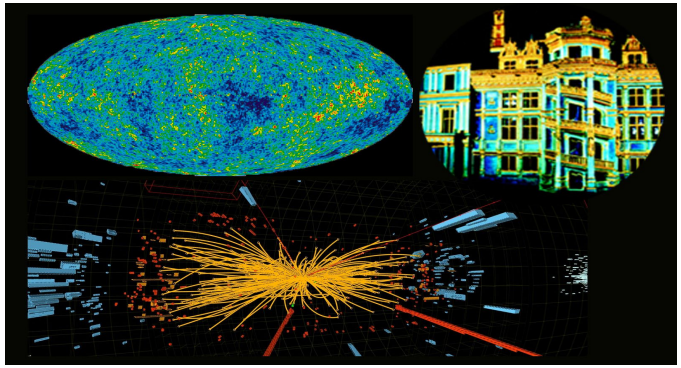
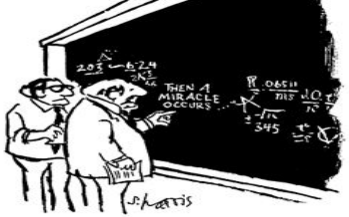


Searches for an extended Higgs boson sector at CMS

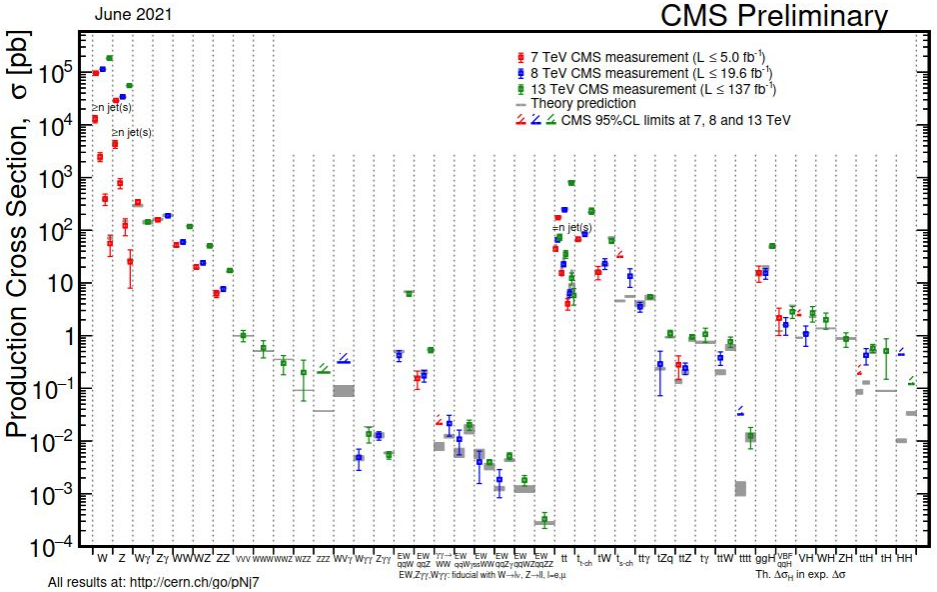
Blois 2021: 32nd Rencontres de Blois
Particle Physics and Cosmology

Khawla Jaffel
on behalf of the CMS collaboration

Why probing extended Higgs sector ?



- **The impressive performance of the Standard Model :**
  - The SM agrees reasonably well with our measurements across 9 orders of magnitude.
- **But that's not the whole story!**
  - The SM provides no dark matter candidate and no explanation for the matter–antimatter asymmetry in the universe, can not explain the strong CP problem or the muon g-2 anomaly… **So there must be physics beyond !**
- **No requirement for the Higgs sector to be minimal.**
  - Extended Higgs sectors come to address some of the shortcomings of the SM.
  - Searches for new BSM physics still remain a frontier in particle physics research.



[CMSPublic/PhysicsResultsCombined]

“ Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed.”

-- Albert Einstein --

Heisenberg's 1926 lecture at Berlin.

- Many of the proposed new physics models come with an extended Higgs sector:
  - **Simple extension :**
    - **2HDMs type (I, II, X Lepton-specific and Y Flipped, III, FCNC-free) :** was proposed as a means to provide an extra source of CP-violation.
    - **MSSM :** Is the SUSY extension with minimal particle content and minimal gauge group and the MSSM Higgs sector corresponds to a type II 2HDM.
      It requires two complex Higgs doublets and it provides a dark matter candidate, allows for the unification of the gauge couplings, and mitigates the hierarchy problem.
  - **More complex models :** N2HDM (2HDM+Singlet, Triplet…), NMSSM
- **Two different approaches can be used to discover or set limits on these models.:**

1. Through their modifications to the SM-like Higgs couplings; can be tested by Higgs coupling precision measurements.
2. Direct searches for BSM Higgses at high energy colliders.

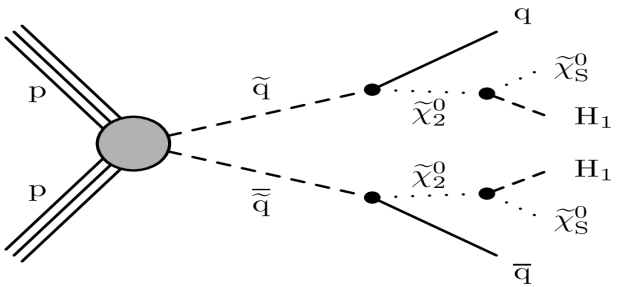
⇒ The discovery of any BSM Higgses will be our evidence for the existence of an extended Higgs sector.

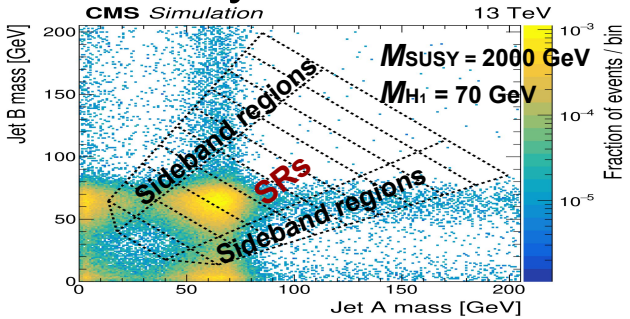
In this talk :

- We will cover some of the **recent direct searches results by the CMS experiment** in the context of the extended Higgs boson sector.
  - **Searches for neutral Higgs bosons:**
    - Light $H_1 \rightarrow bb$: **SUSY** cascade decays ⇒ Ongoing
    - Light $H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$: Exotic decay model independent ⇒ Ongoing
    - Heavy $H \rightarrow h(\rightarrow \tau\tau)\, h_S\, (\rightarrow bb)$: NMSSM ⇒ Published
    - Heavy $H \rightarrow WW \rightarrow (l\nu\, l\nu,\ l\nu\, qq)$: 2HDM ⇒ Published
  - **Searches for charged Higgs bosons:**
    - Heavy $H^{\pm} \rightarrow W^{\pm} Z$ and $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$: Georgi–Machacek (GM) ⇒ Published

CMS-PAS-HIG-20-018

Pair of boosted light $H_1 \rightarrow bb$ from SUSY cascade decays :

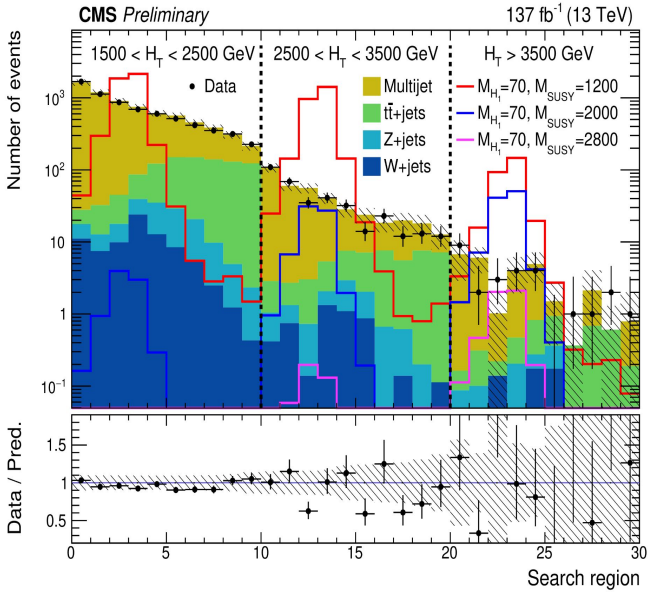




- **Search in the context of NMSSM.**
  - $MH_1 \leq 125$ GeV : $BR(H_1 \rightarrow bb)$ decreases for larger H_1 masses as the WW and ZZ decay channels open up.
  - The search targets squarks and gluinos with masses MSUSY ≥1200 GeV.

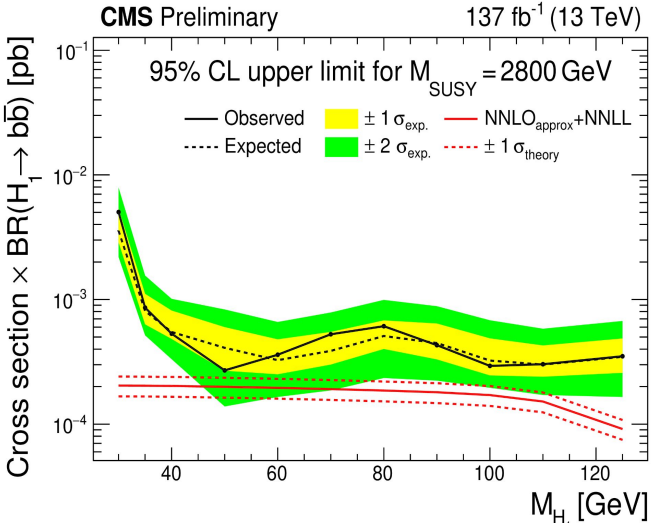
- **Event selection:**
  - High HT == $\sum_{\text{AK4 jets}} p_T$ + >=1 AK4 Jets
  - >= 2 AK8 Jets **A and B** (wide-angle soft radiation is recursively removed from the jet) + double-b tagging algorithm used to reconstruct the b quarks originating from the H_1 bosons decay.

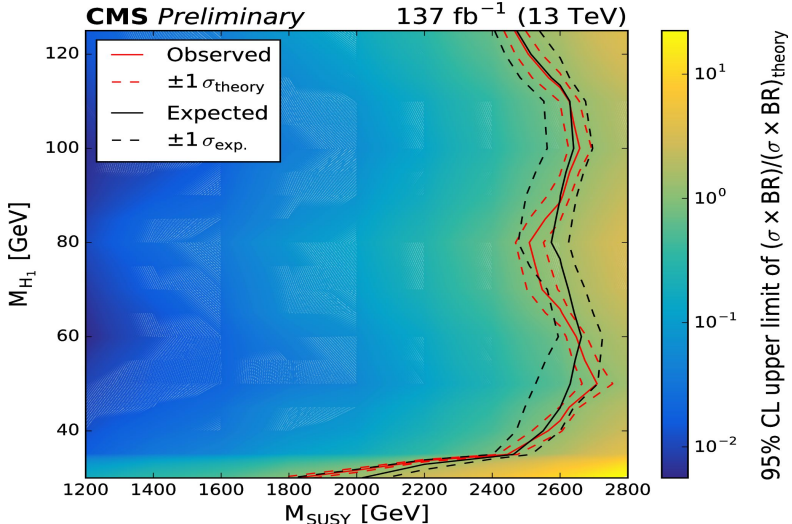
- **Events Classification:**
  3 HT regions 1500–2500, 2500–3500, and 3500+ GeV. Each HT bin is divided into 10 mass SR.
  - Total of 30 search regions for each data-taking year.



Pair of boosted light $H_1 \rightarrow bb$ from SUSY cascade decays :

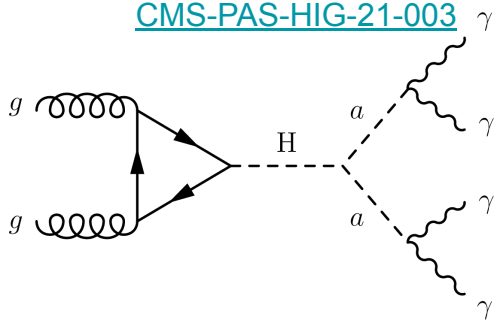
- Binned maximum likelihood fits to the data in the 90 search regions (10 regions S_i per HT bin for each data-taking year) are carried out under background-only and signal-plus-background hypotheses.
- **No evidence is found for any excess of events beyond the background expectations of the SM.**
  - H_1 bosons arising from the decays of squarks or gluinos, with masses in the range 40–120 GeV are excluded at the 95% confidence level.
  - **SUSY masses from 1200–2500 GeV, are excluded at the 95% confidence level.**





H → aa → γγγγ :

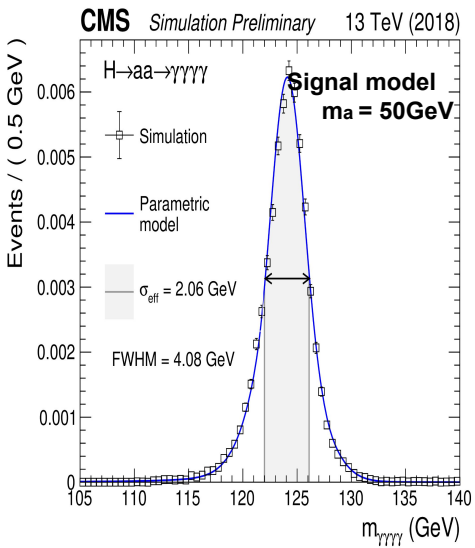
CMS-PAS-HIG-21-003

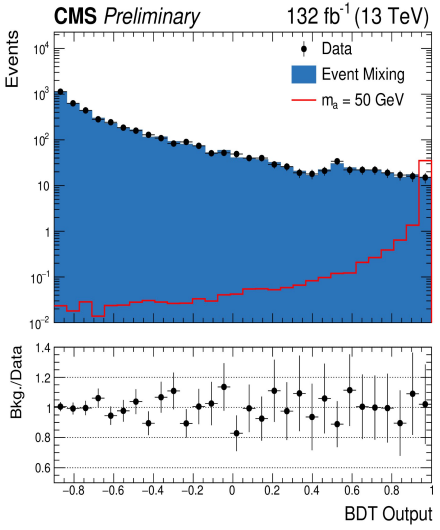


- **Signature :** Two light pseudo-scalars (a) that range in mass from 15 to 60 GeV decay to 4 **well** isolated photons.
- **Main BKG:** γγ + jets, γ + jets, as well as multijet events
- **A BDT classifier** is trained to separate signal from background, parameterized as a function of ma.
  - To maximize the sensitivity of the analysis, events are categorized according to the output of the BDT.
  - The categorization is optimized by maximizing the Approximate Mean Significance :

$$AMS = \sqrt{2\left((S+B)\ln\left(1+\frac{S}{B}\right)-S\right)}$$

- **Double-sided Crystal Ball** function separate for each data taking used **for signal modeling** of $m_{\gamma\gamma\gamma\gamma}$ distributions.
- **Different functional forms used for background modeling** and the choice treated as a discrete nuisance parameter in the likelihood fit to data.

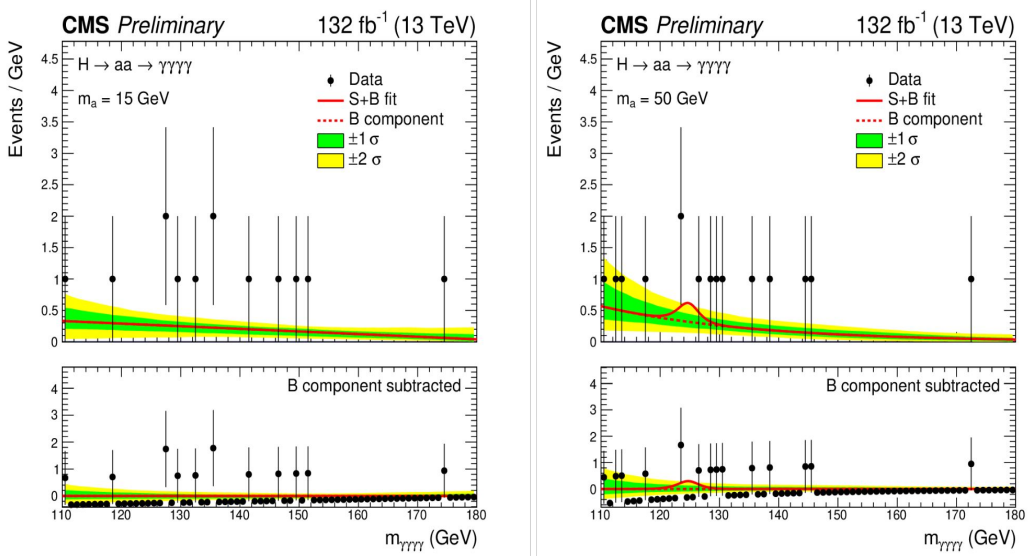


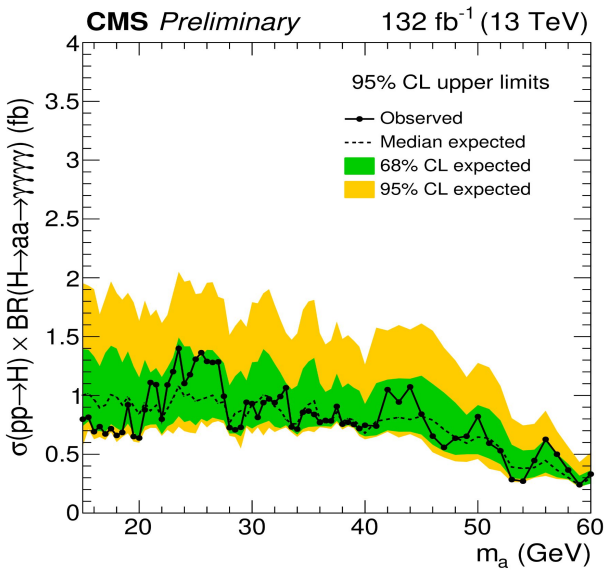


H → aa → γγγγ :

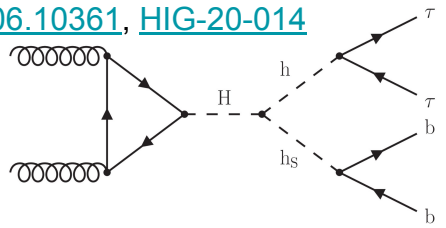
- A simultaneous maximum-likelihood fit is performed of the signal and background models to the observed mass of 4γ distribution in the mass range 110 < $m_{\gamma\gamma\gamma\gamma}$ < 180 GeV for each ma hypothesis.
  - **No significant deviation beyond the background expectations of the SM.**

- The limits range at 95% confidence level is set:
  - **Observed :** 0.8 fb (m_a= 15 GeV) → 0.33 fb (m_a= 60 GeV)
  - **Expected :** 1. fb (m_a= 15 GeV) → 0.3 fb (m_a= 60 GeV)





arxiv-2106.10361, HIG-20-014

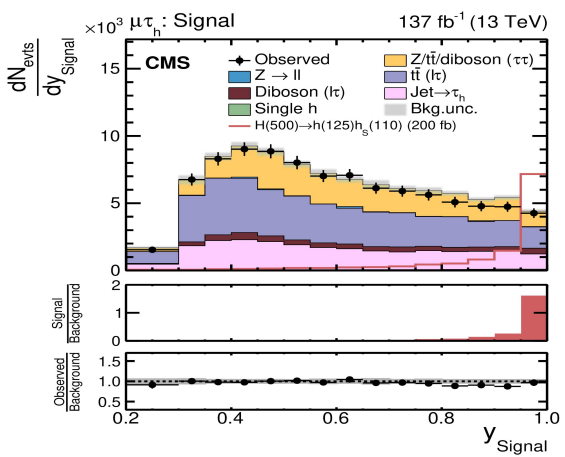


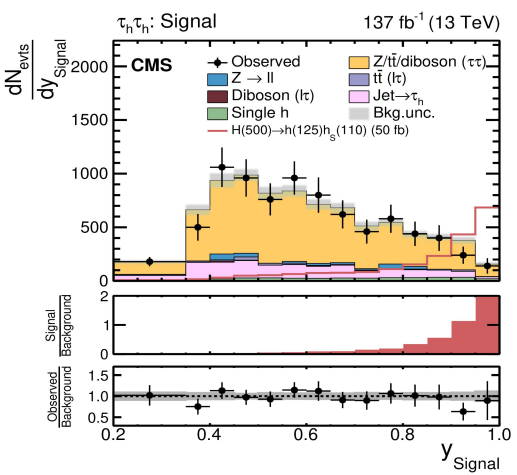
Heavy H→h(→ τ τ) hs (→ bb) :

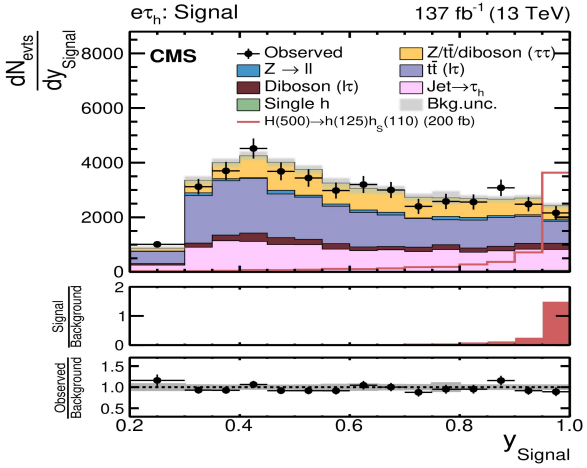
Search for Heavy Higgs boson H decaying into the observed Higgs boson **h(125)** and an extended scalar **ns (mns < mH − mh).**

The search is inspired by the **NMSSM**, where hs could have a dominant admixture of the additional singlet field, leading to a significant suppression of its couplings to SM particles.

- **Mass ranges explored :** 240 GeV - 3 TeV for mH and 60 GeV - 2.8 TeV for mhs
- **Final states :** $e\,\tau_h,\ \mu\,\tau_h\ ,\ \tau_h\tau_h$
- **Event selection :** $1\ell\ 1\tau_h(\,2\,\tau_h)+\geq 2jets(\ \geq 1b\text{-}jet)$
- **Main BKG :** tt̄, multijet QCD, Z, WW ⇒ Event classification in 45 categories ⇒ A total of 68 NNs per final state are used.

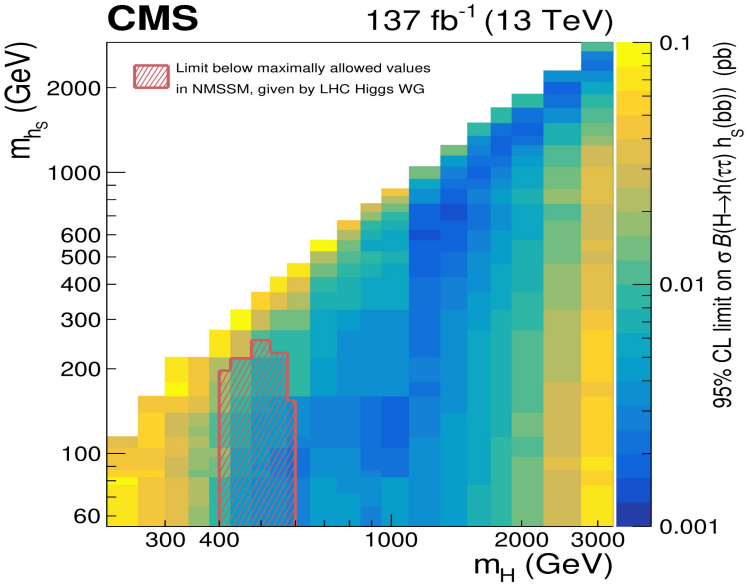


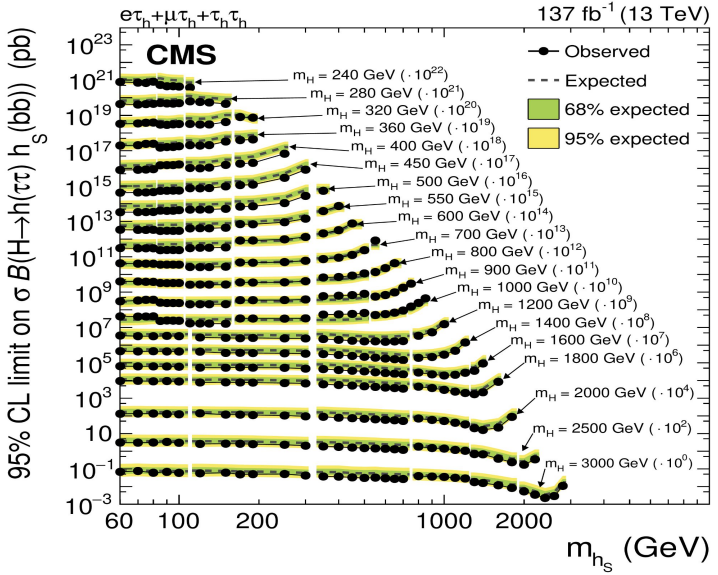




Heavy H→h(→ *τ τ*) hs (→ bb) :

- **Signal extraction:** maximum likelihood fit on NN scores.
- **No signal-like excess is observed in any of the investigated mass combinations.**
- 95% CL upper limits on σ × BR(H→h(→ *τ τ*) hs (→ bb)) is extracted.
- **NMSSM constrained for 400 ≤ mH ≲ 600 GeV and 60 ≤ mhs ≲ 200 GeV .**
- Sensitivity range from 125 fb-1 (for mH = 240 GeV) to 2.7 fb-1 (for mH = 1000 GeV).

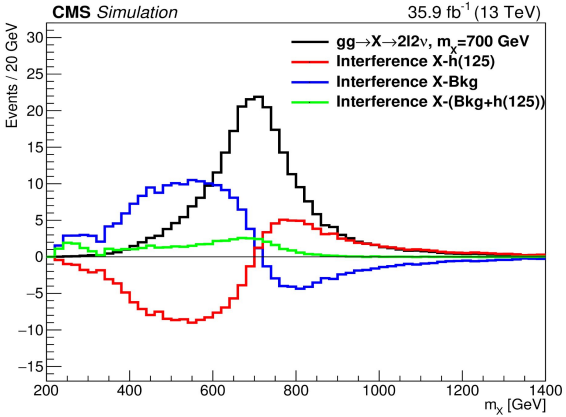


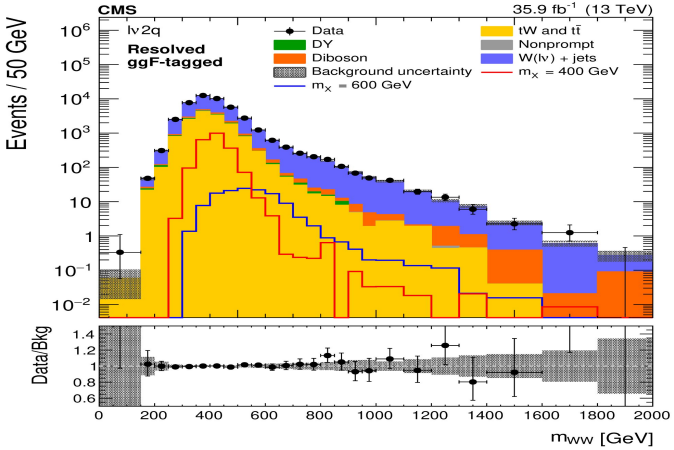


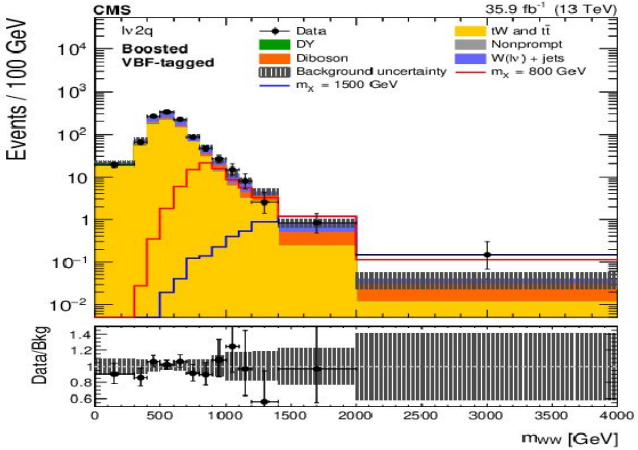
arxiv-1912.01594, HIG-17-033

Heavy H → WW → (lν lν, lν qq) :

- **W boson pair decay:** lνlν, lνqq.
  - **Fully leptonic channel:** >= 2 high-pT opposite charge lepton candidates.
  - **Semileptonic channel:** >= 1 at high-pT lepton + 2 AK4 jets or one AK8 jet.
  - **Search range:** From 0.2 up to 3.0 TeV.
- **Signal production mechanisms:** ggF(+ Interference terms gg→ h(125)), VBF.
  - The ggF cross section decreases with mX while the VBF/ggF cross section ratio increases.
  - Event categorizations based on the kinematic properties of associated jets and ME techniques are employed to optimise the signal sensitivity.

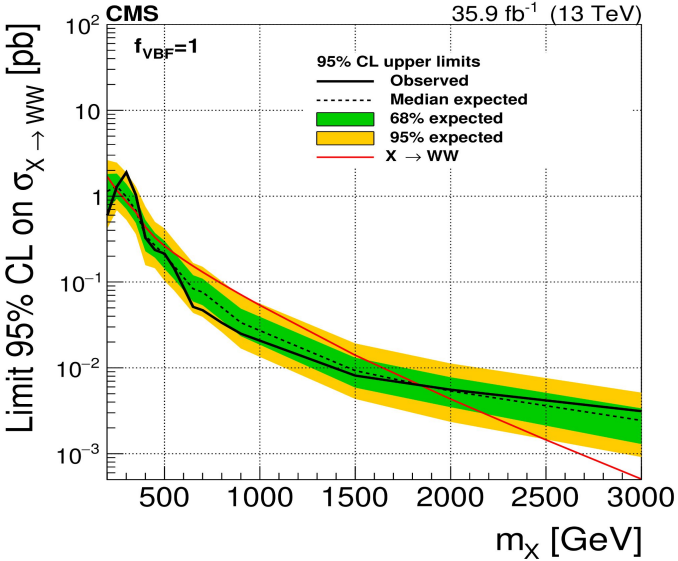


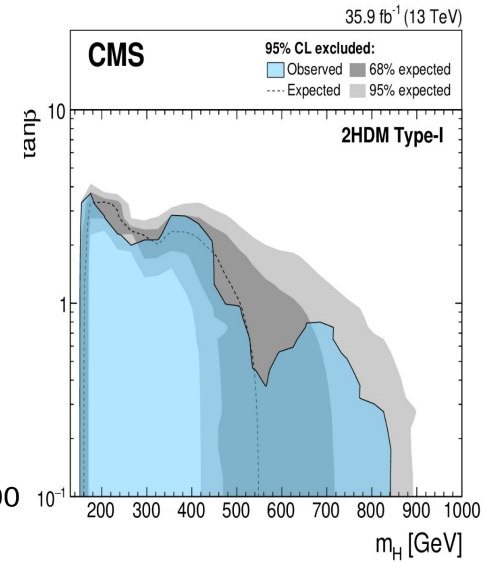


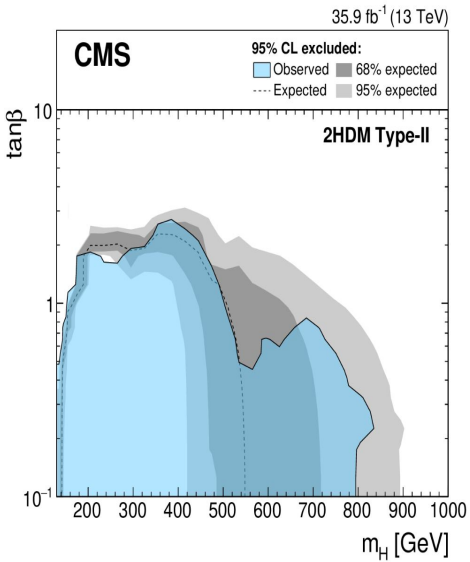


Heavy H → WW → (lν lν, lν qq) :

- Combined upper limits at the 95% confidence level have excluded a heavy Higgs boson H with SM-like couplings and decays in the mass range: 200 GeV - 3TeV.
- Exclusion limits have been set in the context of **2HDM type I and II** with the assumption that mH = mA .
  - The observed exclusion contours reach mH values of ≈ 800 GeV, for tanβ value excluded ≈3.
- For the $m_h^{mod^+}$ and **hMSSM** scenarios the regions at low values of mA~ 430GeV and tanβ~9 have been excluded.

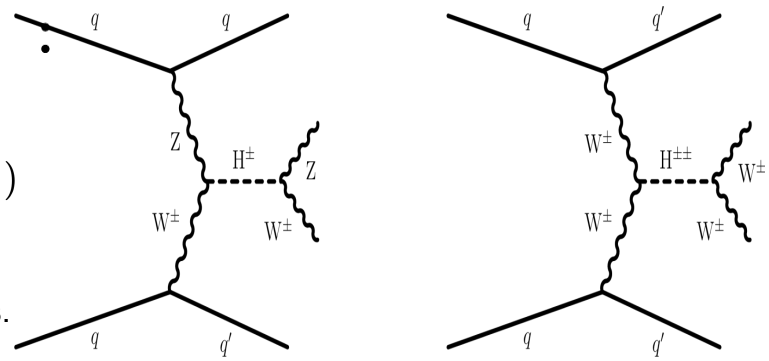






arxiv-2104.04762, HIG-20-017

$H^{\pm} \to W^{\pm}Z \; and \; H^{\pm\pm} \to W^{\pm}W^{\pm}$

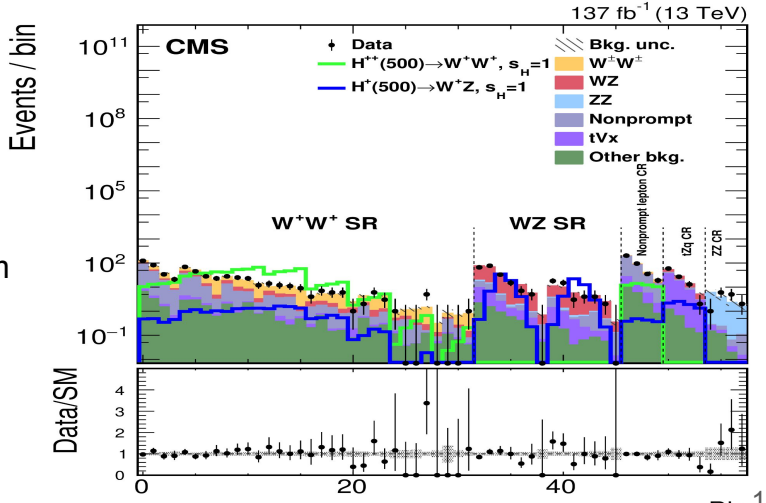


- **Georgi-Machacek model (GM) :**
  - $H^{\pm\pm}$ and $H^{\pm}$ are degenerate in mass at tree level (m_{H_5})
  - The H_5 states are fermiophobic and are assumed to decay to vector boson pairs with branching fraction of 100%.
- **Event selection:** The search performed in the leptonic decay modes.

$$\geqslant 3 \,\text{isolated}\; lep + p_T^{miss} + \geqslant 2\; jets(\text{large}\; m_{jj}\; \text{and}\; \eta)$$

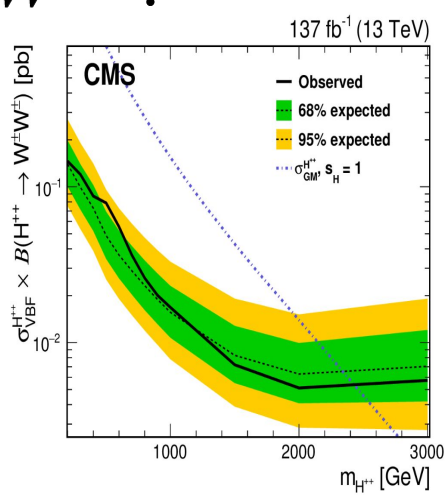
- **Mass range explored :** From 200 to 3000 GeV
- **Signal extraction:** A binned maximum-likelihood fit is performed using the WW and WZ SRs, and the non-prompt lepton, tZq, and ZZ CRs.
- The diboson transverse mass is constructed from the four-momentum of the selected charged leptons and the ~pTmiss

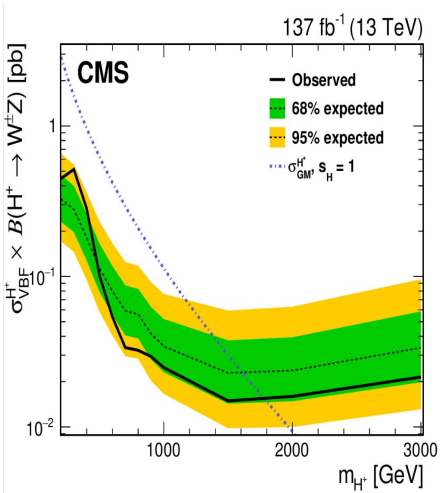
$$m_{\mathrm{T}}^{\mathrm{VV}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2},$$

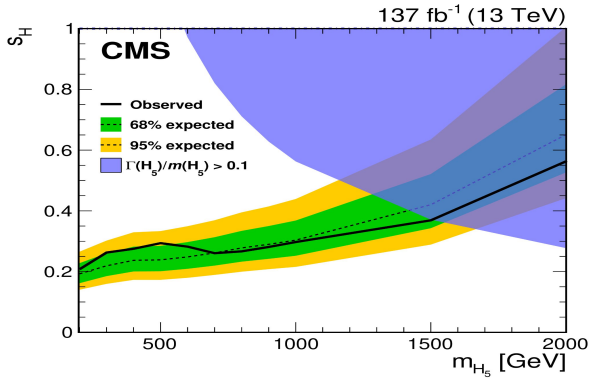


$H^{\pm} \rightarrow W^{\pm}Z \; and \; H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$:

- **No significant excess of events above the expectation from the SM background predictions is found.**
- The 95 % CL upper limits on σ × BR extracted for **VBF** production of the H± and H±± bosons individually.
  - Excluded GM sH parameter values greater than 0.20–0.35 for the mass range from 200 to 1500 GeV.
- The exclusion limits for sH are shown up to mH5 = 2 TeV, given the low sensitivity in the GM model for values above that mass.
  - sH characterizes the fraction of the W boson mass generated by the vev of the triplet fields.
  - Values above the curves are excluded **because of perturbativity and vacuum stability requirements.**

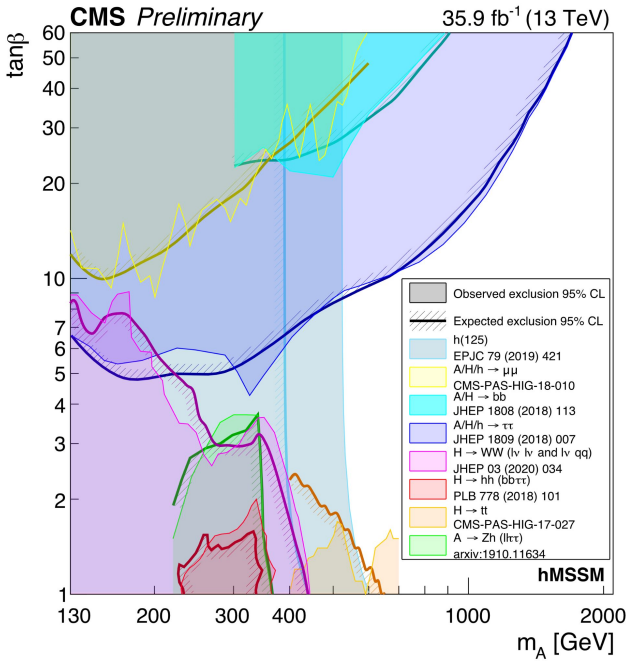






Summary:

- Several searches for additional scalar and Higgs-like particles published or still on-going by the CMS Collaboration.
- Wide ranges of signatures carried out targeting additional neutral and charged Higgs bosons in a variety of models simple or complex.
- All searches profit significantly from the full run-II data; increased sensitivity over wide range of signatures comparing to run-I.
- Despite the absence of **significant deviation beyond the background expectations of the SM,** many effort have led to the exclusion of large parts of the MSSM parameter space.
- A remarkable improvement in search strategies and in object reconstruction (.eg. with machine learning techniques), as several of the researches discussed show.
- **Stay tuned for more results and hopefully discovery !**

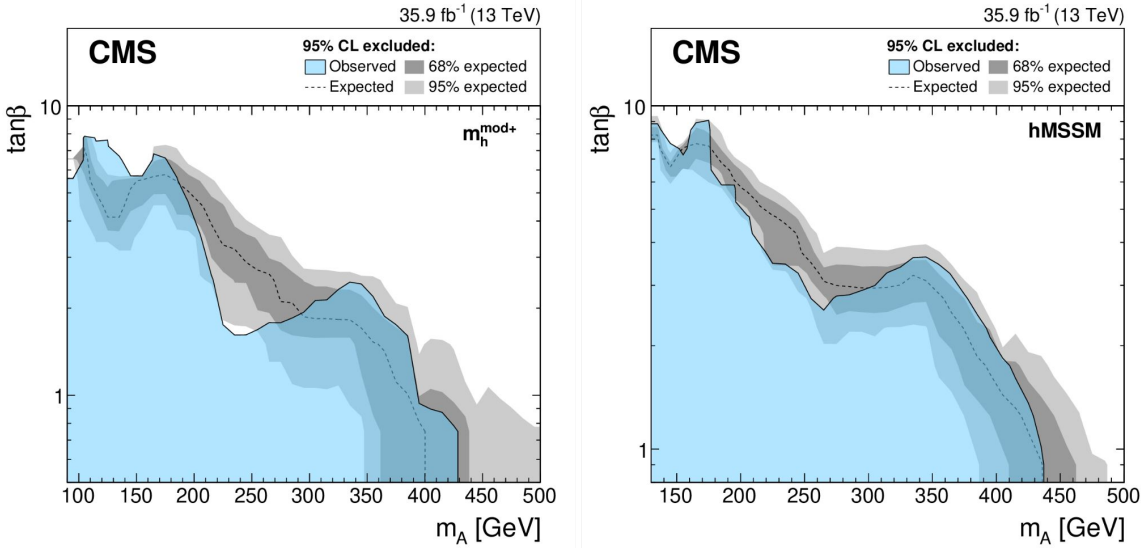


Thank you for listening !

BACKUP

Heavy H → WW → (lν lν, lν qq) :

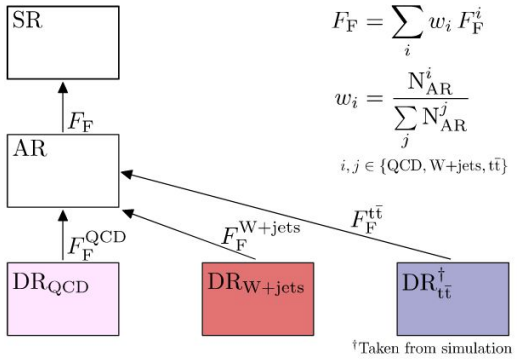
- The maximum tanβ value excluded for both **hMSSM** and $m_h^{mod^+}$ scenarios at 95 %CL is ≈9, for value of mA ≈430 GeV



Heavy H→h(→ τ τ) hs (→ bb) :

Classification and advanced techniques:

- hs → bb: large BR and h → τ τ clean signature
- Events sorted into five categories. One for signal, the other four are enriched with different backgrounds.
- A very good separation between the background events and the signal events is achieved, with a purity and classification sensitivity for the correct signal class of more than 80%
- τ -embedding method F and three independent extrapolation factors F_F are derived for the estimation of the background from QCD multijet, W+jets, and tt events due to the misidentification of jets as hadronic τ lepton decays.



$$F_F = \sum_i w_i F_F^i$$

$$w_i = \frac{N_{AR}^i}{\sum_j N_{AR}^j}$$

$$i, j \in \{QCD, W+jets, t\bar{t}\}$$

Background process	Final state signature	Estimation method τ-emb.	F_F	Sim.
Z	ττ	✓	—	—
	Jet → τ_h	—	✓	—
	ℓℓ	—	—	✓
tt̄	ττ + X	✓	—	—
	Jet → τ_h	—	✓	—
	ℓ + X	—	—	✓
Diboson+single t	ττ + X	✓	—	—
	Jet → τ_h	—	✓	—
	ℓ + X	—	—	✓
W+jets	Jet → τ_h	—	✓	—
QCD multijet	Jet → τ_h	—	✓	—
Single h	ττ	—	—	✓
	bb	—	—	✓

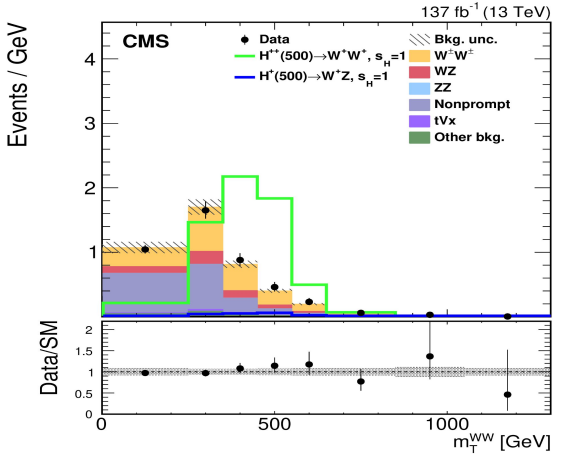
$\ell = e, \mu$

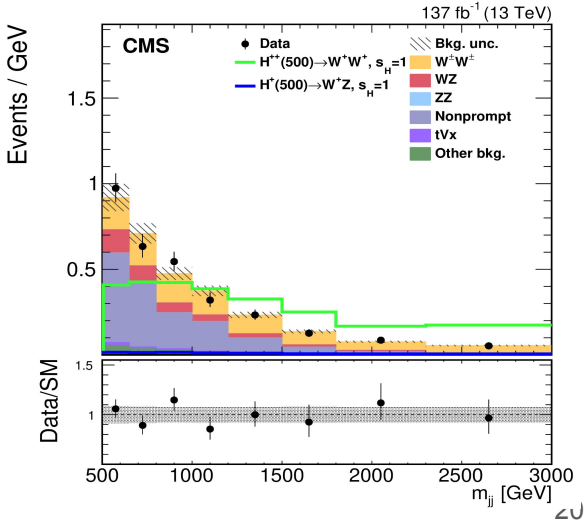
$H^{\pm} \to W^{\pm}Z$ and $H^{\pm\pm} \to W^{\pm}W^{\pm}$:

- 2D distribution is used in the fit :
  - WW SR : 8 bins in mT and 4 bins in mjj.
  - WZ SR : 7 bins in mT and 2 bins in mjj.
- mT is constructed from the four-momentum of the selected charged leptons and the p_T^{miss} :

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

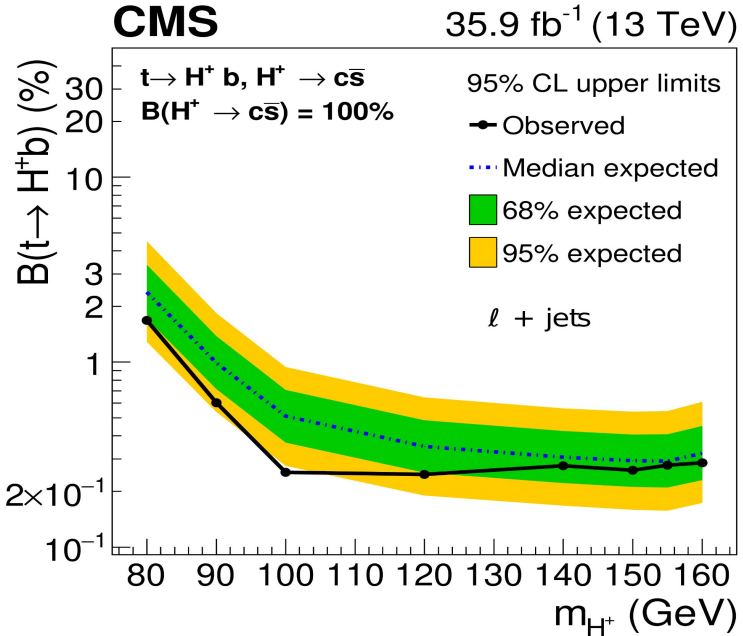
- mT is effective in discriminating between the resonant signal and non-resonant bkg processes.
- mjj is effective in discriminating between all non-VBS processes and the signal (+EW VV) processes because VBF and VBS topologies typically exhibit large values for the dijet mass.





Light Charged Higgs H±→cs :

- An exclusion limit at 95% confidence level on B(H+ → cs) assuming branching fraction B(H+ → cs) =100%.
  - **No significant excess beyond standard model predictions is found in mjj distribution.**
  - An upper limit in the range 1.68 – 0.25 % is set on the B(t→ H+b) for a charged Higgs boson mass between 80 and 160 GeV after the individual charm tagging categories have been combined.

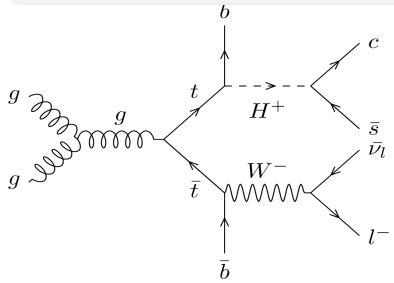


arXiv:2005.08900, HIG-18-021

Light Charged Higgs H±→cs :

- Search performed on 2016 data.
- **Signature in** low-mass (mH+ < mt) **:**
  - An isolated lep (μ, e) + p_T^{miss} (> 20GeV) + at least 4 jets (2b-tagged).
- **The SM tt process is an irreducible background :** 94% of the total expected background in the SR.
- **Final observable:** The invariant mass of the two non-b jets (mjj), assumed to be cs.
- Kinematic fit performed on the reconstructed mjj.
- The events are divided exclusively into the 3 c-tagging working point (L, M, T):
  - The mjj distributions for the exclusive charm categories are used in in the background-only maximum likelihood fit to data.

Signal Process: tt pair decay products include a charged Higgs boson.



The SM decay of a tt pair in the semileptonic decay channel.