CMS

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On behalf of the CMS collaboration

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TWENTIETH LOMONOSOV
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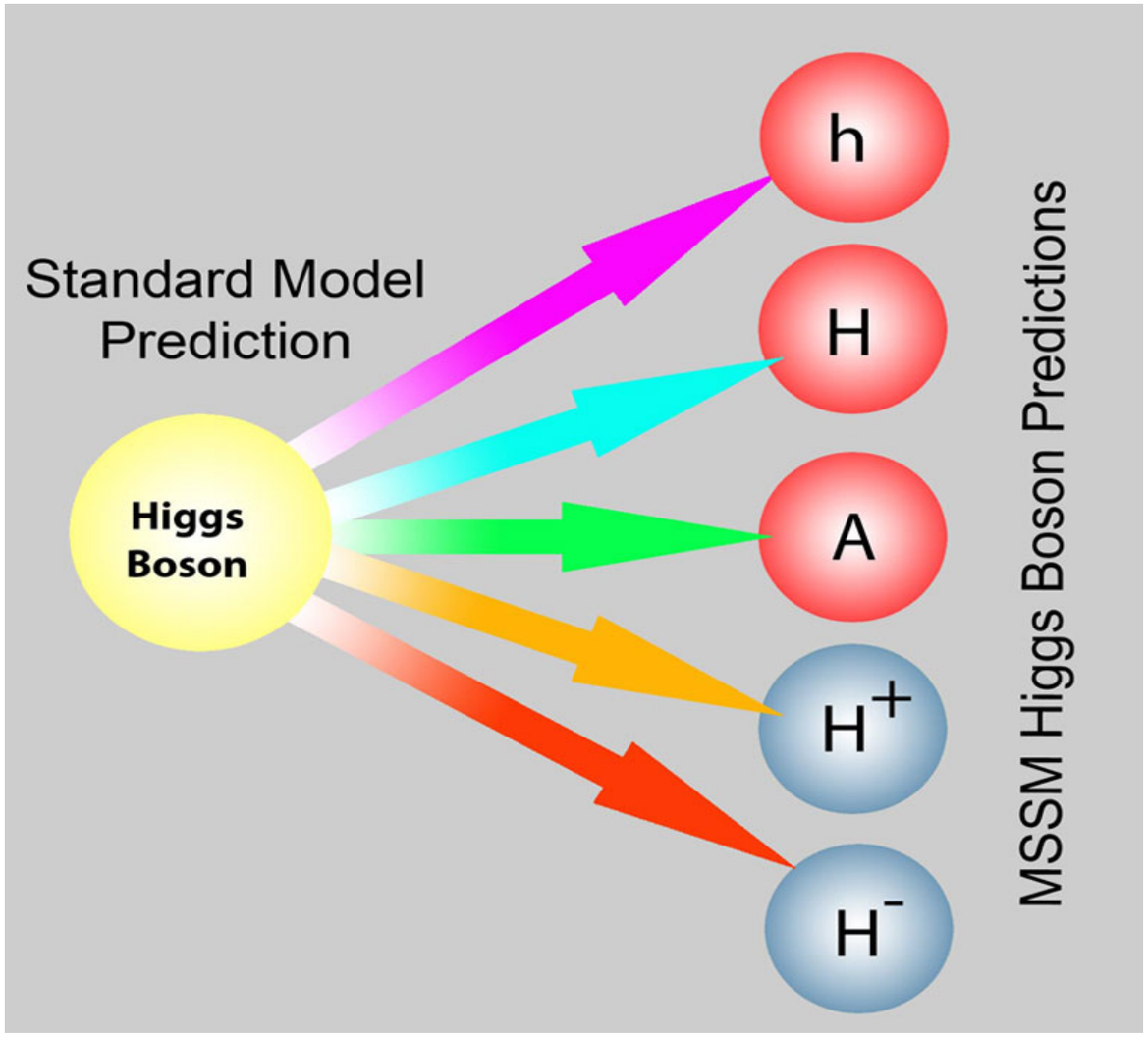
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Introduction

- ✓ Standard Model of particle physics is the most successful theory
- ✓ **But,** the SM cannot explain everything: *dark matter and matter-antimatter asymmetry*
- ✓ **The 2HDM is an extension of the SM adding an extra complex scalar doublet**
- ✓ 2HDM predict:
  - ✤ CP even h^0 (125 GeV) and H^0
  - ✤ CP odd A^0
  - ✤ Electrically charged H^+ and H^-
- ✓ Finding any of the charged Higgs would sign for new physics beyond SM



Model	Type I Fermiophobic I	Type II MSSM-like	Type X Lepton-specific	Type Y Flipped
Φ_1	-	d,ℓ	ℓ	d
Φ_2	u,d,ℓ	u	u,d	u,ℓ

Additional Bosons: CMS Run-2 Results

3rd generation fermion, motivated by the large Yukawa coupling:

$A/H \to tt$: *Eur. Phys. J. C 77 (2017) 578*

$A/H \to bb$: *JHEP 08 (2018) 113*

$A/H \to \tau\tau$: *JHEP 09 (2018)007*

$H^{\pm} \to \tau_h \nu$: *JHEP 10 (2019) 142*

$H^{\pm} \to tb$: *JHEP 01 (2020) 096 + JHEP 07 (2020) 126*

Also in other decay channels

$A/H \to \mu\mu$: *Phys. Lett. B 798 (2019) 134992*

$H^{\pm} \to cb$: *JHEP 11 (2018) 115*

Higgs to Boson

H/A→Z(ll)A/H(bb) JHEP 03 (2020) 055

$H^{+} \to WA$ Phys. Rev. Lett. 123, 131802 (2019)

Boosted	Resolved
$h \to aa \to \mu\mu\mu\mu$	$h \to aa \to \mu\mu\tau\tau$
Phys.Lett.B 796 (2019) 131-154	*JHEP 11 (2018) 018*
$h \to aa \to \mu\mu\tau\tau$	$h \to aa \to \mu\mu bb$
JHEP 08 (2020) 139	*Phys.Lett.B 795 (2019) 398-423*
$h \to aa \to \tau\tau\tau\tau$	$h \to aa \to \tau\tau bb$
Phys.Lett.B 800 (2020) 135087	*Phys. Lett. B 785 (2018) 462*

In all cases data are in agreement with SM

Chasing Charged Higgs at LHC

- ✓ Production at tree level controlled by:

$$tan\beta = \frac{v2}{v1} \text{ and } m_A$$

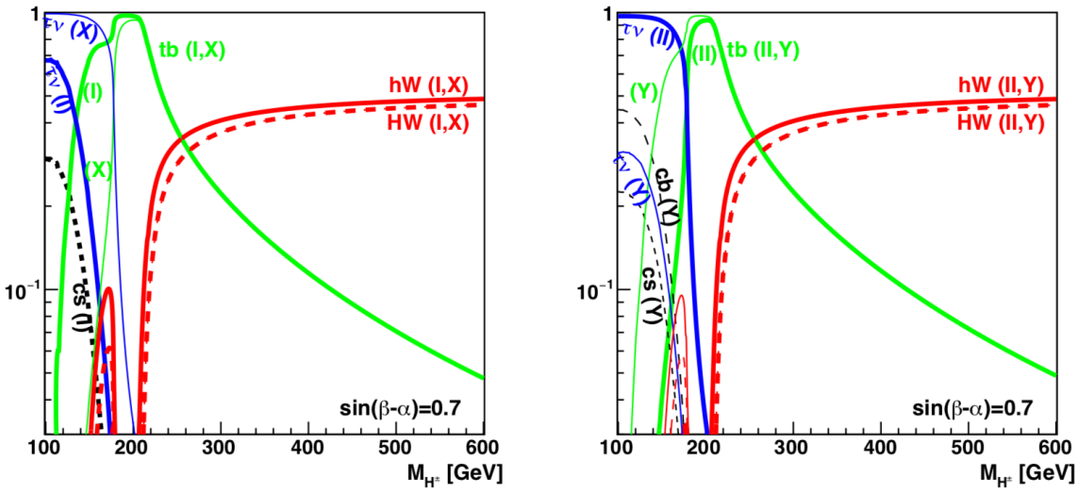
- ✓ Two possible production ways at LHC energies:

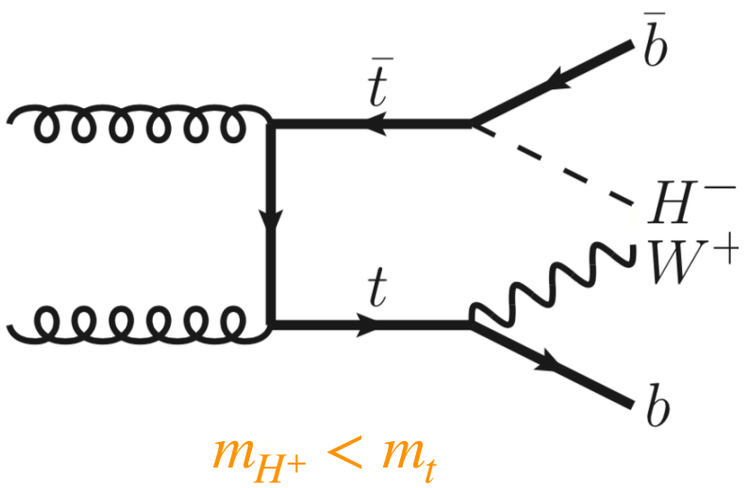
➡ $m_{H^+} < m_t$:

✓ $pp \to t\bar{t} \to bH^+bW^-$ with $t \to bH^+$

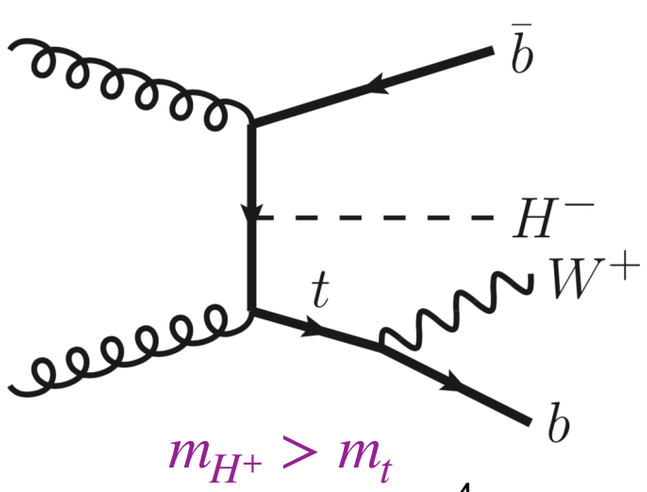
➡ $m_{H^+} > m_t$:

✓ $pp \to tbH^+$





$m_{H^+} < m_t$

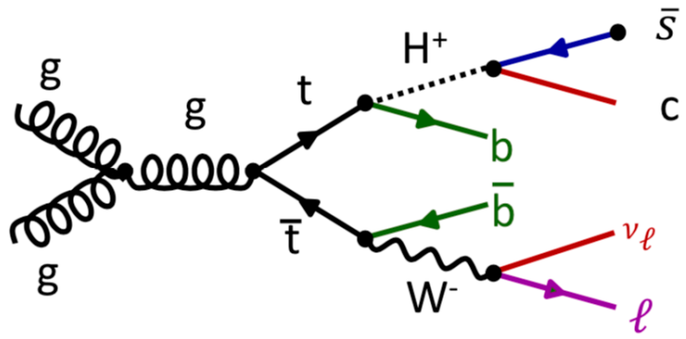


$m_{H^+} > m_t$

- ✓ For $tan\beta < 1$ $\tau^+\nu$ and $c\bar{s}$ dominating at low m_{H^+}
- ✓ tb dominate on large masses once kinematically accessible
- ✓ hW and HW offers new complementary and constraint for 2HDM

https://arxiv.org/pdf/1607.01320.pdf

Charged Higgs to $c\bar{s}$

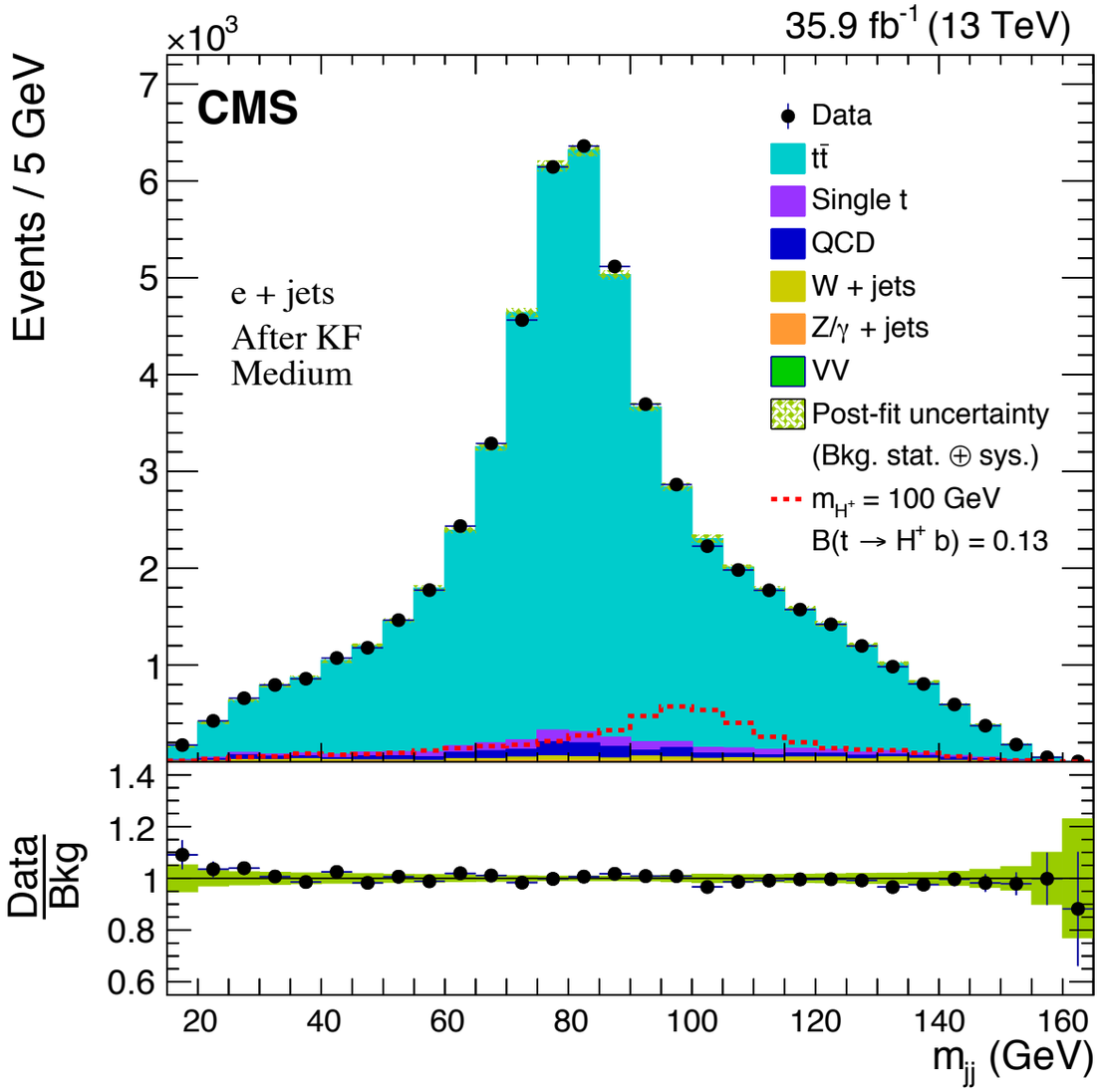


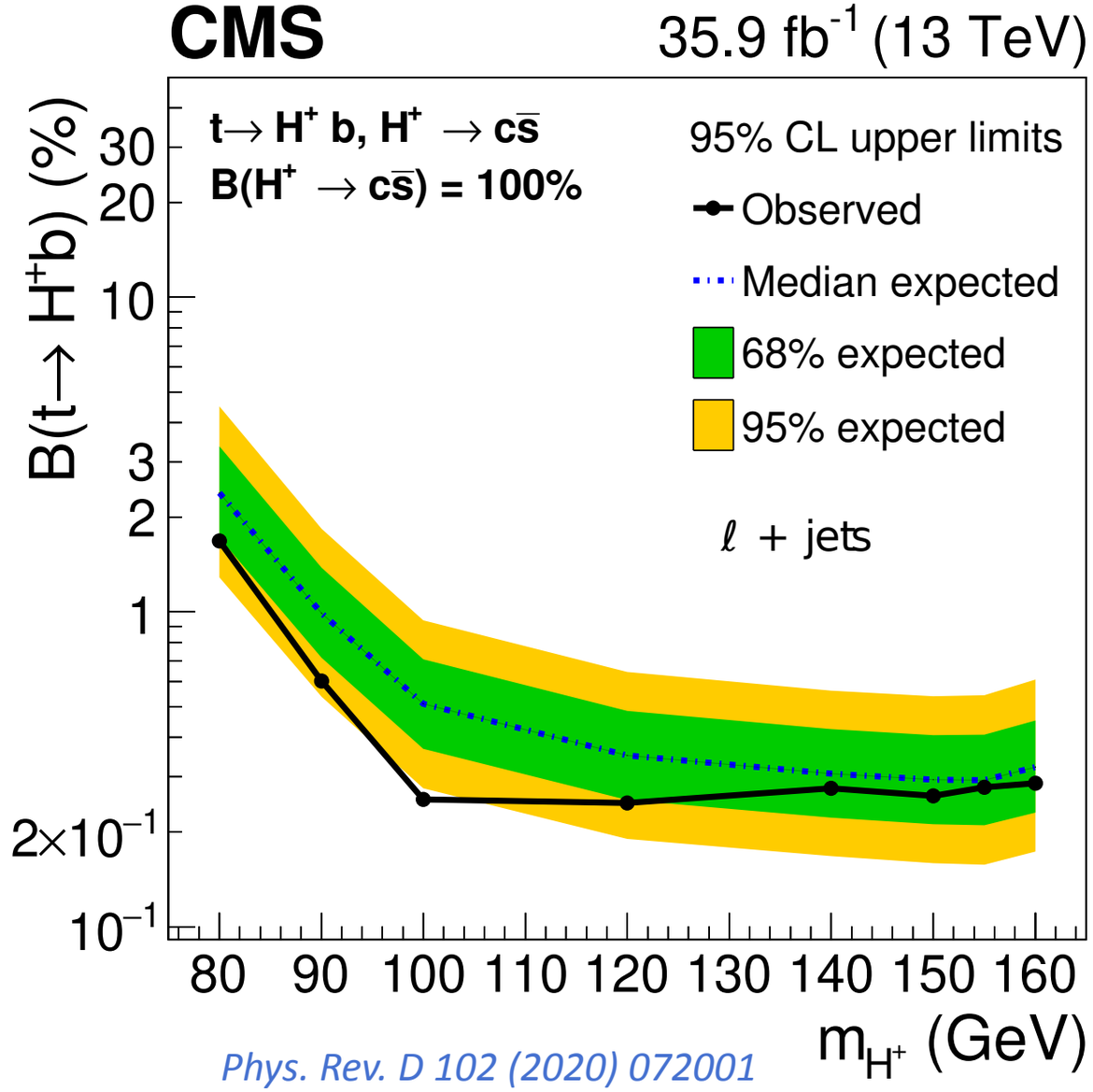
1 tight and isolated lepton → At least 4 jets → Missing transverse energy → 2 btagged jets → Dijet invariant mass with 2 highest p_T jets not tagged as b-jets

- Kinematic fitting is used to improve dijet mass resolution
- Input to Fitter: Reco objects (muons, electrons, jets, and MET) with corresponding resolution
- Both top (hadronic and leptonic decaying) quark mass are constrains to 172.5 GeV

Further event categorization is done using charm tagging

Results: Charged Higgs to $c\bar{s}$





Phys. Rev. D 102 (2020) 072001

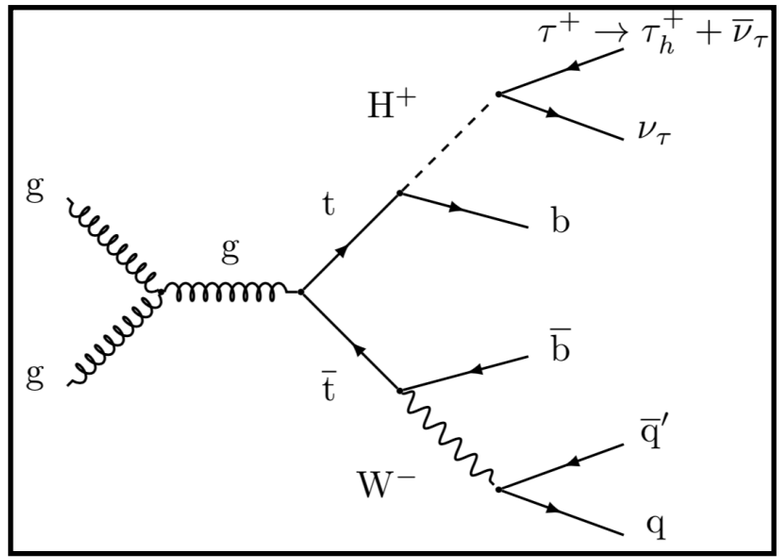
No excess or deficit of events observed

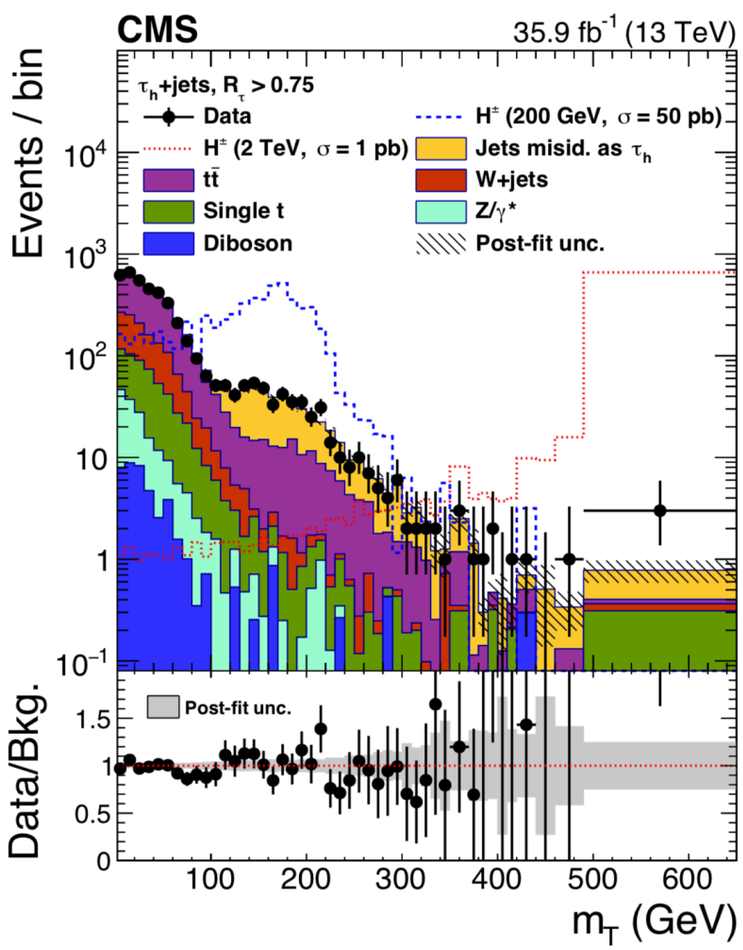
An upper limit on the BR is set in range (1.68-0.25)% for a higgs mass of 80-160 GeV

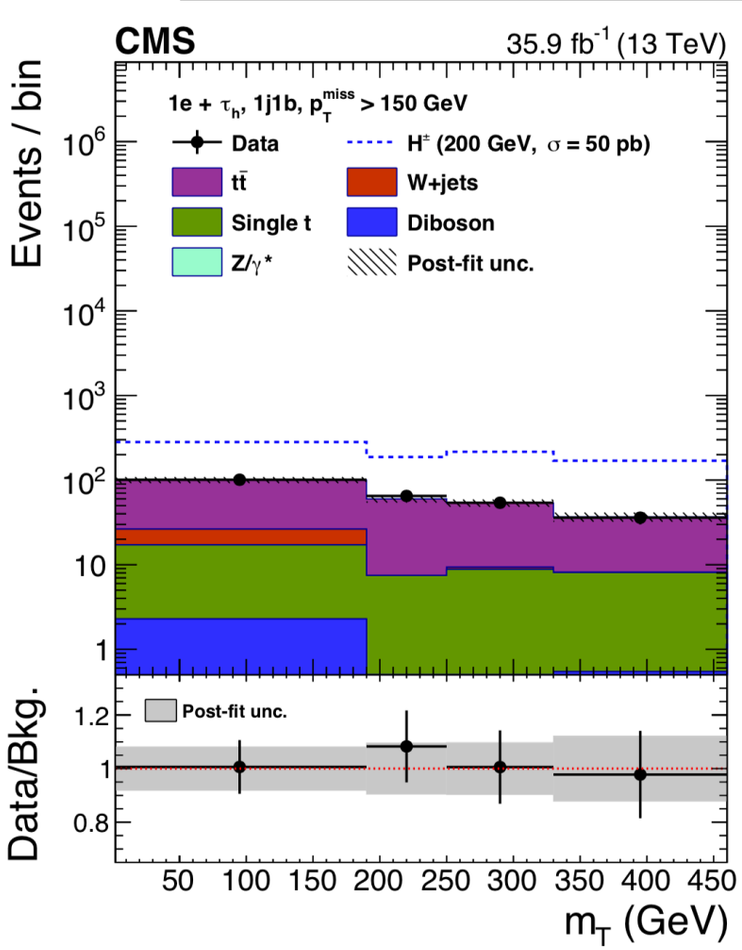
Charged Higgs: $H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$

In 2HDM model a light $m_{H^{\pm}}$ decays solely to $\tau\nu$ and also same for heavy $m_{H^{\pm}}$

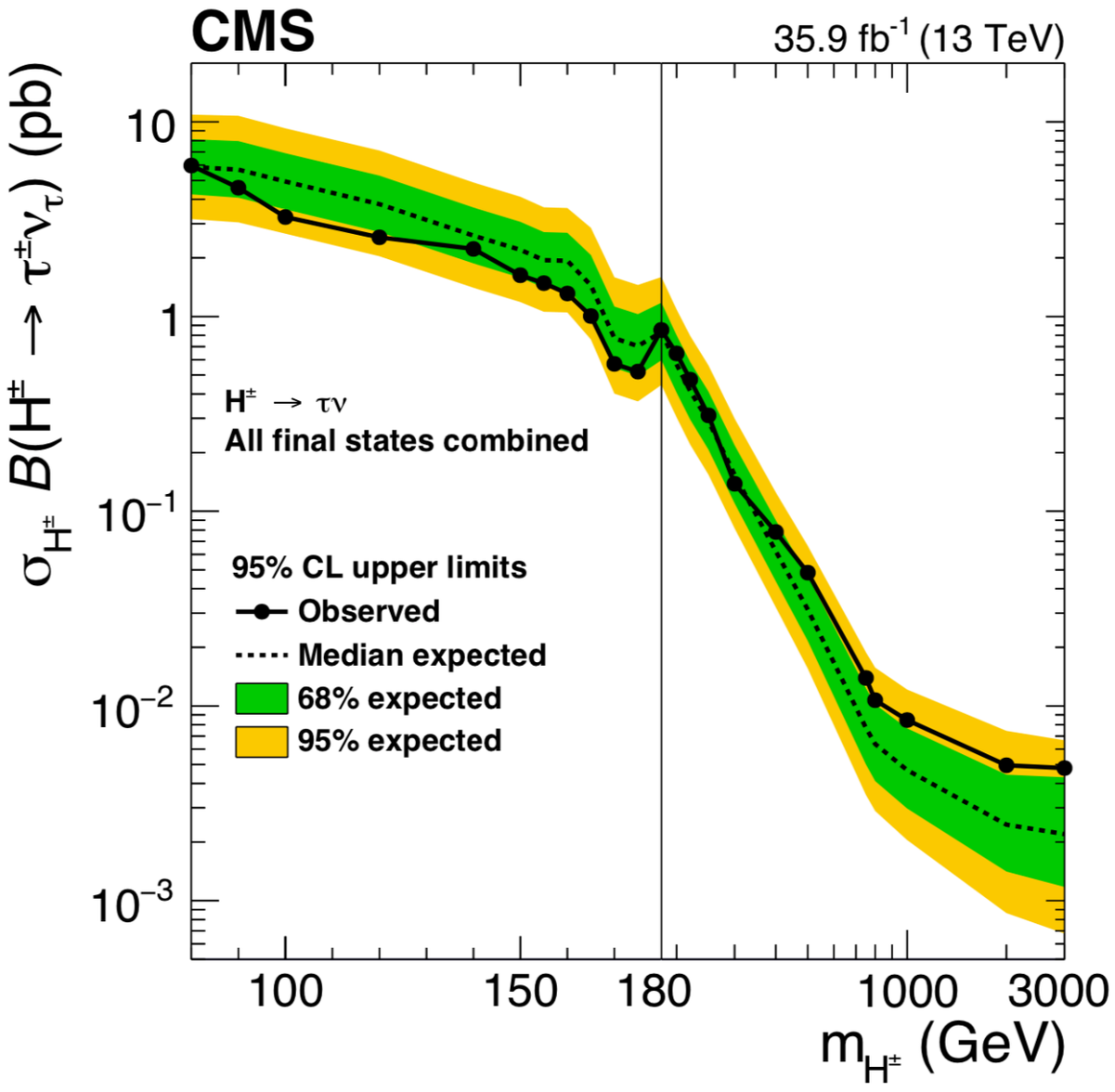
- ☑ Three main final states: τ_h+jets, ℓ+τ_h, ℓ+ no τ_h
- ☑ Major background for τ_h+jets is estimated using $j \rightarrow \tau_h$ (data-driven)
- ☑ (ℓ+τ_h, ℓ+ no τ_h): major background is $t\bar{t}$ (simulation)
- ☑ Simultaneous binned ML fit to $m_T(\tau_h/\ell, p_T^{miss})$

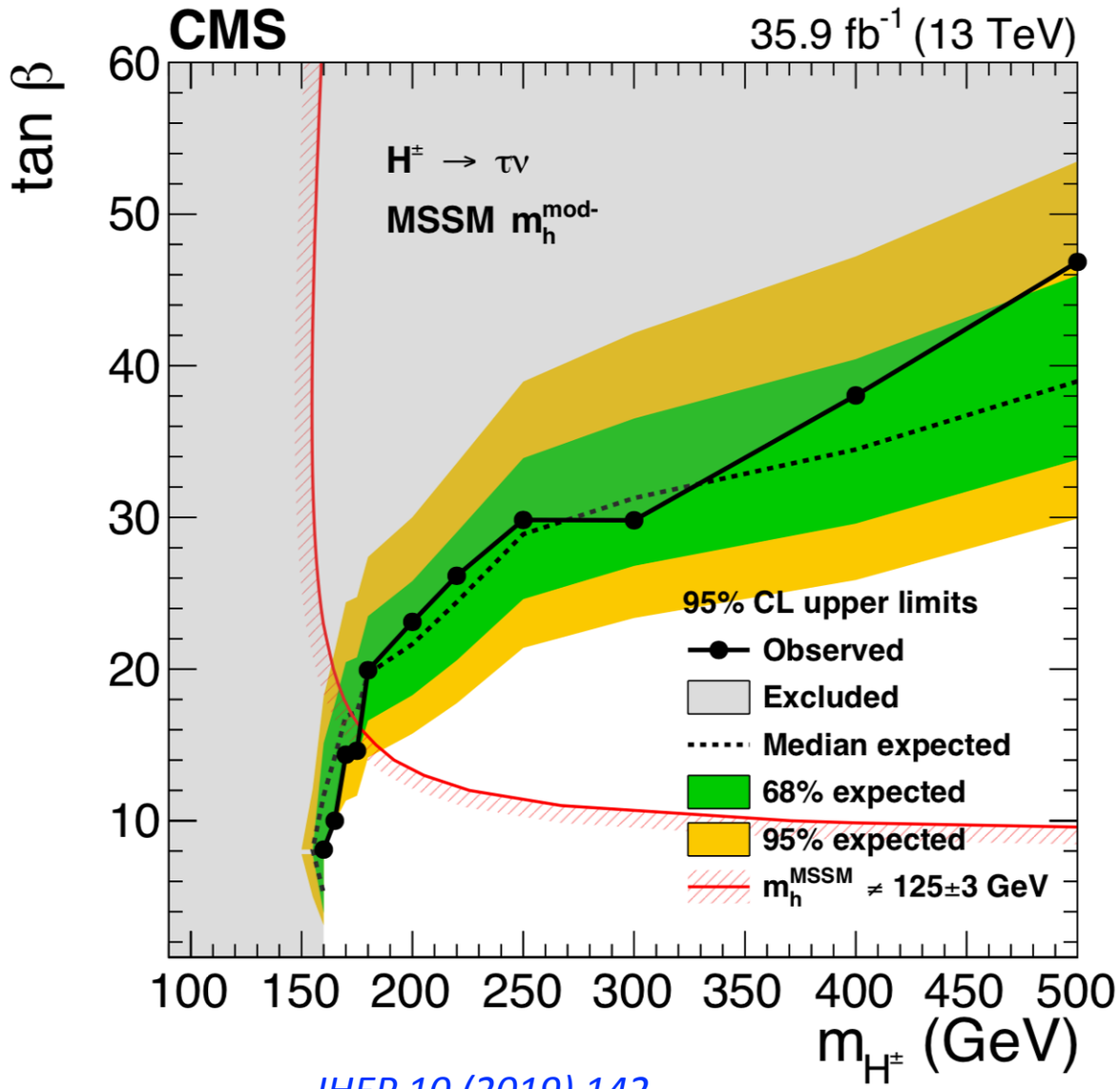






Charged Higgs: $H^{\pm} \to \tau^{\pm}\nu_{\tau}$





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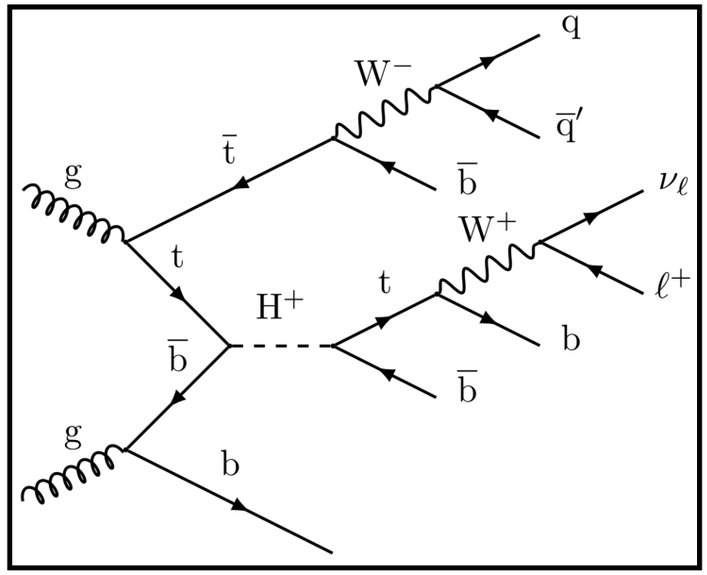
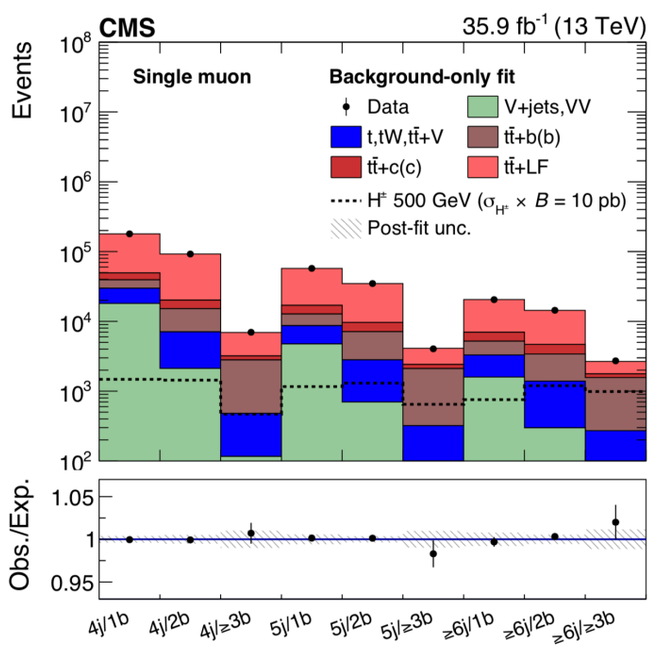
Upper limit on $\sigma_{H^{\pm}} \times B(H^{\pm} \to \tau^{\pm}\nu_{\tau})$ is 6 to 0.005 pb for the Higgs mass range 80 to 3000 GeV

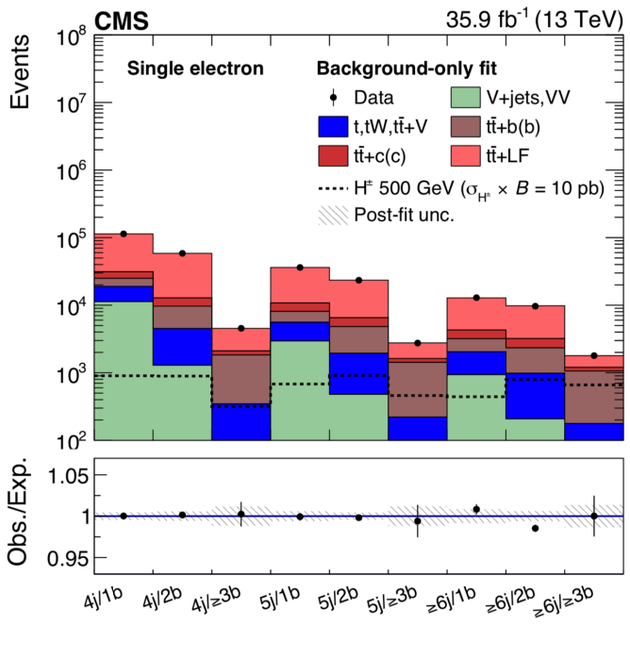
Charged Higgs: $H^{\pm} \rightarrow tb$ Leptonic

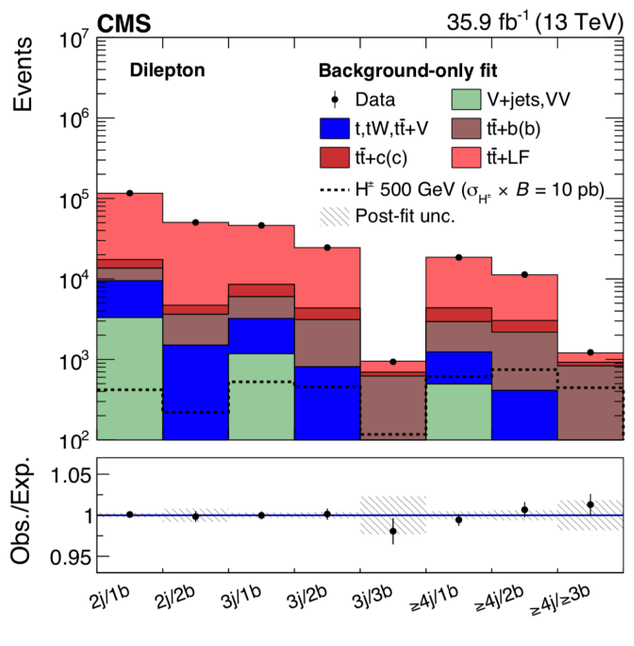
H^{+} decay into top and bottom quarks is dominant for heavy $m_{H^{\pm}}$

- Final states: Two W bosons (leads to single lepton or dilepton final states)
- Total five states: $e^{\pm}, \mu^{\pm}, e^{+}e^{-}, e^{\pm}\mu^{\mp}, \mu^{+}\mu^{-}$
- >= 4 jets (2 jets) for single (dilepton) final states
- >=1 b-tagged jet for both
- Events are categorized in N_{jets} and $N_{b\ jet}$ bins
- Major background is $t\bar{t}$, minor: Single-t , electroweak



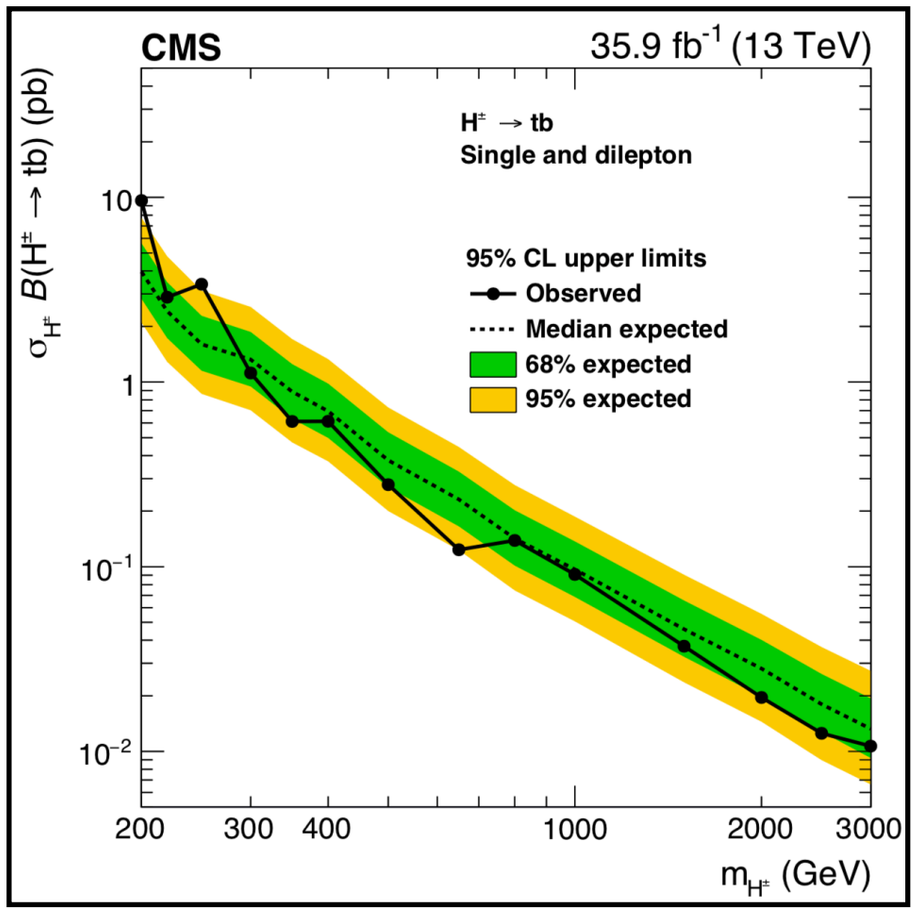




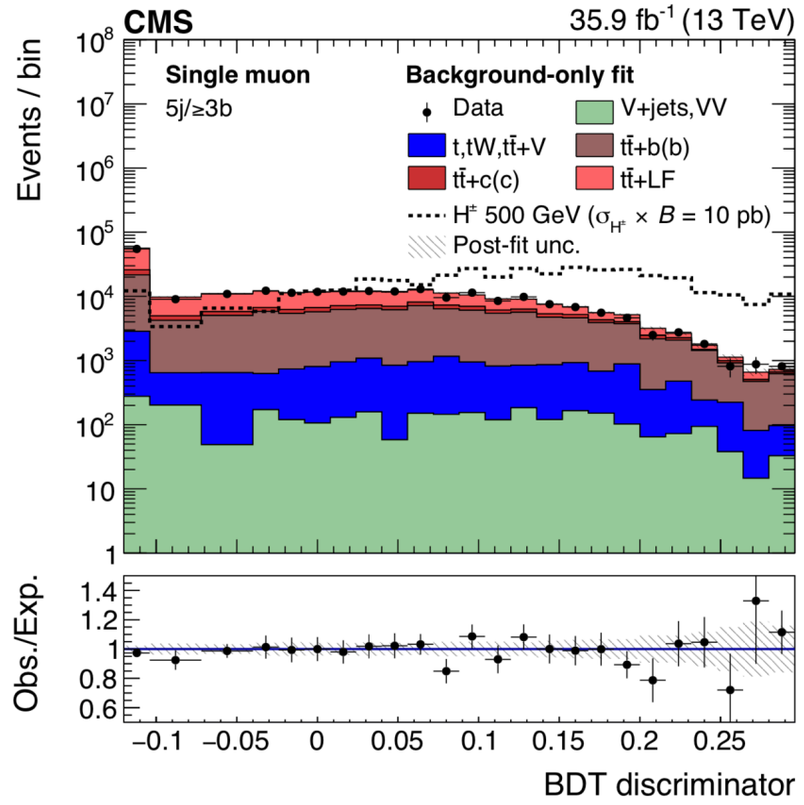


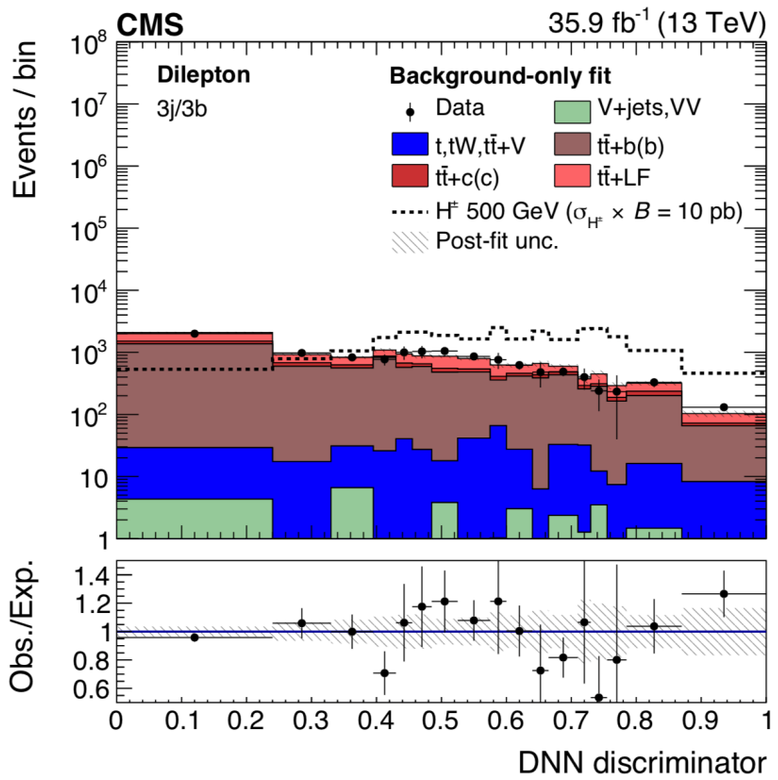
Charged Higgs: $H^{\pm} \to tb$ Leptonic

- ☑ Final discriminant: BDT output for $(e^{\pm}, \mu^{\pm})$ final state
- ☑ Dilepton $(e^{+}e^{-}, e^{\pm}\mu^{\mp}, \mu^{+}\mu^{-})$ uses DNN classifier as final discriminant
- ☑ Simultaneous binned ML is performed



Upper limits of 9.6–0.01 pb are set on the $m_{H^{\pm}}$ range (200-3000 GeV)

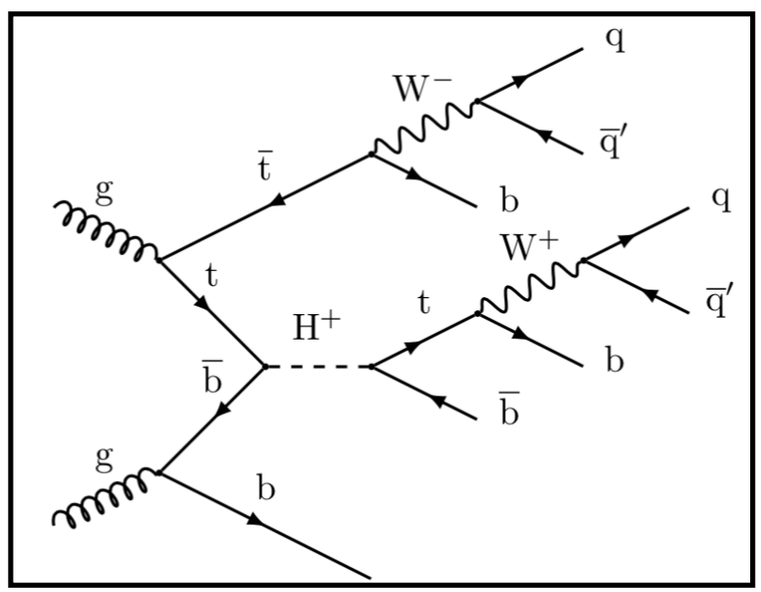


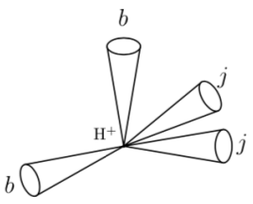


Charged Higgs: $H^{\pm} \rightarrow tb$ Hadronic

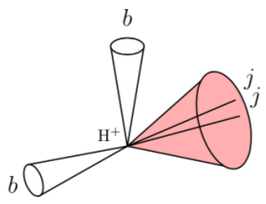
H^{+} decay into top and bottom quarks is dominant for heavy $m_{H^{\pm}}$

- ☑ Fully hadronic final states: largest branching fraction ~45%
- ☑ Resolved top and boosted $W^{\pm}$/t topologies
- ☑ Major background are mis identified b-jets and QCD multijet
- ☑ Fit discriminants are m_{tb} and H_T

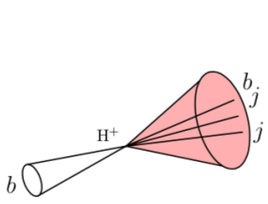




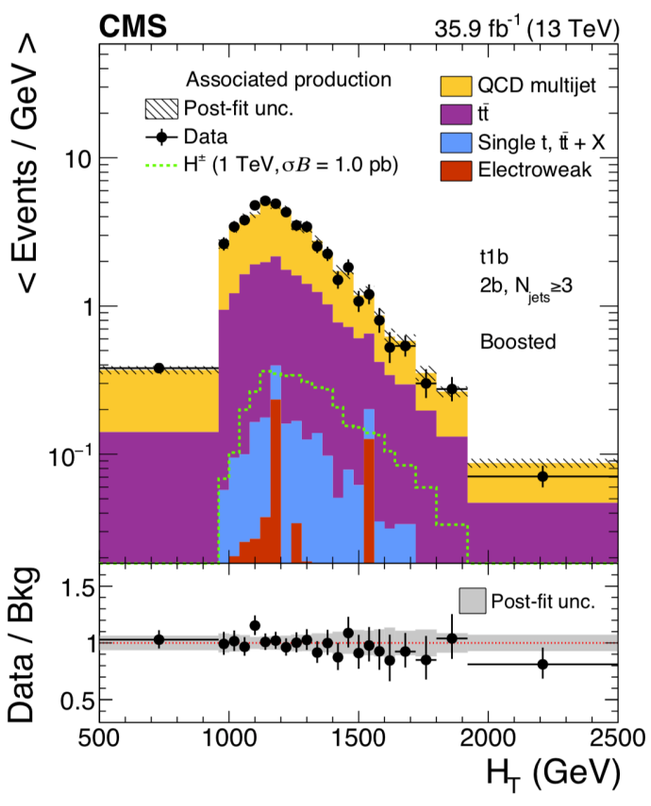
resolved t

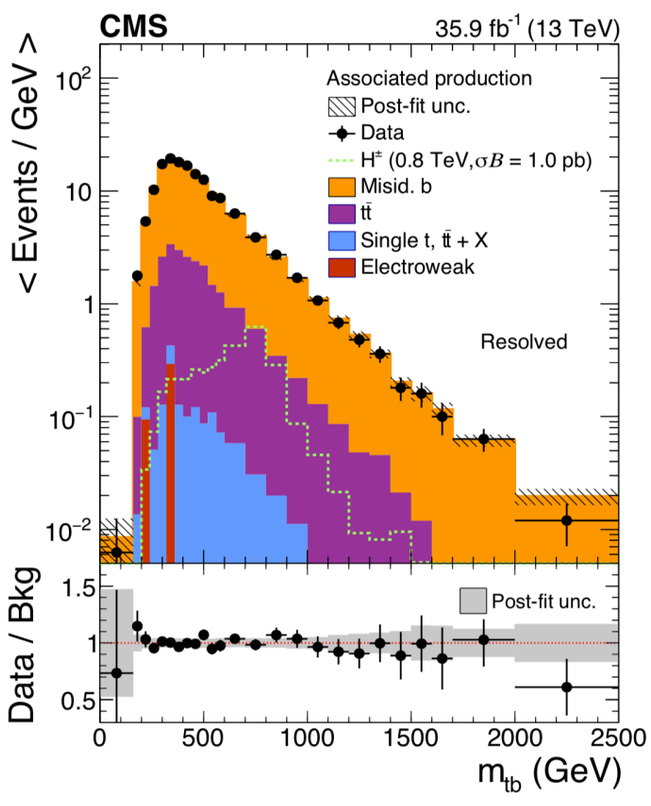


boosted W

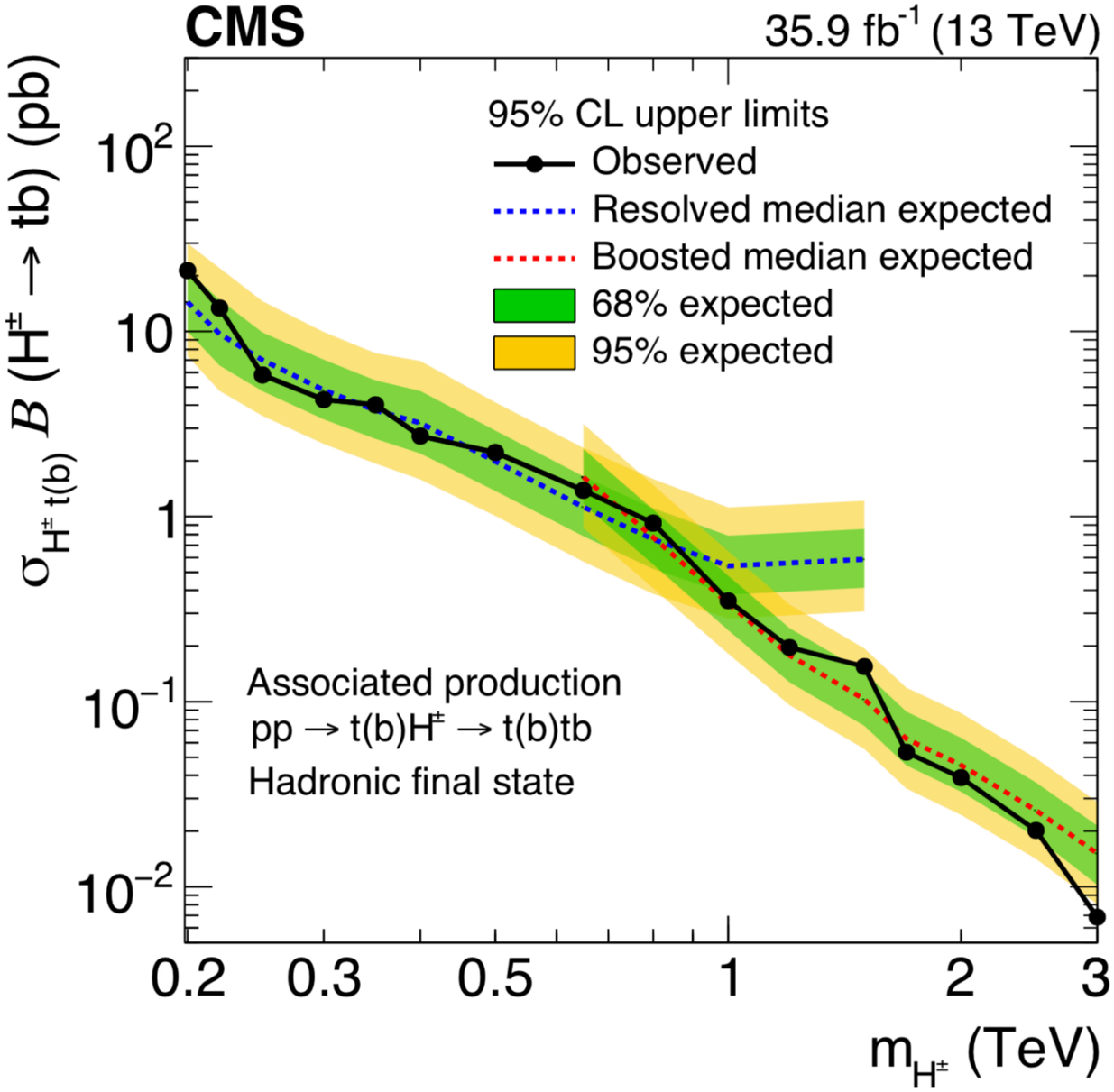


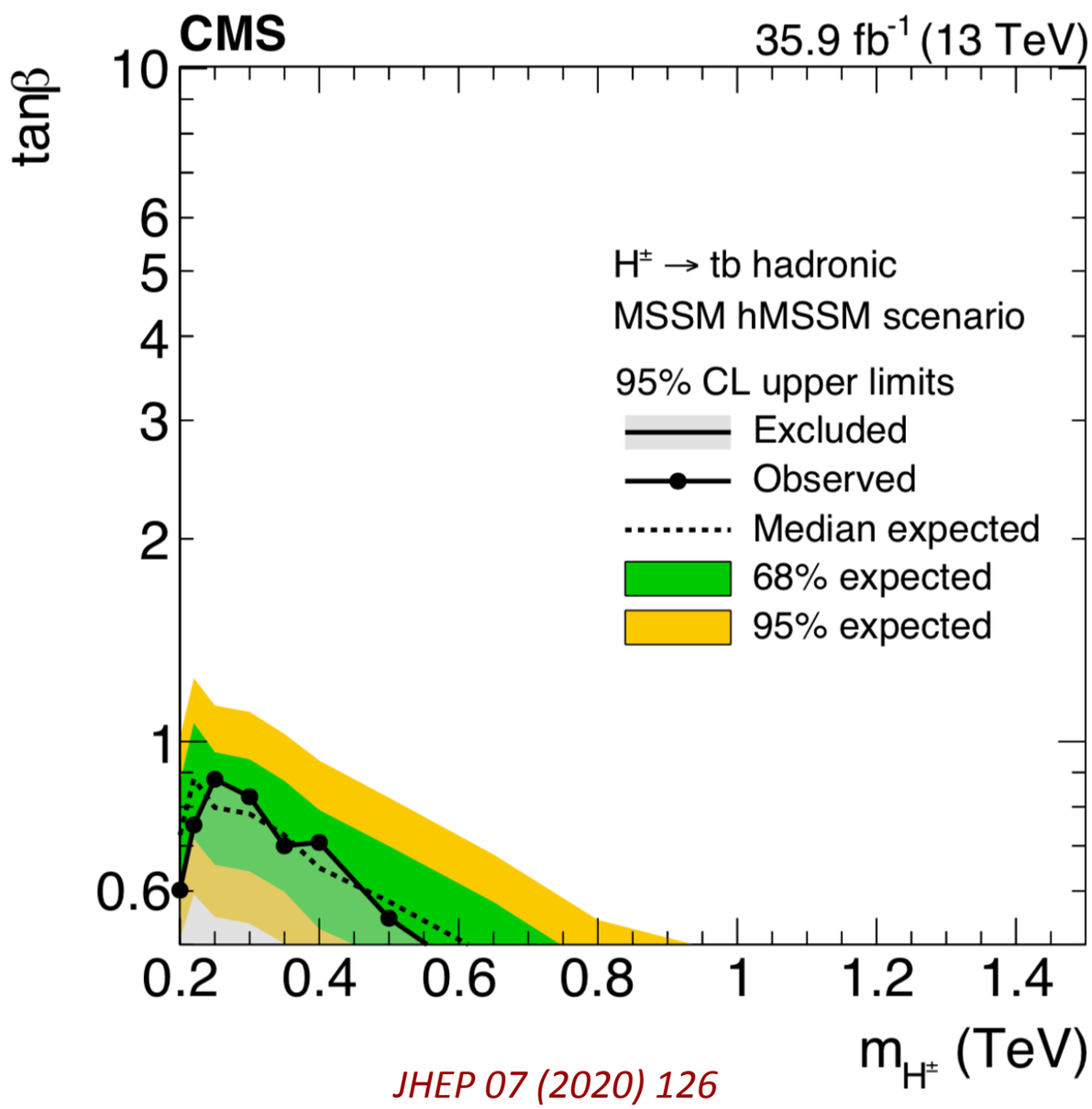
boosted t





Charged Higgs: $H^{\pm} \rightarrow tb$ Hadronic





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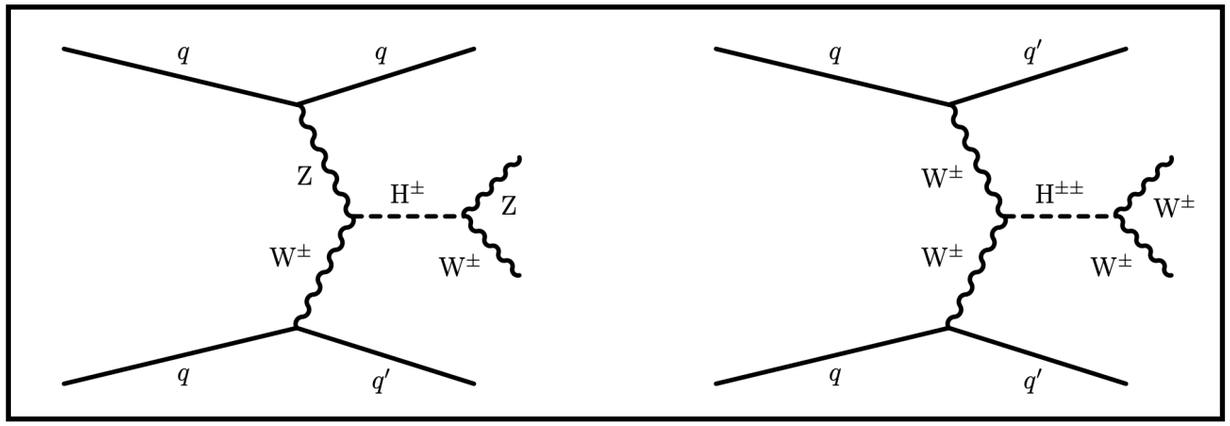
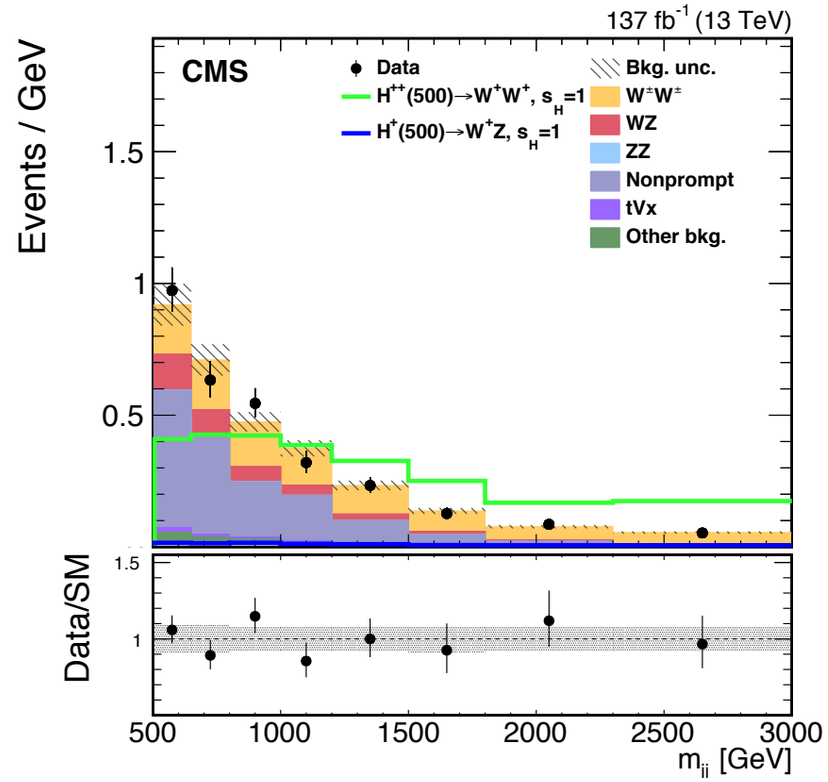
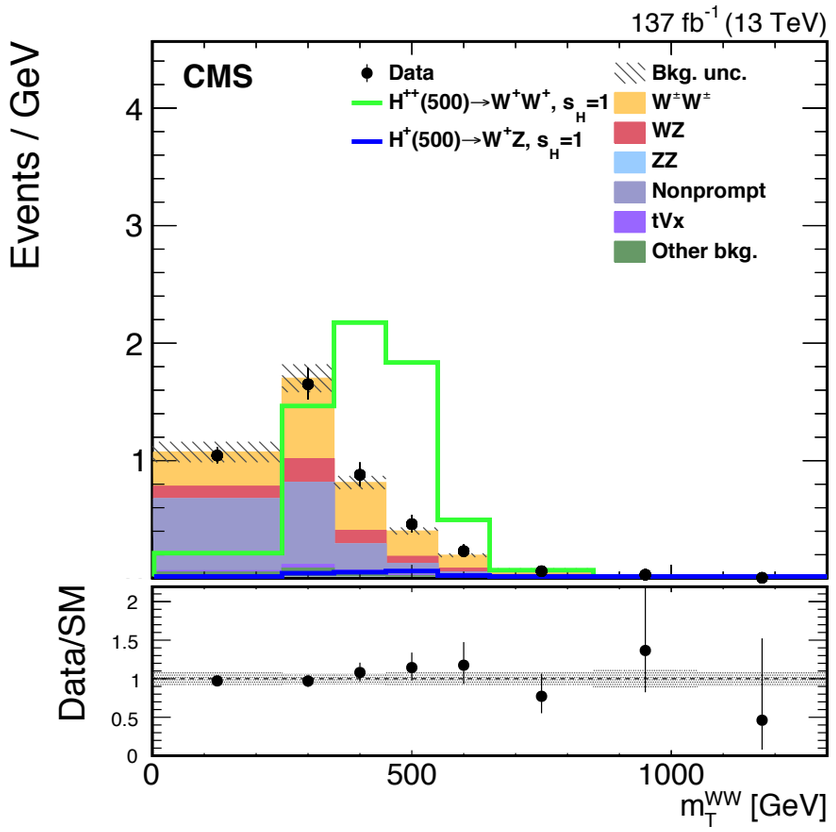
Model independent upper limit on the $\sigma_{H^{\pm}} \times B(H^{\pm} \rightarrow tb)$ is 6 to 0.007 pb are set for the Higgs mass range 200 to 3000 GeV

Charged Higgs Decay to Bosons

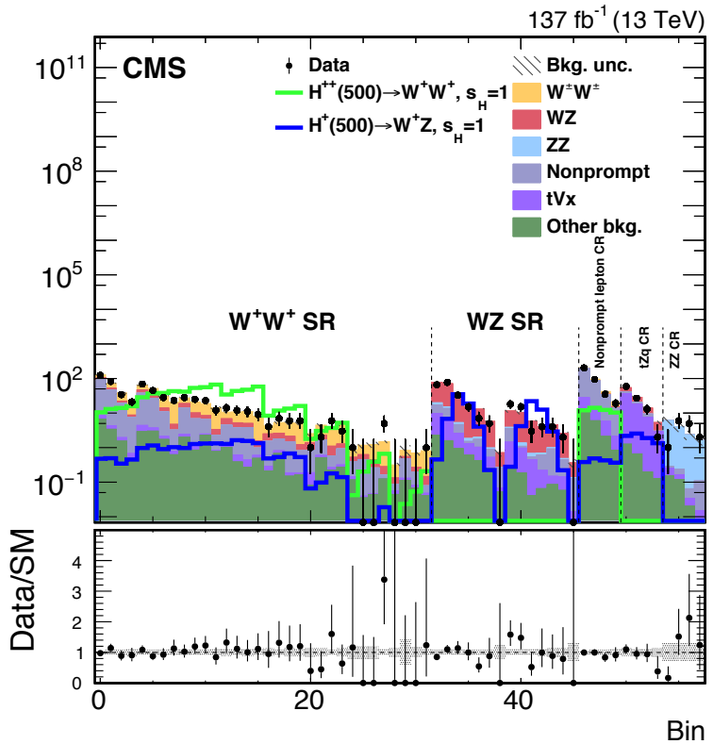


- ✓ Motivated by Georgi-Machacek model with SU(2) doublets or triplets scalars to the SM introduce couplings of gauge bosons to heavy neutral or charged Higgs bosons
- ✓ **Clean signature: Same Sign (2l) or (3l) final state + two VBF jets**
- ✓ **Search is done in bins of M_{jj} and M_T^{VV}**
- ✓ WW and WZ measured on the fly
- ✓ Non prompt / Fakes from data CR

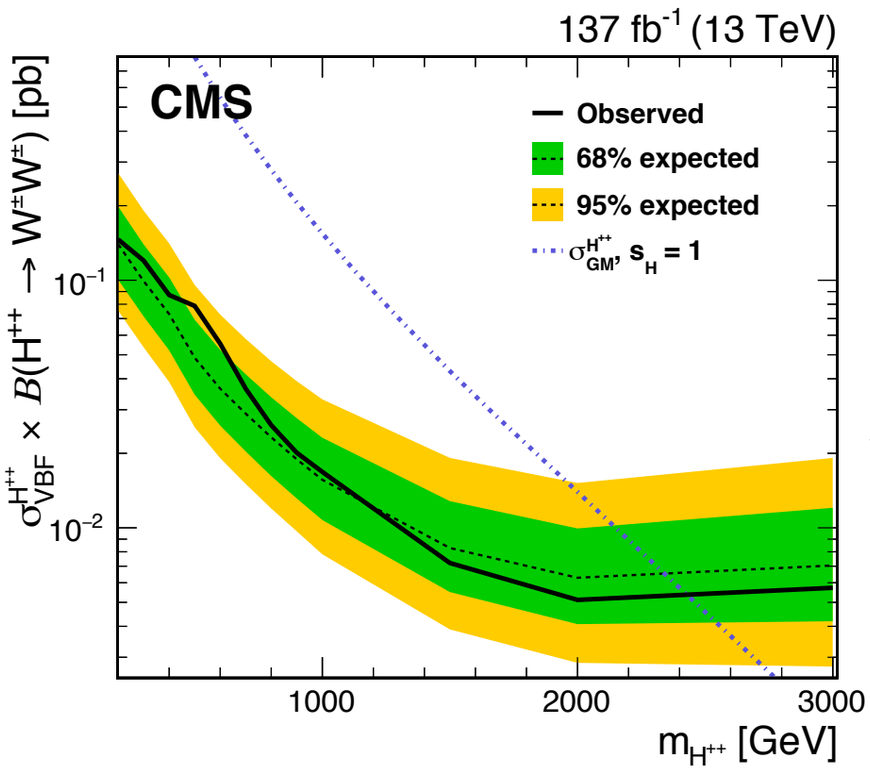




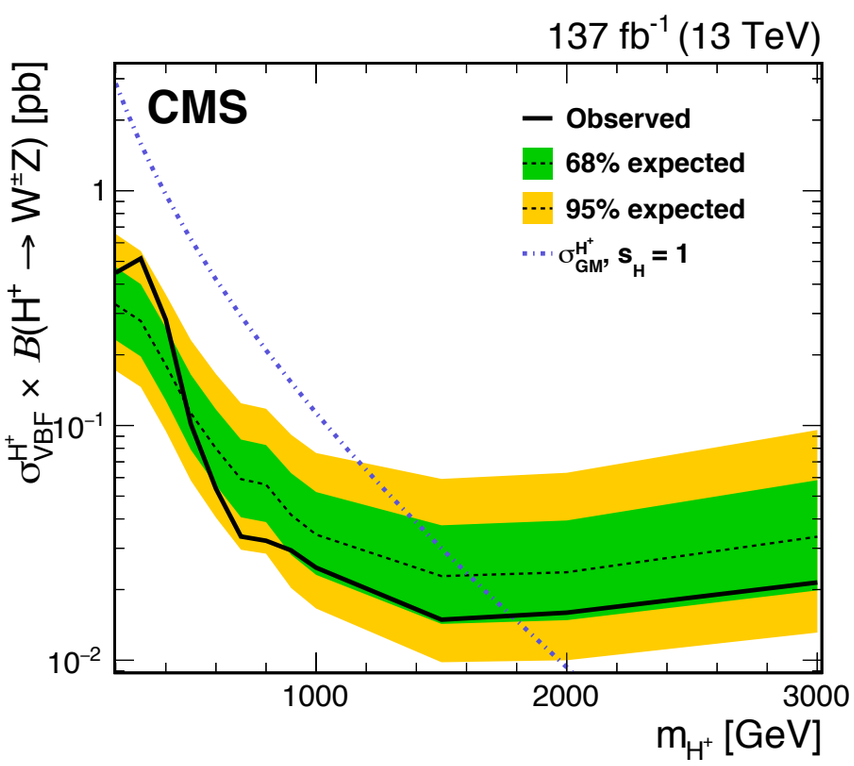
Charged Higgs Decay to Bosons



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



$H^{+} \to W^+Z$

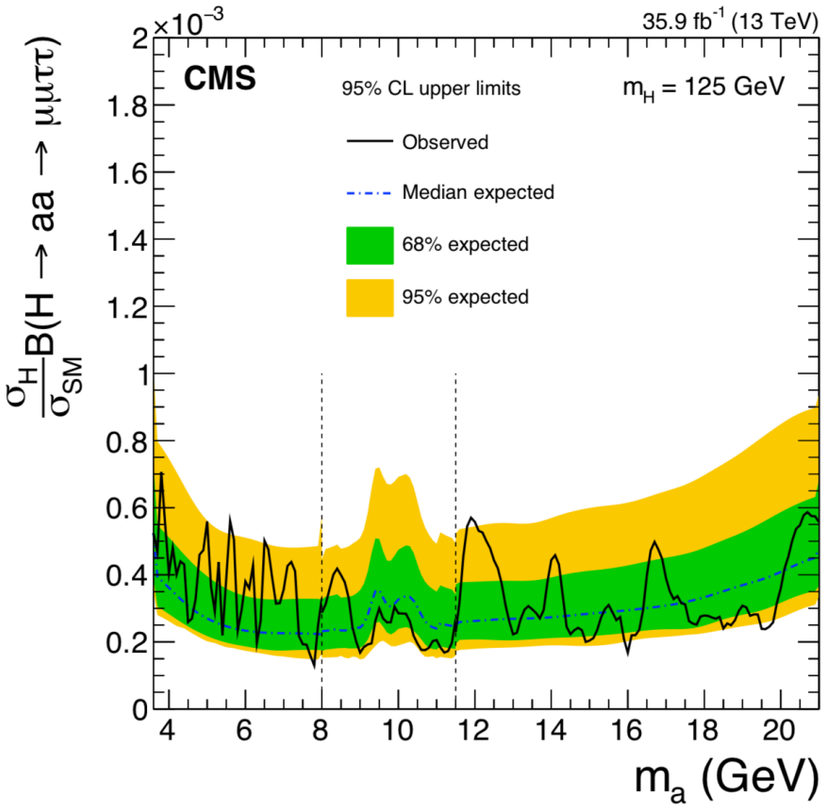


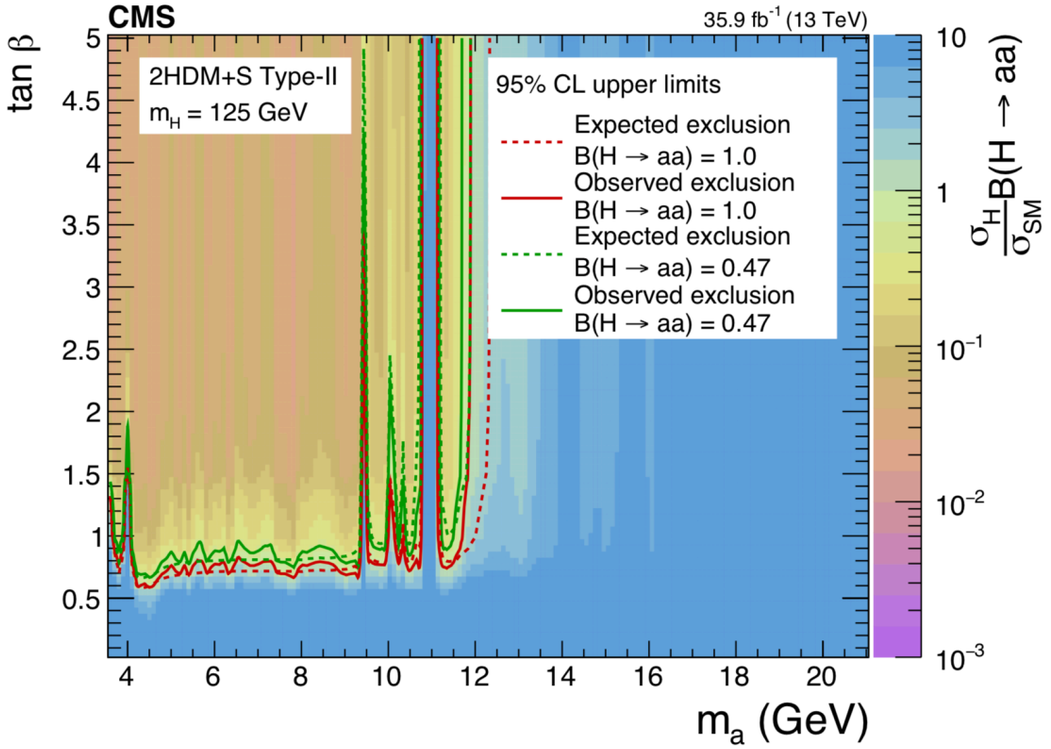
arXiv:2104.04762

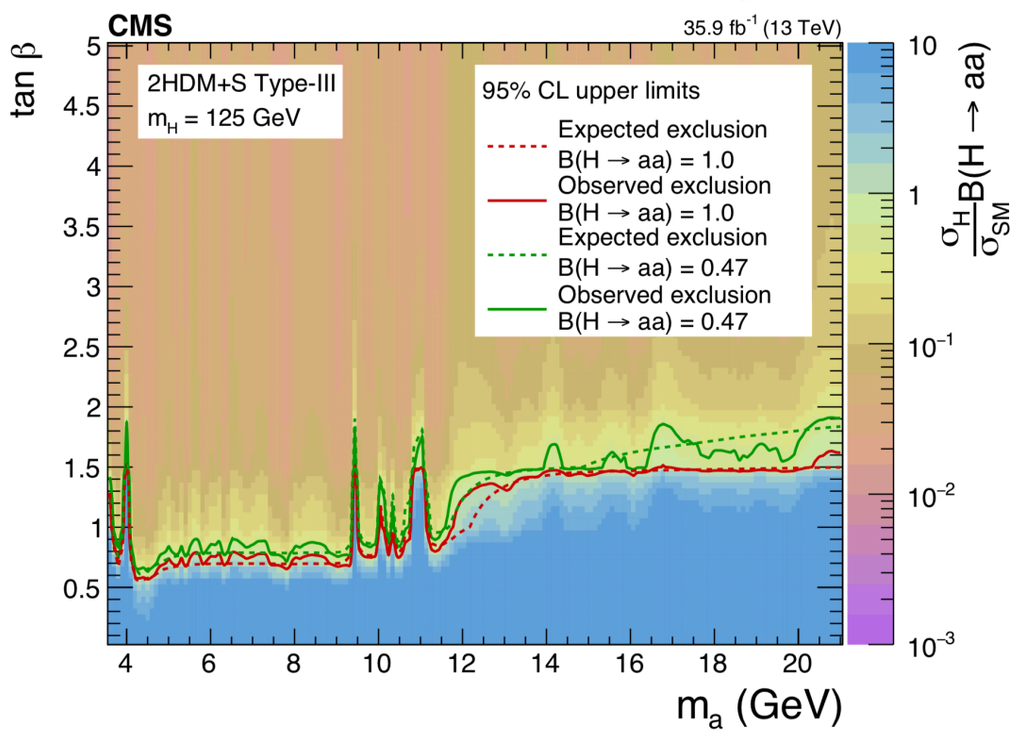
- No significant excess of events above the expectation from the SM
- Exclusion for charged Higgs $m_{H^{++}} \approx 2.5$ TeV and $m_{H^{+}} \approx 2$ TeV

$h \to aa \to \mu\mu\tau\tau$ *JHEP 08 (2020) 139*

- ☑ Mass range: 3.6 < m_a < 21 GeV
- ☑ h, H(300) production mechanisms: ggH (main) and VBF
- ☑ Used special reconstruction technique to efficiently identify $a \to \tau_h\tau_h$
- ☑ Signal extraction: fit to unbinned 2D $m(\mu,\mu)$ vs. $m(\mu,\mu,\tau_h,\tau_h)$ distribution
- ☑ Background estimation: Z+Jets and QCD-multijet dominates, modeled using CR in data







Summary & Outlook

- ☑ The recent results of charged higgs sector has been presented
- ☑ The discovery of a charged Higgs boson will be a clear sign of BSM physics
- ☑ New promising decay channel are being exploited
- ☑ Further improvements will be obtained with Run-3 data, and finally with HL-LHC data

CMS is analysing the full Run-2 dataset
and also preparing for Run-3 data

Stay tuned!

Acknowledgements

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

EXCELLENCE/0918/0379

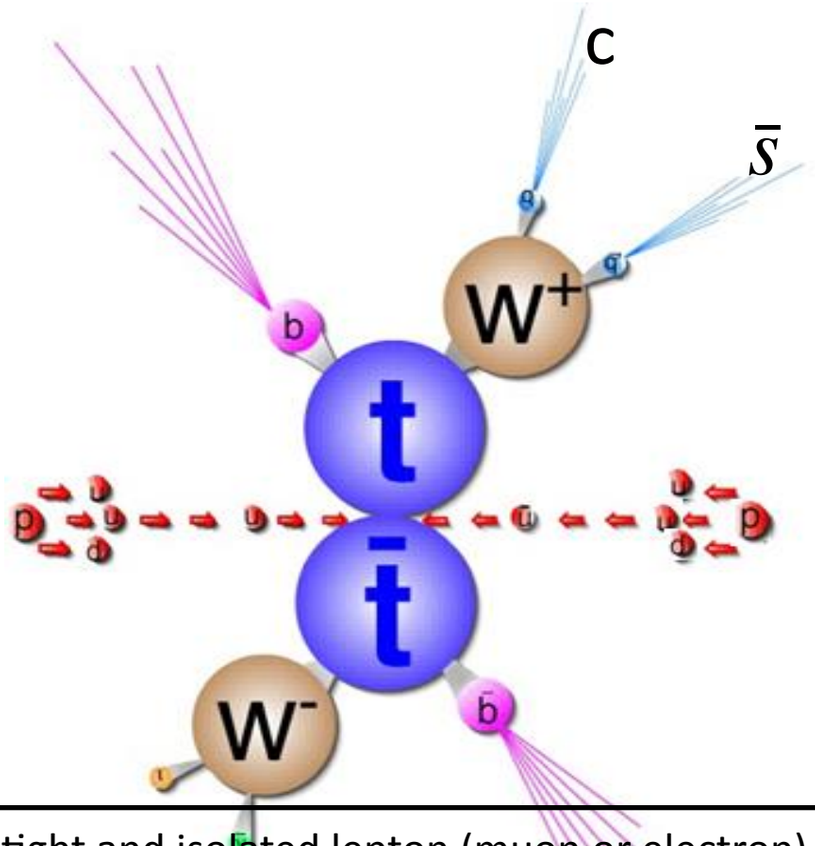
Ευρωπαϊκή Ένωση
Ευρωπαϊκά Διαρθρωτικά και Επενδυτικά Ταμεία

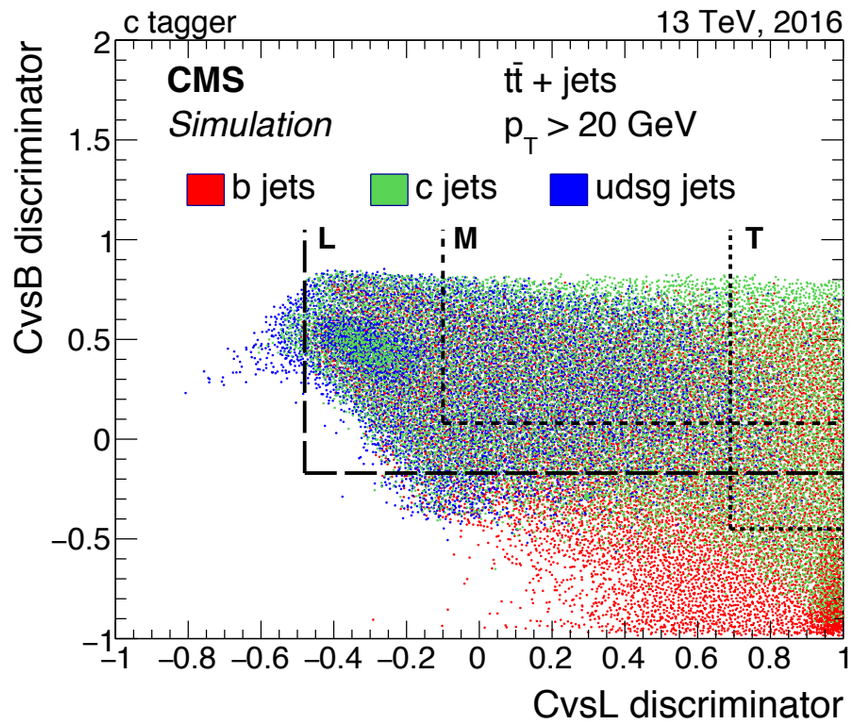
Κυπριακή Δημοκρατία

Διαρθρωτικά Ταμεία
της Ευρωπαϊκής Ένωσης στην Κύπρο

Back up

Back up:Charm Tagging





JINST 13 (2018) no.05, P05011

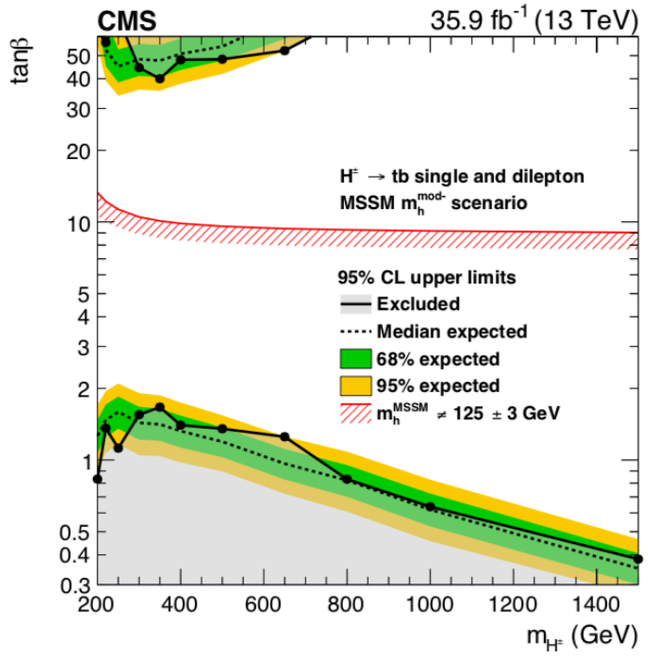
1 tight and isolated lepton (muon or electron)

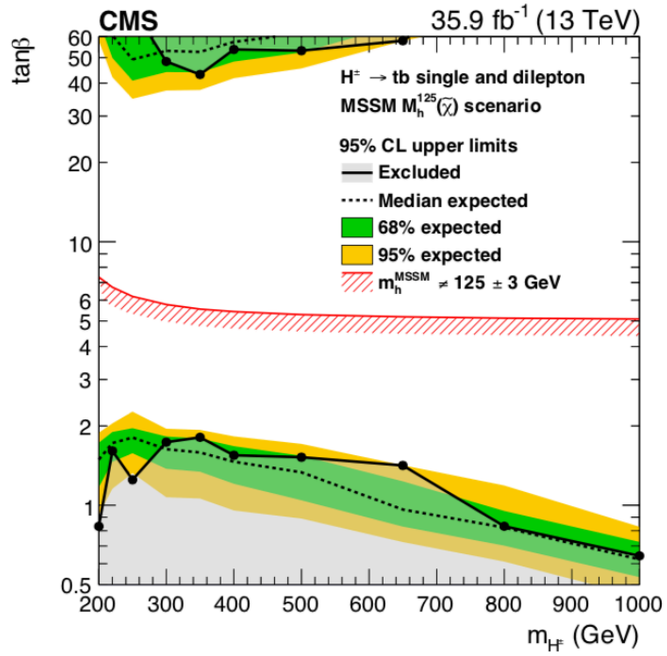
PF Rel. Isolation < 0.15 (muon) or 0.08(EB)/0.07(EE) (electron)

p_T > 26 GeV, $|\eta|$ < 2.4 [muon] and
p_T > 30 GeV, $|\eta|$ < 2.5 [electron]

- p_T > 25 GeV, $|\eta|$ < 2.4 [Jets]
- E_T^{miss} > 20 GeV
- At least 2 b-tagged jet
  (CSVv2 tagger with medium work point)

Back up: $H^{\pm} \to tb$ Leptonic

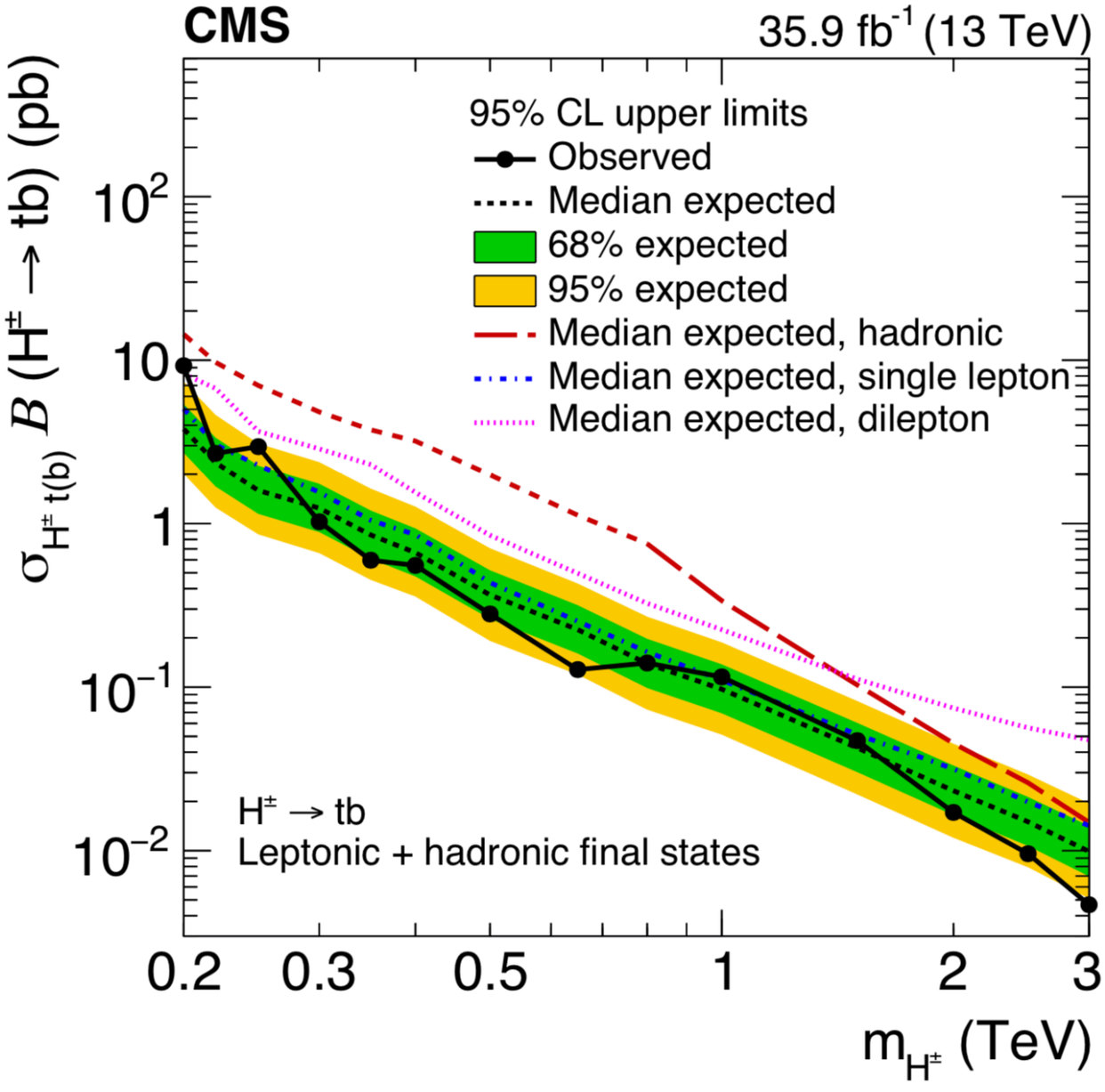




Common to 1ℓ and 2ℓ	H_{T}	Scalar sum of the jet transverse momenta
	p_{Tb}	Largest p_{T} among the b-tagged jets
	$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum
	$\min m(\ell,\mathrm{b})$	Minimum invariant mass between the lepton and the b-tagged jet
	$\max \Delta\eta(\mathrm{b},\mathrm{b})$	Maximum pseudorapidity separation between b-tagged jet pairs
	$\min \Delta R(\mathrm{b},\mathrm{b})$	Minimum separation between b-tagged jet pairs
	p_{T}-$\langle\mathrm{CSV}\rangle$	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 p_{T} 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}
	$m_{\mathrm{T}}(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of the system constituted by the lepton and the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
	$\Delta R(\ell,\mathrm{bb})$	Distance between the b-tagged jet pair with the smallest ΔR separation and the lepton
	$\langle\Delta R(\mathrm{b},\mathrm{b})\rangle$	Average separation between b-tagged jet pairs
2ℓ	N_{jets}	Number of selected jets
	$N_{\mathrm{b\,jets}}$	Number of selected b-tagged jets
	$\Delta R(\ell,\mathrm{b})$	Distance between the lepton and the b-tagged jet with largest transverse momenta
	$p_{\mathrm{T}\ell}$	Largest p_{T} between the leptons
	$\frac{p_{\mathrm{T}\ell 1}-p_{\mathrm{T}\ell 2}}{p_{\mathrm{T}\ell 1}+p_{\mathrm{T}\ell 2}}$	Lepton p_{T} asymmetry
	$m(\ell,\mathrm{b})$	Invariant mass of the lepton+b-tagged jet system with the largest p_{T} (top quark candidate)
	m_{T}^{min}	The smallest of the transverse masses constructed with the leading b-tagged jet and each of the two W boson hypotheses: $\min\left[m_{\mathrm{T}}(\mathrm{b}, p_{\mathrm{T}\ell 1}+\vec{p}_{\mathrm{T}}^{\mathrm{miss}}), m_{\mathrm{T}}(\mathrm{b}, p_{\mathrm{T}\ell 2}+\vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]$

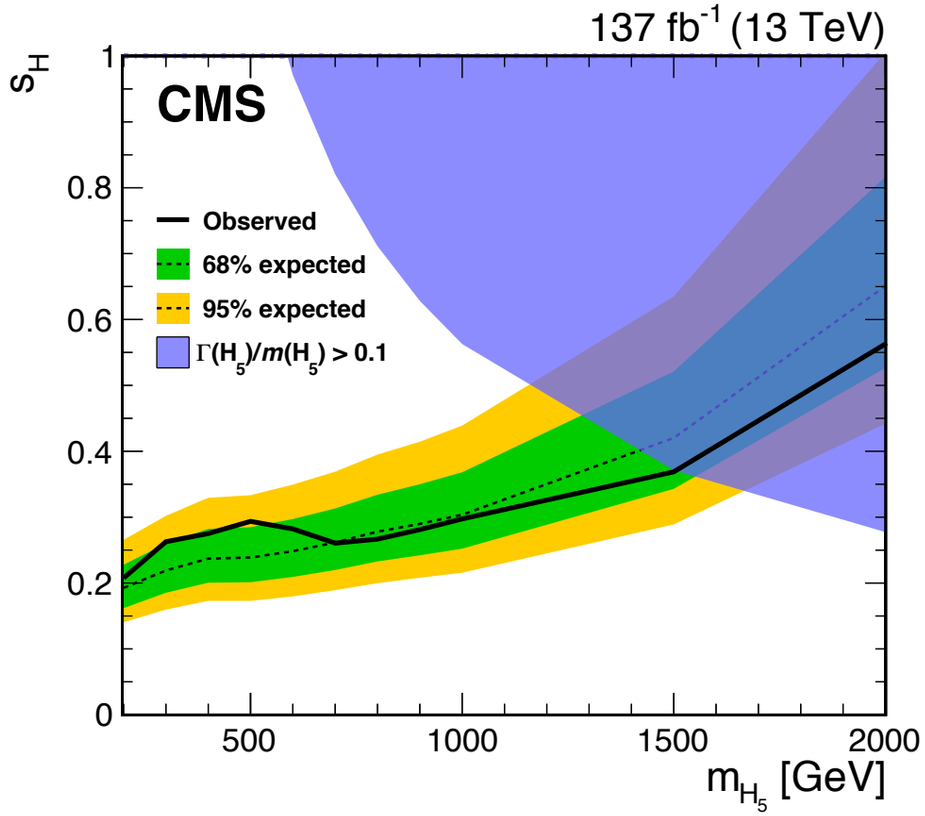
Back up: $H^{\pm} \rightarrow tb$ Hadronic

Combined with leptonic and hadronic final states



Back up:Charged Higgs Decay to Bosons

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



Backgrounds are divided in three classes:

- ✓ WW and WZ measured on the fly
- ✓ Non prompt / Fakes from data CR
- ✓ Prompt irreducible from simulations:
  - ✓ Measured in the CR with ZZ and tZq

Diboson Transverse mass

$$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$

E_i and $p_{z,i}$ are the energies and longitudinal components of the momenta of the leptons and neutrinos from the decay of the gauge bosons