Search for heavy $H^+ \to tb$

Proseminar: Physics at the Large Hadron Collider

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Outline

Standard model of particle physics (SM)

- Consistent theory that describes today's knowledge in particle physics
- High agreement with most experimental data
- Predicts one Higgs-Boson

- Open questions in particle physics:
  - Hierarchy problem
  - Neutrino masses
  - Matter–antimatter asymmetry
  - Dark matter

$\Rightarrow$ **BSM physics has to exist**

Figure 1 SM particles.

Physics beyond the Standard Model (BSM)

Minimal Supersymmetric Standard Model (MSSM)

- Considers only "the [minimum] number of new particle states and new interactions consistent with phenomenology"[1]
- Cures problems of the SM
- Supersymmetric extension of the SM
  - Superpartner for every SM particle differing by Spin-1/2

- Nomenclature:
  - Fermions: write s in front of name
  - Bosons: append -ino

Figure 2 Superpartners.

[1] *Weak Scale Supersymmetry* (Baer & Tata - 2006)

Higgs mechanism
Standard Model

- **Higgs field:**
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) + i\zeta(x) \end{pmatrix}$$
- **Lagrange density:**
$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V$$
$$V = \mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2$$
  - $\mu^2 < 0$
  - $\lambda > 0$
- **Vacuum expectation value:**
$$\phi_0 = \frac{|\mu|}{\sqrt{2\lambda}} = \frac{v}{\sqrt{2}} \approx \frac{246}{\sqrt{2}} \text{ GeV}$$

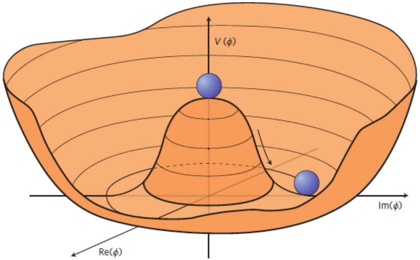


Figure 3 The Higgs potential.

Higgs mechanism
Supersymmetric 2HDM

- Single Higgsino leads to a gauge anomaly, theory would be inconsistent
- Simplest theory adds two scalar Higgs doublets (2HDM)
  - $\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \;\; a = 1, 2$
  - 8 fields
    - Reduced by 3 to give mass to $W^{+/-}, Z$
    - Remaining 5 are the pyhsical Higgs fields (H, h, A, $H^{+/-}$)[2]
  - Type-II: up- and down-type quarks couple to separate doublets
- α and β determine the interactions of Higgs fields with vector bosons + fermions
- ratio of vacuum expectation values: $\tan\beta = \frac{v_{\phi_1}}{v_{\phi_2}}$

$\Rightarrow$ **considered Theory:** SUSY $\rightarrow$ MSSM $\rightarrow$ 2HDM $\rightarrow$ Type-II

[2] *Theory and phenomenology of two-Higgs-doublet models* (Branco, Ferreira, Lavoura, Rebelo, Sher, Silva - 2006)

Outline

The Experiment

Large Hadron Collider (Proton Mode)

- Circular collider with circumference of 26.7 km
- World's largest and highest-energy artificial particle collider
- Proton-proton collisions
- $\sqrt{s}$ = 13 TeV
- L = $2.1 \cdot 10^{34}$ cm^{-2}s^{-1}

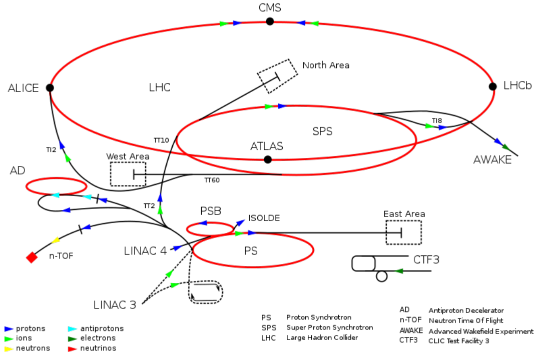
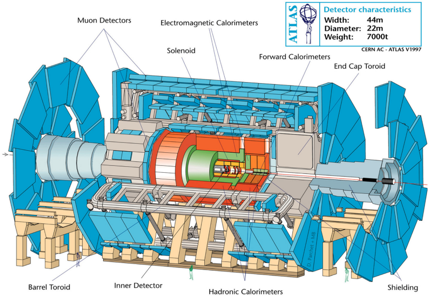


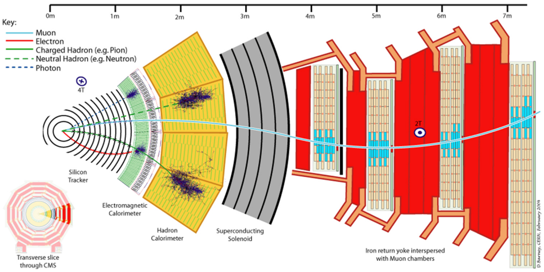
Figure 4 CERN accelerator complex.

The Experiment
Detectors

ATLAS
(A Toroidal LHC Apparatus)



CMS
(Compact Muon Solenoid)

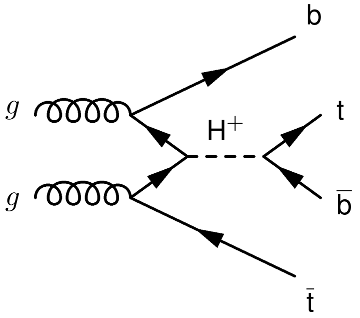


Outline

The search for new physics

The event:

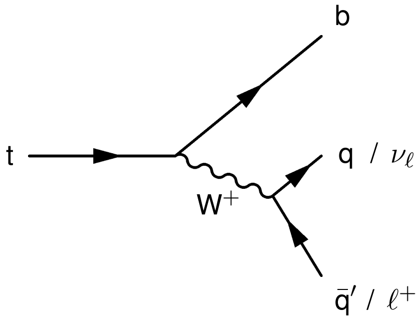
- Search for heavy charged H production (in association with tb)
  - Heavy: $\mathrm{m_{H^{\pm}}} > \mathrm{m_t}$
- Charged H decaying into tb
  - Higgs coupling $\propto$ particle mass
- Large b-jet multiplicity



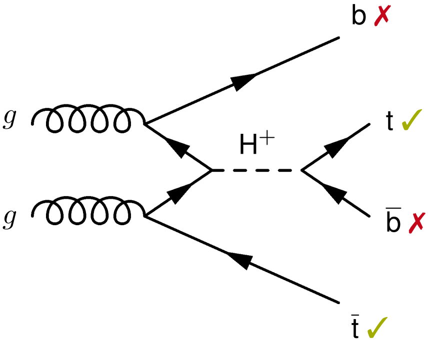
The event

The top quark

- Top quark decay leads to clear signature in the detector
- $m_t = 172.76 \pm 0.3$ GeV
  $\Rightarrow$ short lifetime $\tau \approx 5 \cdot 10^{-25}$ s
- t decay via weak force faster than the hadronization time
- 99.8% of the top quarks decay to bW
  $\Rightarrow$ CKM-preferred
- W decays leptonically or hadronically



The event



The event
b-tagging

- High b-jet multiplicity
- $\mathrm{m_b} = 4.18$ GeV much more massive than its decay products
  $\Rightarrow$ decay products have high $\mathrm{p_t}$
- b - decay CKM-suppressed
  $\Rightarrow$ Long lifetime
  $\Rightarrow$ Secondary vertex tracking

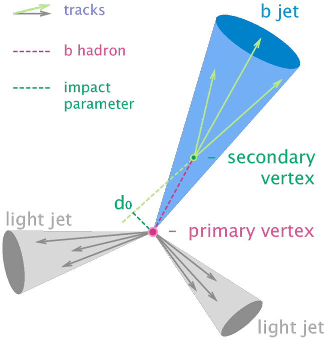
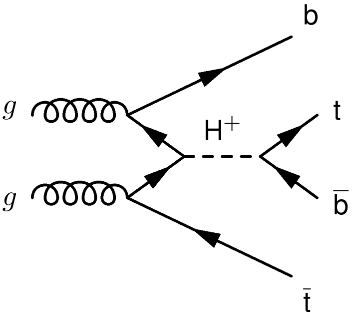
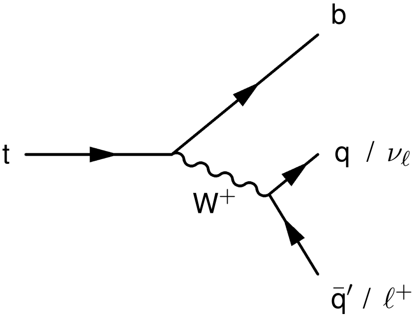


Figure 5 b Identification.

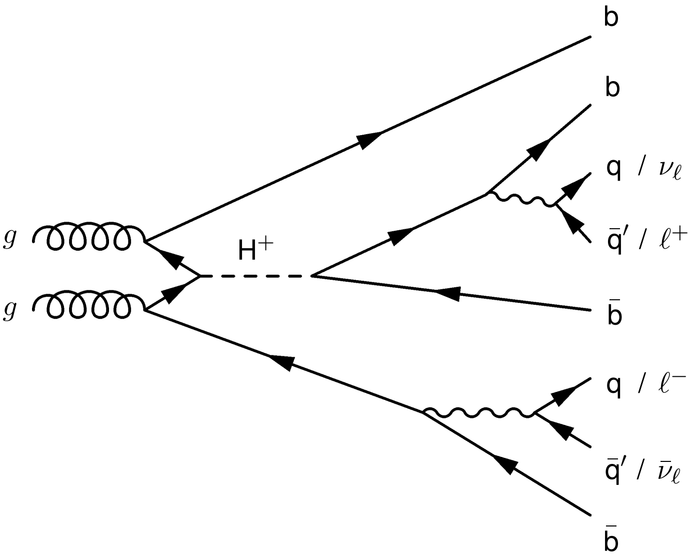
The event





The event

- 8 decay products
- 4 directly related to $\mathrm{H}^{\pm}$
- 4 b
- Up to 4 light jets
- Up to two l/ν_l - pairs



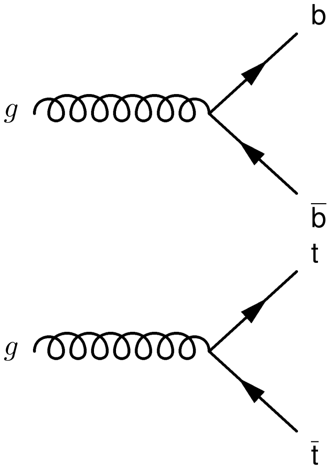
Background

Main backgrounds:

- QCD mulijet events
- $t\bar{t}\ (+b\bar{b})$

Other backgrounds:

- Single top quark production
- $t\bar{t} + X$ with $X = (W, Z, \gamma, H, t\bar{t})$
- V+jets
- Diboson (WZ, ZZ, WW, VH)



Outline

Analysis strategy
General approach

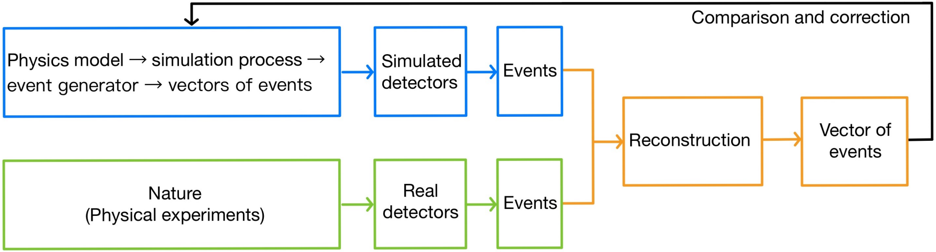


Figure 6 Event generation, detection and reconstruction.

Analysis strategy

Search for charged H to tb

1. Monte Carlo simulations of
   (a) SM processes (⇒ Background)
   (b) 2HDM Type-II for 18 $m_{H^\pm} \in [200\ \mathrm{GeV}, 2000\ \mathrm{GeV}]$ (⇒ Signal)
2. Kinematic restrictions on reconstructed observables to select specific phase-space region ($H^\pm \to t\bar{b}$)
3. Machine Learning to determine signal
4. Apply maximum likelihood approach to fit MC predictions to the data
5. Apply identical restrictions to data and compare it to simulation

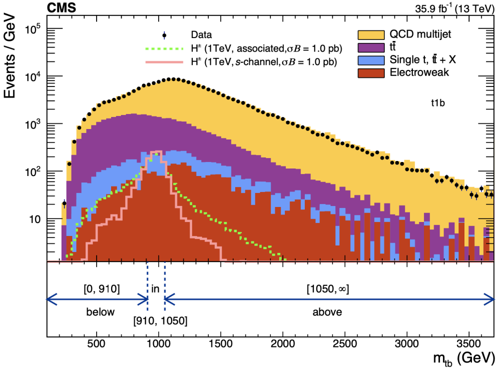


Figure 7 Data and SM background as a function of $m_{H^\pm}$ (CMS all-jet).

Event Selection

Event categories

CMS all-jet final state

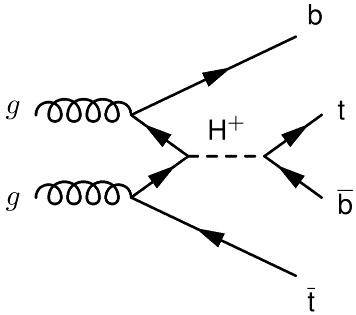
- resolved: qq from W decay + additional jet b tagged
- boosted: top-flavored jet / W-jet
- at least one b-tagged jet
- no leptons / τ-jets

CMS (l+j) final state

- single-lepton
  - one $e/$ or μ
- dilepton
  - additional opposite-sign e/μ
- at least two jets
  - at least one b-tagged

ATLAS (1l+j) final state

- one e/μ with a lepton of the same flavor
- at least five jets
  - at least two b-tagged



Event Selection
Machine Learning

CMS (single lepton, jet only)

- Boosted decision tree with gradient descent (BDTG)
- train-val-test: 1/3 of the data set each

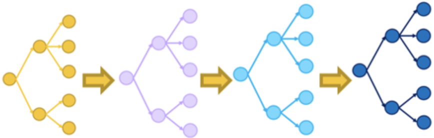


Figure 8 Schematic representation of a BDT.

CMS (dilepton)

- Deep Neural Network
- train-val-test: 1/3 of the data set each

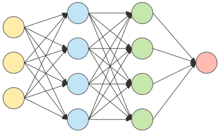


Figure 9 Schematic representation of a NN.

Event Selection

Input parameters (CMS lep)

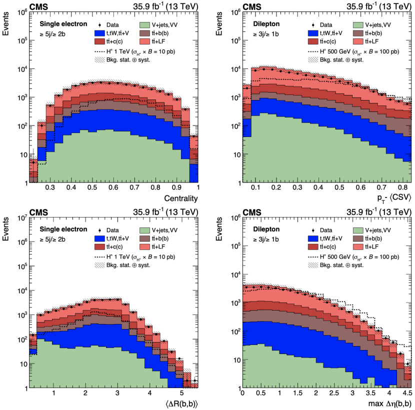


Figure 10 Representative input parameters of the NN.

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_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-⟨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 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
	$m_T(\ell, \vec{p}_T^{miss})$	Transverse mass of the system constituted by the lepton and the $\vec{p}_T^{miss}$
	$\Delta R(\ell, bb)$	Distance between the b-tagged jet pair with the smallest ΔR separation and the lepton
	$\langle \Delta R(b, b) \rangle$	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 p_T 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+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: $\min\left[m_T(b, p_{T\ell 1} + \vec{p}_T^{miss}), m_T(b, p_{T\ell 2} + \vec{p}_T^{miss})\right]$

Figure 11 Input variables used in the analysis of the single-lepton and dilepton final states.

Event Selection

Machine Learning

ATLAS

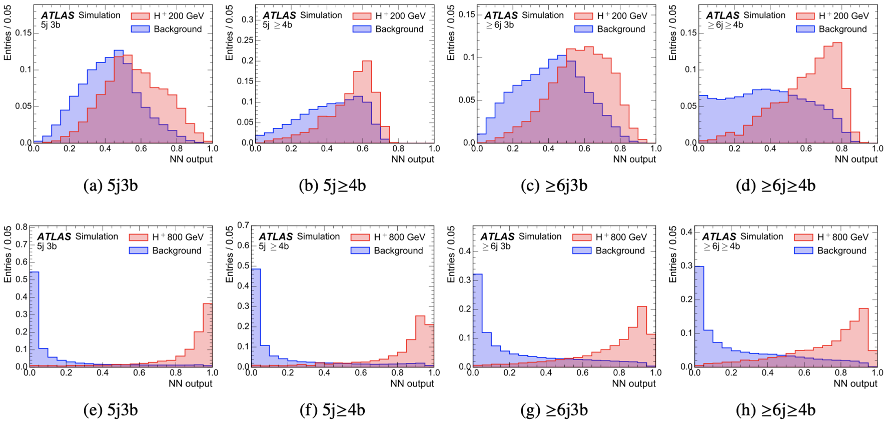
- Neural Network (NN)
- Two fully connected layers of 64 nodes
- Activation function: rectified linear units
- Batch normalisation
- Loss function: binary-cross-entropy
- Optimizer: Adam
- Dropout at 10% rate

NN variables
p_T of the leading jet
p_T of fifth leading jet
Scalar sum of the p_T of all jets
Second Fox–Wolfram moment calculated using all jets and leptons [97]
Invariant mass of the b-jet pair with minimum ΔR
Invariant mass of the b-jet pair with maximum p_T
Largest invariant mass of a b-jet pair
Invariant mass of the jet triplet with maximum p_T
Invariant mass of the untagged jet-pair with minimum ΔR
Average ΔR between all b-jet pairs in the event
ΔR between the lepton and the pair of b-jets with smallest ΔR
Centrality calculated using all jets and leptons
Kinematic discriminant D defined in the text
Number of jets (only in ≥6j3b and ≥6j≥4b regions)
Number of b-jets (only in 5j≥4b and ≥6j≥4b regions)

Figure 12 Input parameters of the NN.

Event Selection

Network output (Atlas)



(a) 5j3b (b) 5j≥4b (c) ≥6j3b (d) ≥6j≥4b

(e) 5j3b (f) 5j≥4b (g) ≥6j3b (h) ≥6j≥4b

Figure 13 Expected distributions of the NN output for different and final states and $m_{H^{\pm}}$.

Systematic Uncertainties

- Pileup
- Jet energy scale (JES)
- Jet energy resolution (JER)
- Uncertainty integrated luminosity (ATLAS: 1.7%, CMS: 2.5%)
- B-tagging / misstagging uncertainty
- Correction factors (CF) are applied to compensate the error
  - Control region: Hadronical/leptonical vector boson decay
- event acceptance $\mathrm{H}^{\pm}$ signal is mass dependent
  - 2% at 200 GeV
  - 8.5% at 1000 GeV
  - 6% at 2000 GeV

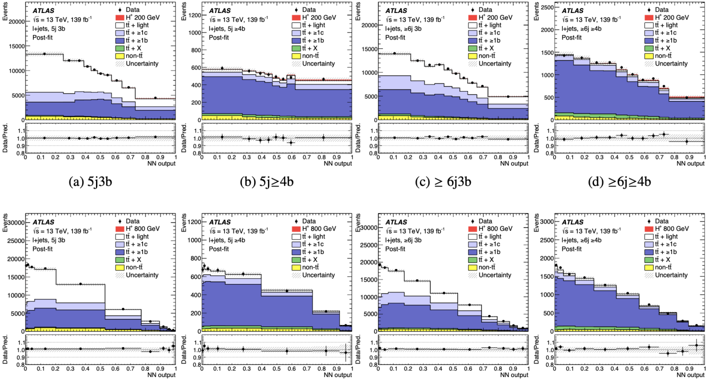
Outline

Results
Overview

1. ATLAS
2. CMS jet
3. CMS lep
4. CMS combined

Results

Atlas



(a) 5j3b (b) 5j≥4b (c) ≥ 6j3b (d) ≥6j≥4b

(e) 5j3b (f) 5j≥4b (g) ≥ 6j3b (h) ≥6j≥4b

Figure 14 NN output after fit for 200 GeV (top) and 800 GeV (bottom) $m_{H^\pm}$ hypotheses in the four analysis regions.

Results
Atlas

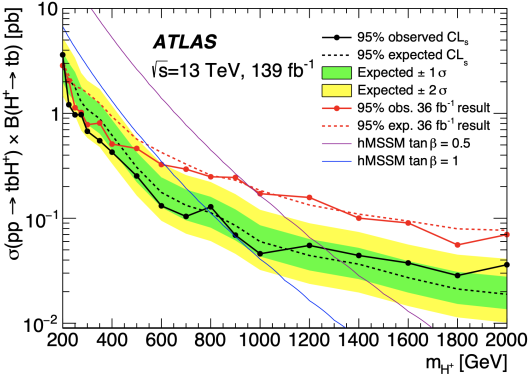


Figure 15 Observed and expected upper limits for the production of $\mathrm{H}^{\pm} \to \mathrm{tb}$ in association with a top quark and a bottom quark. NN output distribution is used in maximum likelihood fit.

Results
Atlas

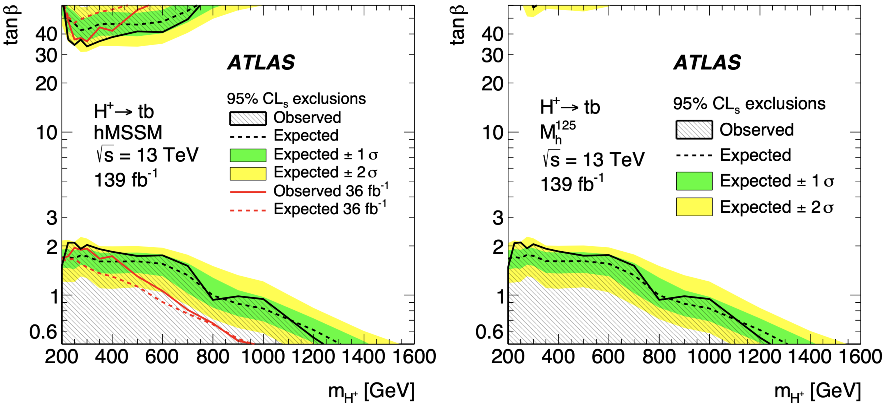


Figure 16 Observed and expected limits on $\tan\beta = \frac{v_{\phi_1}}{v_{\phi_2}}$ as a function of $m_{H^\pm}$.

Results
CMS jet

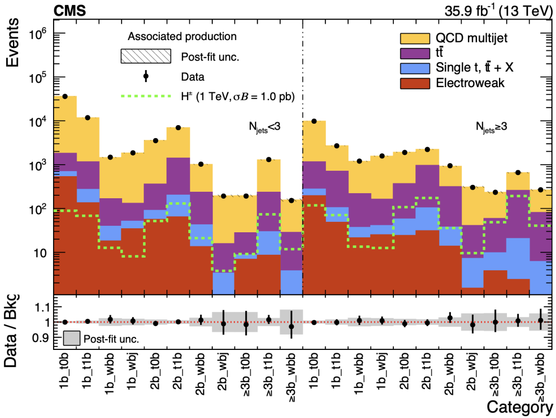


Figure 17 Expected event yields for the boosted analysis.

Results

CMS jet

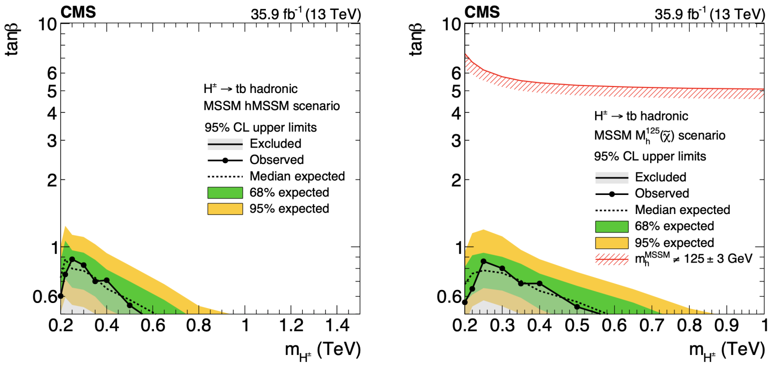


Figure 18 Excluded parameter space region in the hMSSM scenario (left) and M125($\tilde{\chi}$) (right) using the association production model. The invariant mass $\mathrm{m_{tb}}$ of the $\mathrm{H}^{\pm}$ candidate is used in a binned ML fit.

Results

CMS lep

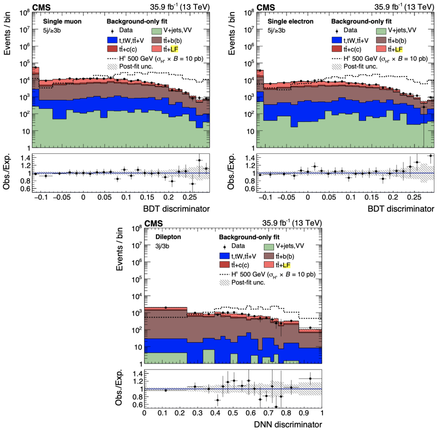


Figure 19 MVA outputs of the data and the SM expectation after the background-only fit.

Results

CMS lep

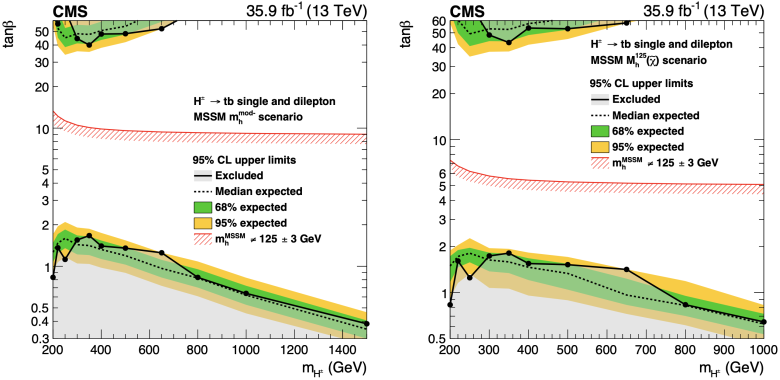


Figure 20 Excluded parameter space regions.

Results

CMS combinded

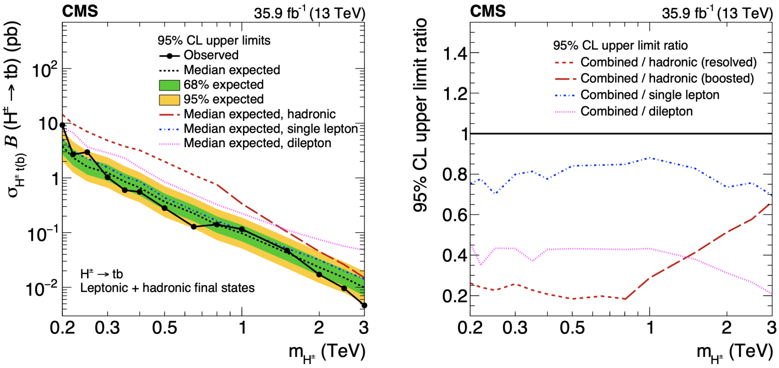


Figure 21 Upper limits at 95% CL on the product of the H^+ production cross section and branching fraction as a function of $\mathrm{m}_{\mathrm{H}^\pm}$.

Conclusion

Search for $H^+ \to tb$

ATLAS

- no significant excess above the expected SM background found
- σ x $\mathcal{B}$ improved by 5% to 70% depending on the $m_{H^\pm}$

CMS

- No significant deviation is observed above the expected SM background
- for production in association with a top quark, limits of 21.3 to 0.007 pb are set for $m_{H^\pm}$ in the range 0.2 to 3 TeV
- tanβ excluded for in the range of 0.5-2.1 for $m_{H^\pm}$ between 200 and 1200 GeV

References

CMS Collaboration
Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV
Journal of High Energy Physics (2019), arXiv:1908.09206.

CMS Collaboration
Search for charged Higgs bosons decaying into a top and a bottom quark in the all-jet final state of pp collisions at $\sqrt{s}$ = 13 TeV
Journal of High Energy Physics (2020), arXiv:2001.07763.

ATLAS Collaboration
Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s}$ = 13 TeV with the ATLAS detector
Journal of High Energy Physics (2021), arXiv:2102.10076.

Thank you for your attention!

Special thanks to Dr. Dominik Duda

Outline

Further production channels

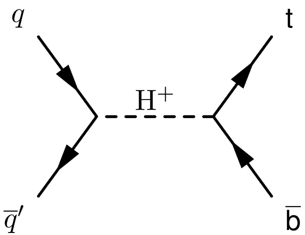


Figure 22 s-channel process.

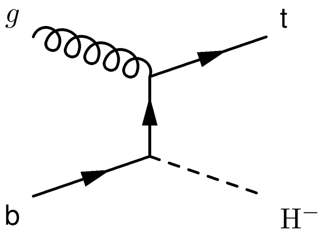


Figure 23 Five-flavor scheme (5FS).

Event Selection

Phase space restrictions

ATLAS (1l+j) final state

- Exactly $1\ e/\mu$
  - $p_{\mathrm{T}} > 27\mathrm{GeV}$
- $\nu_{e/\mu}$ within $\Delta R < 0.15$
- $\geq 5j, \geq 2b$

CMS (l+j) final state

- At least $1\ e/\mu$
  - $p_{\mathrm{T}} > 35/30\mathrm{GeV}$
- $p_{\mathrm{T}}^{\mathrm{miss}} > 30\mathrm{GeV}$

CMS all-jet final state

- $p_{\mathrm{T}} > 40\mathrm{GeV}$
- $|\eta| < 2.4$
- $H_{\mathrm{T}}^{\mathrm{trig}} < 450\ \mathrm{GeV}$
- No e/μ with $p_{\mathrm{T}} > 10\ \mathrm{GeV}$
- $p_{\mathrm{T}}^{\mathrm{miss}} < 200\ \mathrm{GeV}$