Obra Social
Fundación "la Caixa"

Report from the *Extended Higgs sector* subgroup Theory part

The 22nd Workshop of the LHC Higgs Working Group

December 3 2025

Thomas Biekötter

On behalf of the subgroup conveners:
Lidija Zivkovic (ATLAS), Nikolaos Rompotis (ATLAS),
Alexandra Carvalho (CMS), Khawla Jaffel (CMS),
Tania Robens (Theory)

Who are we?

Extended Higgs sectors subgroup

Structure: Subgroup of WG3: BSM Higgs

Subgroup conveners:

ATLAS: Lidija Zivkovic, Nikolaos Rompotis

CMS: Alexandra Carvalho, Khawla Jaffel

Theory: Tania Robens, Thomas Biekötter

Twiki: Everything you can see here (and more) you can find on our **TWiki**.

Mailing lists:

Extended Higgs sector subgroup: lhc-higgs-neutral-extended-scalars@cern.ch

WG3 BSM Higgs: lhc-higgs-bsm@cern.ch

E-group: **lhc-higgs-neutral-extended-scalars**

Indico: Past/future topical events and regular meetings can be found on the **WG3 Indico**.

Summary of last year's activities

Meetings:

Nov 5 2025: Extended Higgs Sector subgroup meeting, **Indico**

Mar 5 2025: WG2 + WG3 CPV in Extended Higgs Sector topical meeting, **Indico**

Theory predictions:

neutral Higgs bosons: 13.6 TeV recommendations for SM-like Higgs boson

charged Higgs bosons: work in progress and **new results**

Contribution on CP-violating benchmarks: work in progress, WG2 + WG3

→ see Rui Santos' lightning session talk on **Friday**

LHC DM WG overlap: Dark Higgs model, 2HDM+a – Our involvement?

Subgroup meeting: November 5

Call: Online meeting of extended scalars subgroup of the BSM Higgs WG3

Send to our email list: lhc-higgs-neutral-extended-scalars@cern.ch.

If you missed it, please subscribe! Instructions: **TWiki**

Contributions: Six talks → one afternoon session [**Indico**]

An exploration of the NMSSM using deep learning to fit hints of new scalars, R. Raymundo

The cS2HDM as a unified framework for dark matter and electroweak baryogenesis, P. Gabriel

Deconstruction approach to di-Higgs production, L. Panizzi

The Importance of Interference Effects in Di-Higgs Analyses, K. Radchenko

Explaining 95 and 650 GeV Anomalies in the 2-Higgs Doublet Model Type-I, A. Khanna

Impact of Interference Effects on Higgs-boson Searches in the Di-top Final State, R. Kumar

Format: Regular meetings, platform to bring together theory and experiment

(Some) topics: Overlooked signatures, interference effects, CPV, dark matter, baryogenesis, ...

Subgroup meeting: November 5

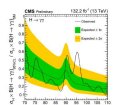
Di-photon Excess

- Di-photon resonances played a vital role in the discovery of 125 GeV Higgs Boson.
- CMS – 8 TeV (Run 1) and 1st year 13 TeV (Run 2) - 2.8 σ at 95.3 GeV

$$\mu(\Phi_{95})^{\mathrm{2nd-year}}_{\gamma\gamma} = 0.6 \pm 0.2.$$

- CMS – Full dataset 13 TeV - 2.9 σ at 95.4 GeV

$$\mu(\Phi_{95})_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$$



Akshat Khanna

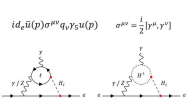
Electric dipole moment (EDM)

EDMs strongly constrain CP-violating models

Scalar-scalar and scalar-fermion CP violating interactions are needed for EDMs to be present [P.33]

Cancellation mechanism needed to meet experimental limits.

$$id_u\bar{u}(p)\sigma^{\mu\nu}q_\nu\gamma_5 u(p) \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$



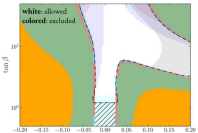
Pedro Gabriel — The c2HDM as a unified framework for DM and EW baryogenesis — 5

Relevance of resonant limits

Higgs Tools: arXiv: 2210.09332
Bahl, Biekütter, Heinemeyer, K.R., Weiglein, WIP

m_H = 450 GeV, $m_A = m_{H^\pm}$ = 650 GeV and $m^2_{12} = m^2_H c_\beta s_\beta$

white: allowed
colored: excluded

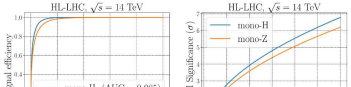


Other constraints ▸ thdmTools Bieküttur, Heinemeyer, No, K.R., Olea, Weiglein arxiv:2305.17431

Resonant hh searches

DESY. Kateryna Radchenko Serdula — 17

Predicting signatures for mono-H and Z: HL-LHC



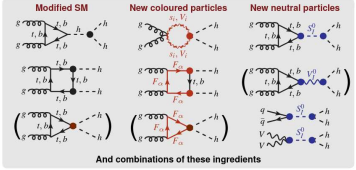
$$\sigma = \left[2\left((N_s+N_b)\ln\frac{(N_s+N_b)(N_b+\sigma_b^2)}{N_b^2+(N_s+N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2}\ln(1+\frac{\sigma_b^2 N_s}{N_b(N_b+\sigma_b^2)})\right)\right]^{1/2},$$

N_s, N_b number of signal and background events, respectively
σ_b systematic uncertainty, assumed 10%

Raymundo Ramos

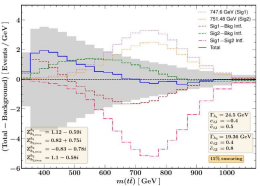
Di-Higgs signal elements

What can the signal be from a general perspective?



The number of possibilities is limited!

Luca Panizzi — Deconstruction approach to di-Higgs production



Nightmare scenario

M(S1) = 750 GeV
M(S2) = 766 GeV

A large destructive signal-signal interference cancels the sum of the two signal resonances

"No signal" in an experimental analysis

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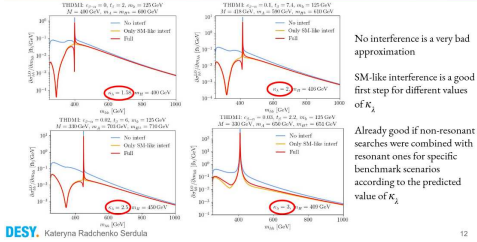
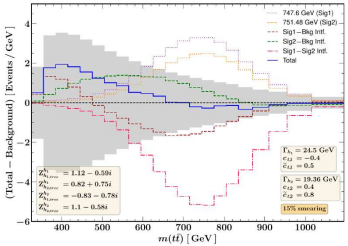
Romal Kumar

Subgroup meeting: November 5

Higgs-boson pair production: 2HDM



Searches for $t\bar{t}$ resonances: C2HDM



Nightmare scenario

M(S1) = 750 GeV
M(S2) = 766 GeV

Romal Kumar

Several talks highlighted the importance of **interference effects** in BSM searches

WG2+WG3 topical meeting: CPV

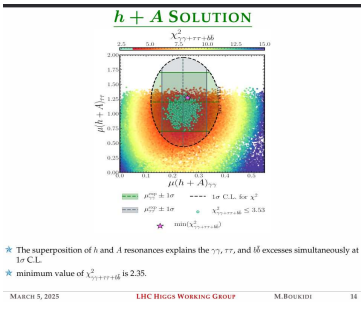
Series of meetings on **CP violation in extended Higgs sectors**

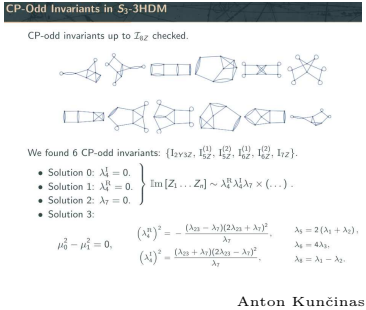
Last meeting on March 5 2025 with three contributions [Indico]

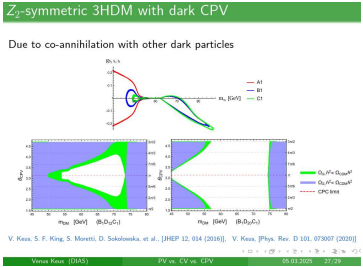
Superposition of CP-Even and CP-Odd Higgs Resonances: Explaining the 95 GeV Excesses within a 2HDM, Mohammed Boukidi

Complex S3-symmetric 3HDM, Anton Kunčinas

Distinguishing P-violation and C-violation in CP-violating extended Higgs sectors, Venus Keus







Updated cross section recommendations

Neutral Higgs bosons:

Since last year 13.6 TeV cross sections available for SM-like Higgs bosons

http://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG/Higgs_XSBR_YR4_update.xlsx

Thanks to WG1!

Update from this year: new recommendations for $t\bar{t}H$

Thanks to Henning Bahl who generated the cross sections for `HiggsTools`

Updated cross section recommendations

Charged Higgs bosons:

13.6 TeV cross sections for single-$H^{\pm}$ production work in progress

$\rightarrow$ extended mass range and newer PDFs

Main contact persons: Emanuele Bagnaschi and Michael Spira (MSSM subgroup theory)
see Emanuele's talk from last year for details [**Indico**]

New results: [**LHCWG note**]: Charged Higgs Pairs at the LHC: A NLO Analysis
Mohamed Ahmed, Lisa Biermann, Harald Ita, Irina Rusetski,
Michael Spira, Yelizaveta Yedelkina

GM model: VBF production cross sections for H_5^0, $H_5^{\pm}$ and $H_5^{\pm\pm}$ only available for 13 TeV
[LHCHXSWG-2015-001] Heather Logan, Marco Zaro

ATLAS and CMS will soon request VBF cross sections at 13.6 TeV

Suggestion by Marco Zaro: generate new cross sections using `MadGraph5_aMC@NLO`

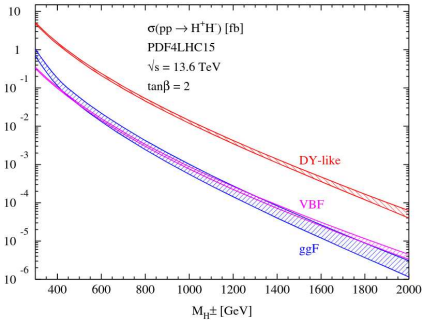
arXiv:1512.01243 Céline Degrande, Katy Hartling, Heather E. Logan,
Andrea D. Peterson, Marco Zaro

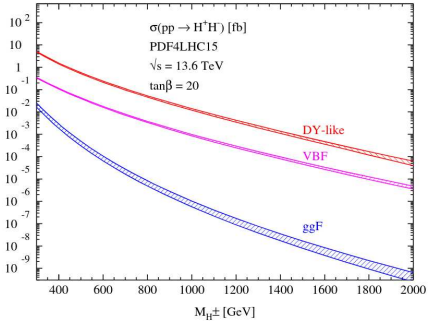
Charged Higgs Pairs at the LHC

NLO QCD predictions for H^+H^- production in the 2HDM → **Michael's talk on Thursday**

→ dominant Drell–Yan-like process not suppressed for large $\tan\beta$

→ gluon-fusion process depends on trilinear hH^+H^- and HH^+H^- couplings



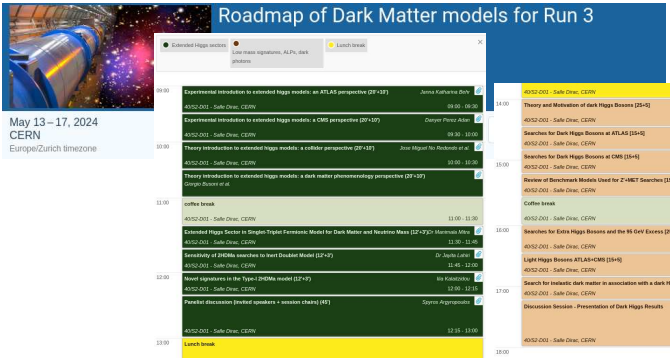


[**LHCWG note '25**, Mohamed Ahmed, Lisa Biermann, Harald Ita, Irina Rusetski, Michael Spira, Yelizaveta Yedelkina]

- All relevant productions modes at NLO
- Theory uncertainties from scale dependence, PDFs and α_s

Overlap with LHC DM WG

LHC Dark Matter Working Group: big focus on extended scalar sectors:
2HDM+a, "Dark Higgs" model [arXiv:1810.09420] [arXiv:2305.16169]



- Should be coordinated
- Do we want to be involved?
- How do we get involved?
- How to avoid "double counting" of work?

October 2024: Kick-off 2HDM+a white-paper for Run 3 [Indico]

Thanks!

Extended Higgs sector subgroup

ATLAS: Lidija Zivkovic, Nikolaos Rompotis

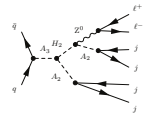
CMS: Alexandra Carvalho, Khawla Jaffel

Theory: Tania Robens, Thomas Biekötter

November 24: https://indico.cern.ch/event/1475594/

(slides from J. P. Pino Goncalves, 2HDM+ complex singlet)

particle content: $H_{1,2,3}$, $A_{2,3}$

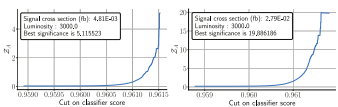


- **Two** opposite charge, same flavour leptons (**muons or electrons**);
- At least **four jets** from 1st/2nd generation quarks (**originate from A_2**);
- Two pairs of jets with identical mass;
- Pre-selection **LO cross-section**: $\mathcal{O}(10^{-1}) - \mathcal{O}(10^{-2})$ fb.

Potentially observable at **run-III** or at the **HL phase** of the LHC. Two pseudoscalars and one CP-even scalar running as internal propagators, **all on-shell** such that

$$M_{A_3} > M_{A_2} + M_{H_2} \quad \text{and} \quad M_{H_2} > M_{Z^0} + M_{A_2}$$

$$M(j) > 10 \text{ GeV and } \Delta M < 35 \text{ GeV}$$



(a) $M_{A_2} = 215$ GeV/$M_{H_2} = 400$ GeV (b) $M_{A_2} = 300$ GeV/$M_{H_2} = 600$ GeV

Relaxed constraints on jet mass distributions increases the significance. Particularly helpful for lower mass scalar fields. Still, **high cuts** on data for optimal results.

November 24: https://indico.cern.ch/event/1475594/

(slides from M. Krab, FCNC 2HDM)

Signal vs. Background

Signal: $c\bar{b} \to H^+ \to W^+H \to \ell^+\nu t(\to \ell^+\nu b)\bar{c} \to \ell^+\ell^+ + \nu\nu + b\bar{c}$

BKG: $t\bar{t}V$ ($V = W, Z$), tZj, tth, $4t$, tW, WZ, ZZ

BP	η_2	η_3	η_4	η_5	η_7	m_H	m_A	m_{H^+}	μ^2_{22}/v^2
1	1.40	2.00	−0.82	−0.82	−0.55	**200**	300	**300**	0.49
2	2.88	4.75	−2.64	−2.64	0.16	**300**	500	**500**	1.75

Table: For BP1, $\rho_{tc} = \rho_{tt} = 0.1$, while for BP2, $\rho_{tc} = 0.3$, $\rho_{tt} = 0.5$.

Simulation: `MadGraph5_aMC@NLO` ($\sqrt{s} = 14$ TeV) + `Pythia` + `Delphes`

- $N_j \geq 2$ with $P_T^j \geq 20$ GeV
- At least one b-tagged ($N_b \geq 1$)
- SS2ℓ ($N_\ell = 2$), $P_T^{\ell_{(2)}} \geq 25(20)$ GeV
- $\Delta R_{\ell\ell}$, $\Delta R_{\ell j} > 0.4$, $E_T^{\text{miss}} > 35$ GeV
- p_T sum of all jets and two SS leptons $H_T < 400$ GeV

Background	Cross section
$t\bar{t}W$	1.61
$t\bar{t}W$	1.09
WZ	0.54
tZj	0.40
$t\bar{t}Z$	0.10
$t\bar{t}h$	0.05
ZZ	0.02
$4t$	0.0004
Q-flip	0.0018
Fake	0.0002

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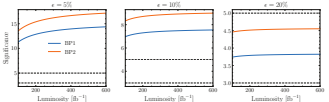
Significance

We estimate our signal sensitivity using Kumar and Martin, PRD'15

$$\mathcal{Z} = \sqrt{2\left[(S+B)\ln\left(\frac{(S+B)(B+\Delta_B^2)}{B^2+(S+B)\Delta_B^2}\right) - \frac{B^2}{\Delta_B^2}\ln\left(1+\frac{\Delta_B^2 S}{B(B+\Delta_B^2)}\right)\right]},$$

with $\Delta_B = \epsilon B$, where S (B) is number of signal (background) events, and ϵ refers to systematic uncertainty in background estimation.



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Extended Scalars Subgroup:

ATLAS/CMS results since the last workshop

The 22nd Workshop of the LHC Higgs Working Group, 3-5 December 2025

Experiment contacts:
Lidija Zivkovic, Nikolaos Rompotis (ATLAS)
Alexandra Carvalho, Khawla Jaffel (CMS)

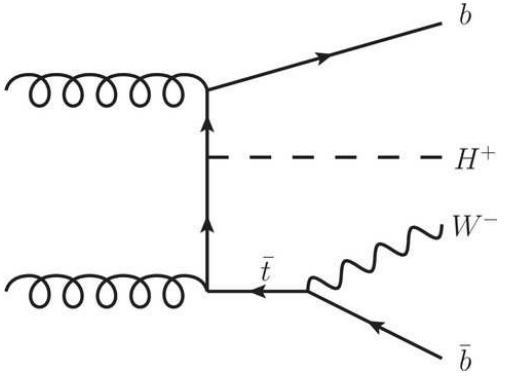
Theory contacts:
Thomas Biekötter, Tania Robens

Some ATLAS results

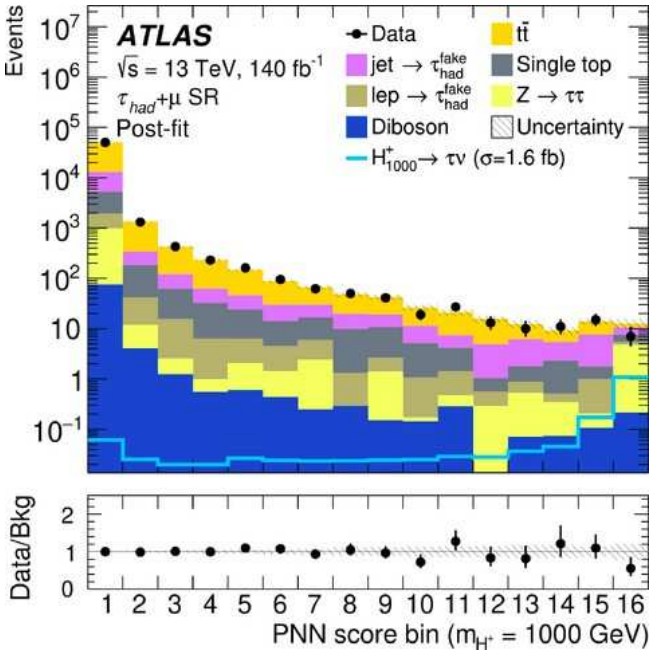
HDBS-2018-39

- ## Charged Higgs to taunu

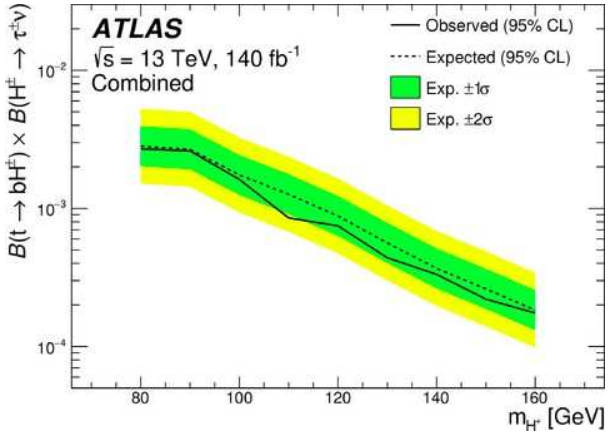
Full run-2 covering from 80 GeV till 3 TeV

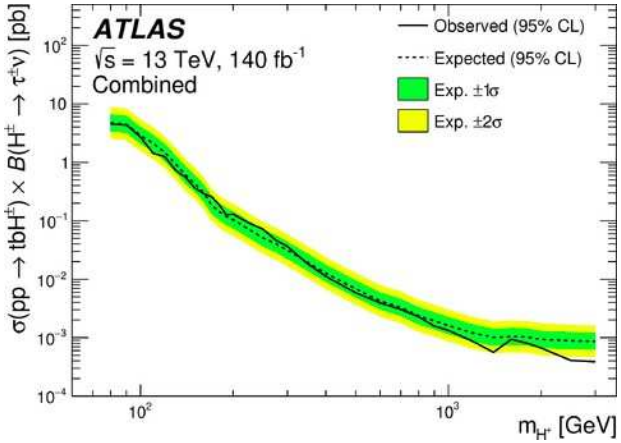


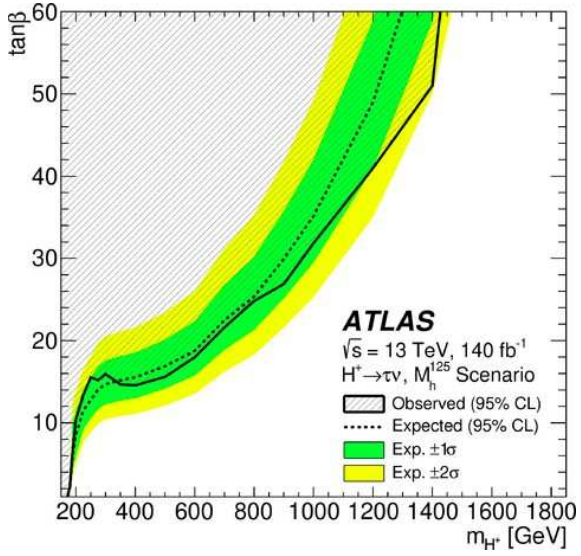
Both leptonic and hadronic tau decays are considered. Parametric NN that uses kinematics a final discriminant



Branching ratio limits (low mass), cross section limits (high mass) and interpretation in various MSSM scenarios

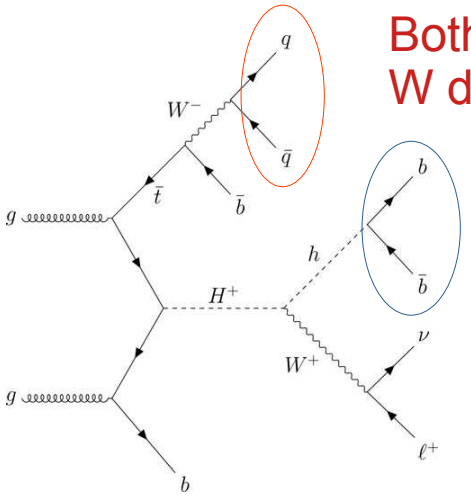






Some ATLAS results

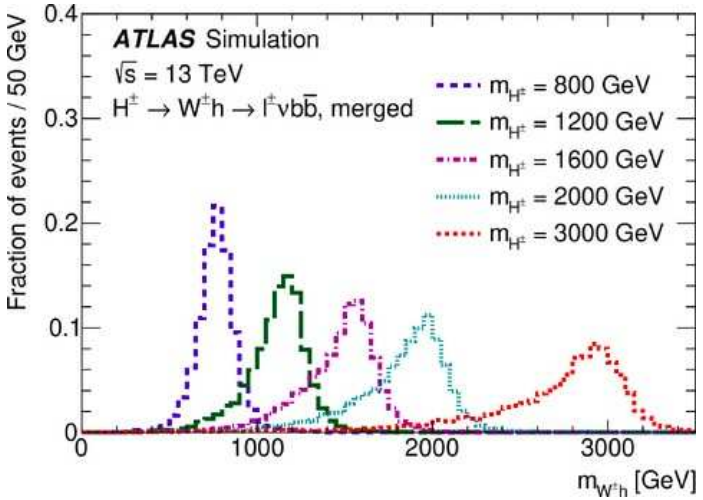
- H+ ⟶ W+ h HMBS-2024-45 Full run-2 covering m_{H+} from 250 GeV till 3 TeV

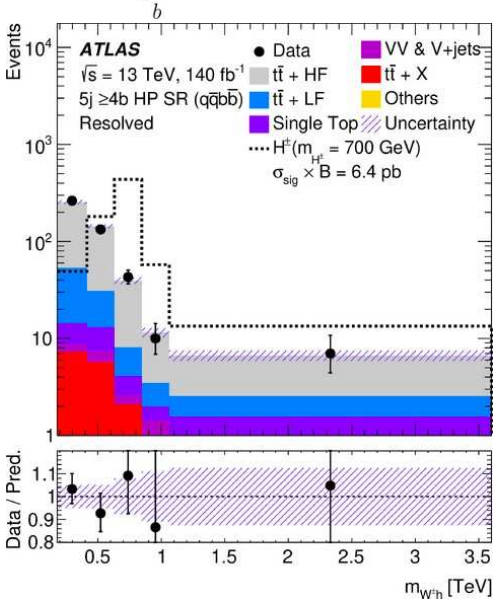


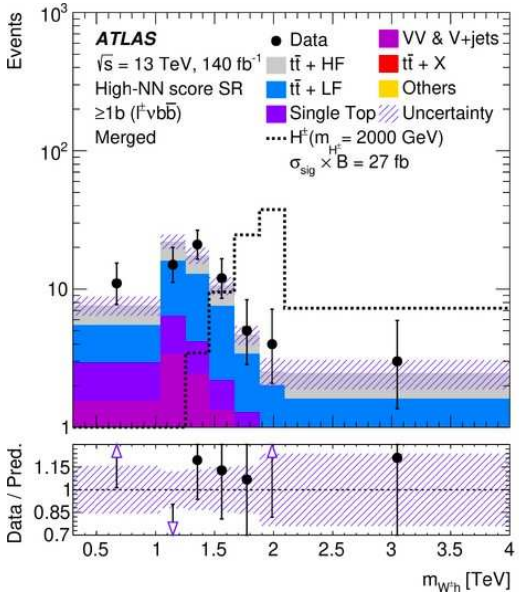
Both leptonic and hadronic W decays are considered

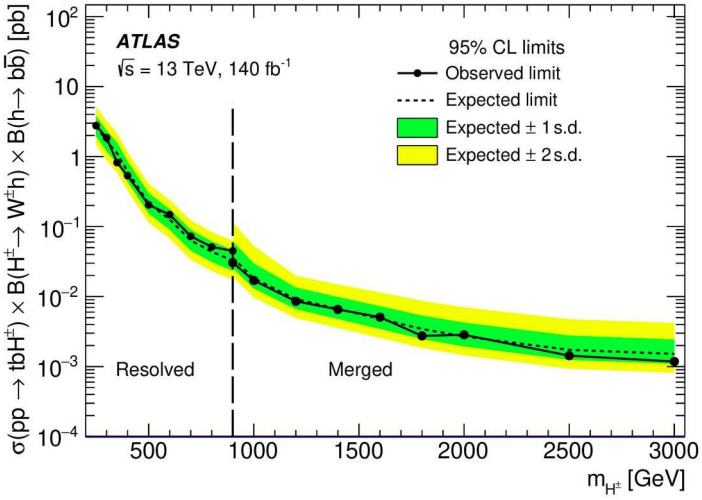
bb pair resolved or merged

Several categories depending how many jets and how many of them are b-tagged





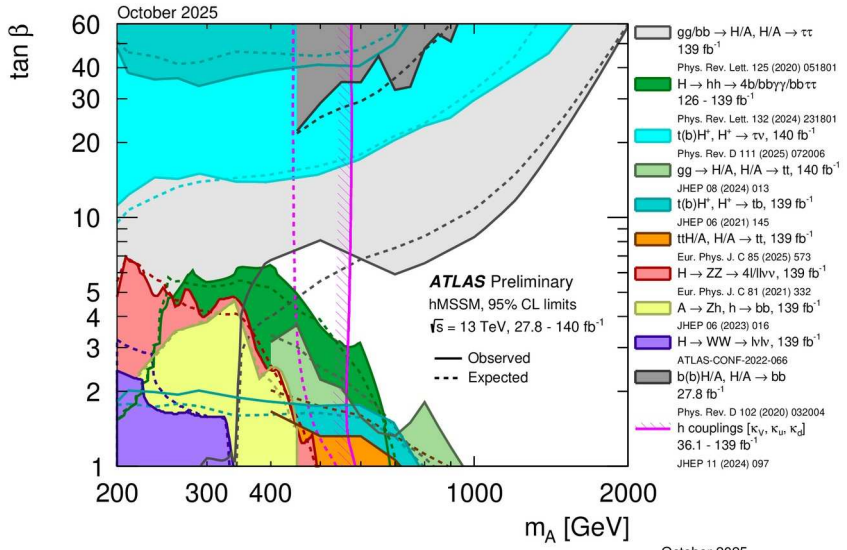


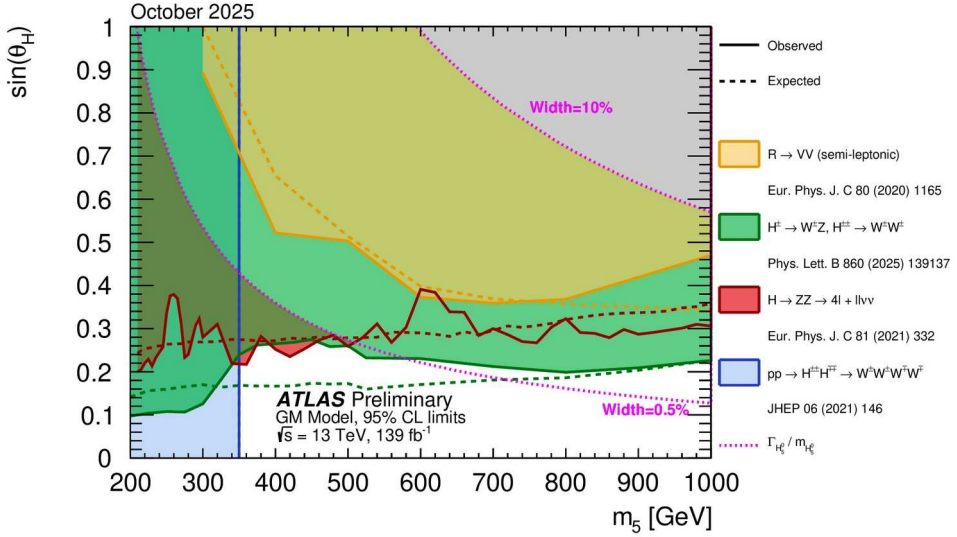


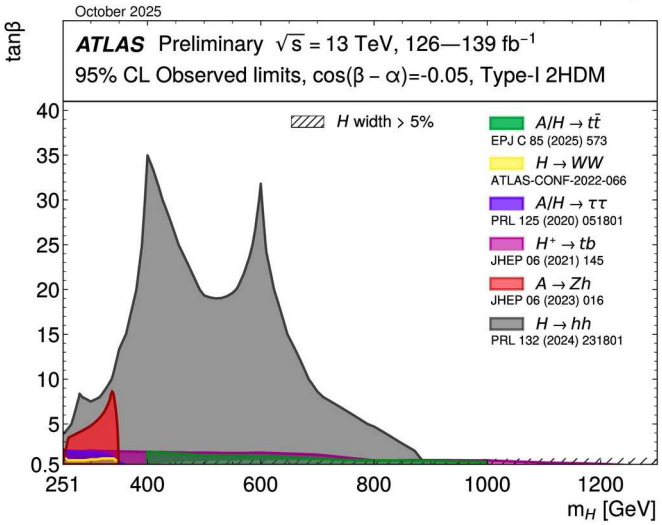
Some ATLAS results

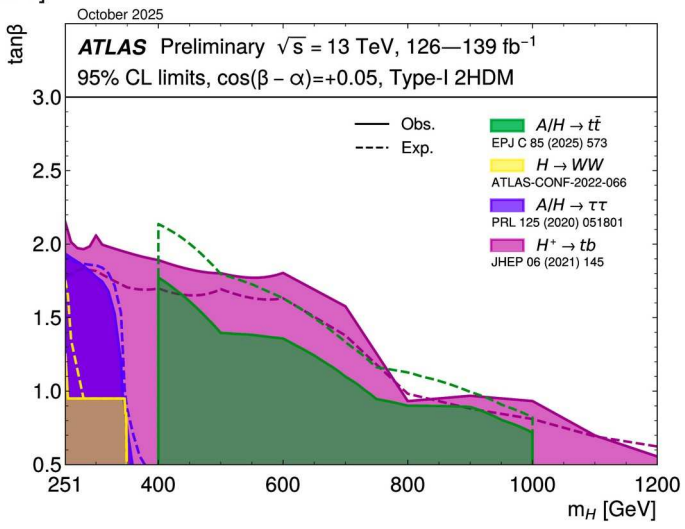
- Summary plots

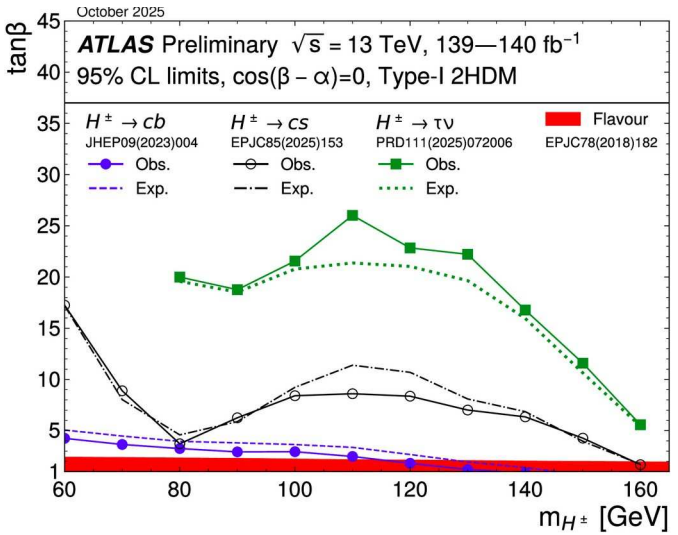
ATL-PHYS-PUB-2025-042











Some CMS results

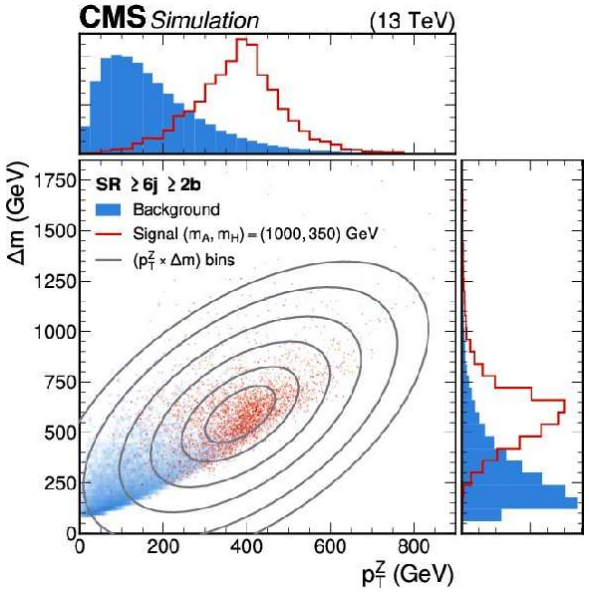
- A→ZH→ll tt

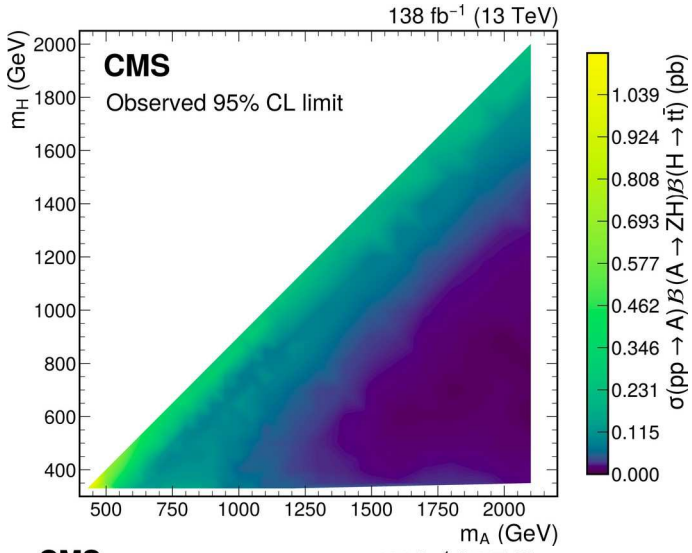
B2G-23-006
Full Run 2 data

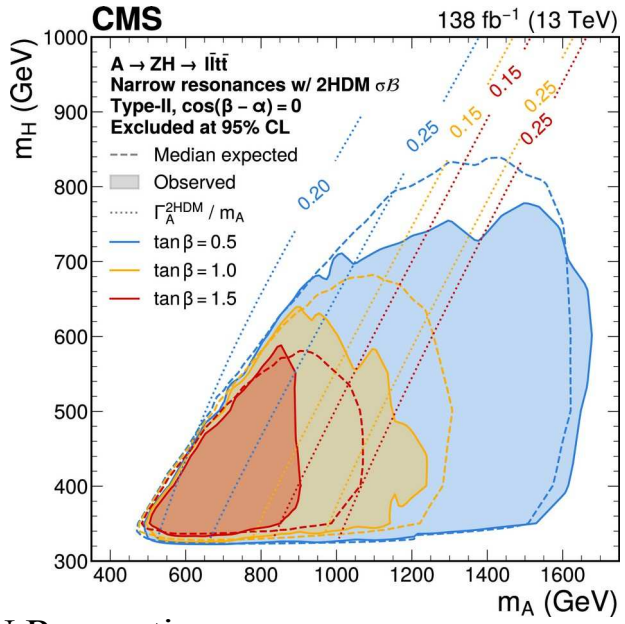
Z→ ee/μμ and fully hadronic ttbar

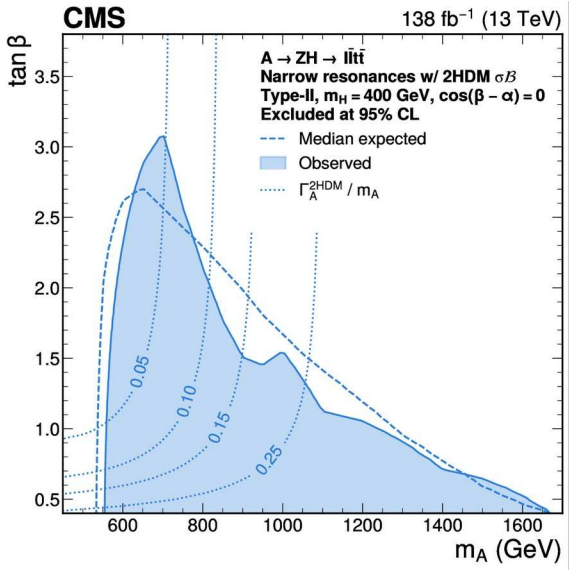
Results obtained by a simultaneous fit of the $\Delta m = m(ttZ) - m(tt)$ and the p_T^Z variables.

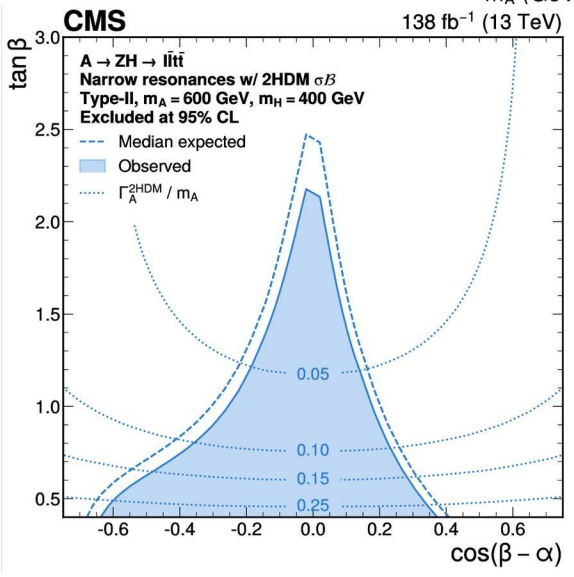
2D cross section limits are provided, as well as interpretations on the 2HDM









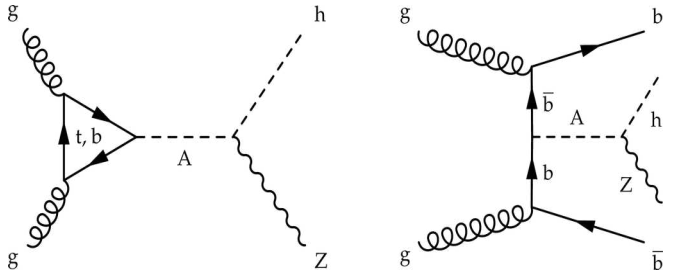


Some CMS results

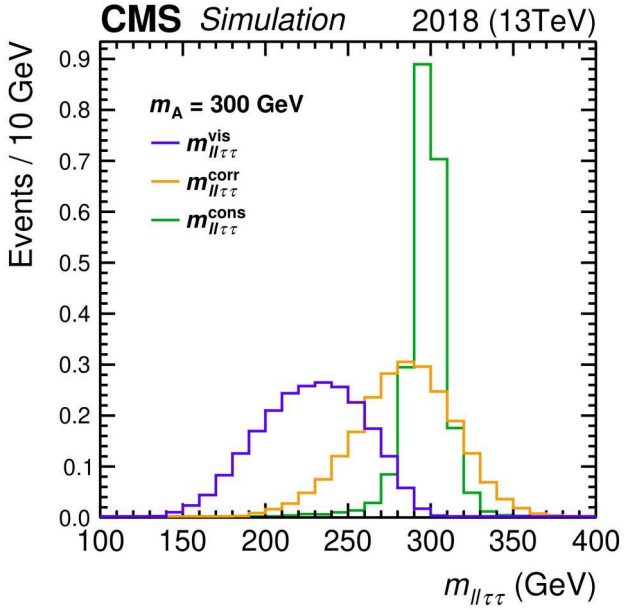
HIG-22-004
Full Run 2 data

- A→ Zh

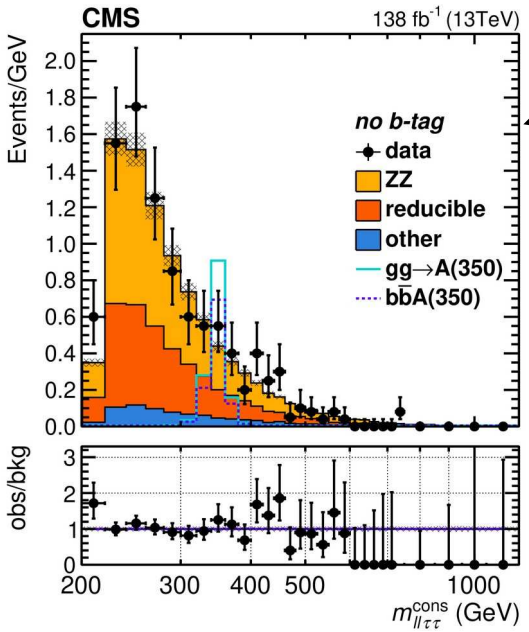
With Z→ ee/μμ and h→ ττ in the lephad and hadhad channels
Both ggF and b-associated productions are included



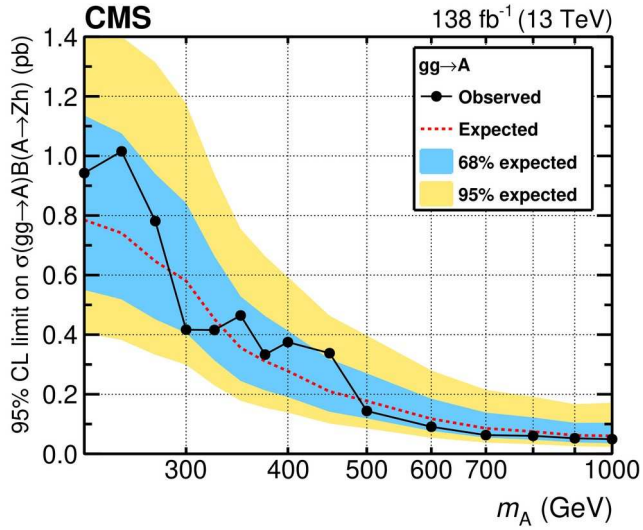
Using dedicated techniques to improve ττ mass resolution and in addition the h-mass constraint to obtain m_A resolution of 5-7%

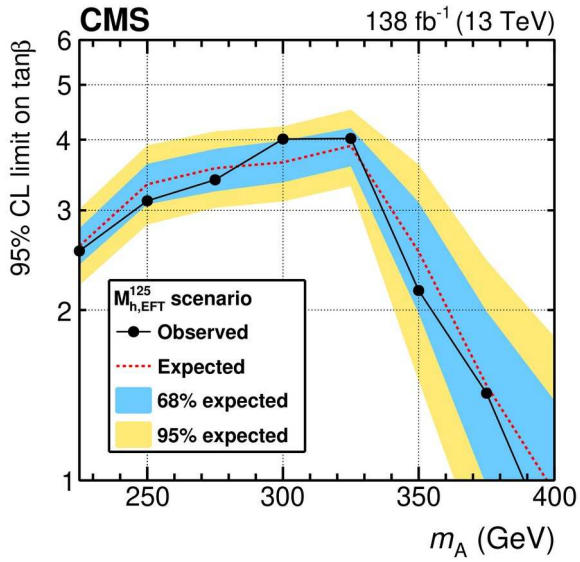


Signal region fit



Cross section limits, interpretation and 2D limits as well (not shown here)

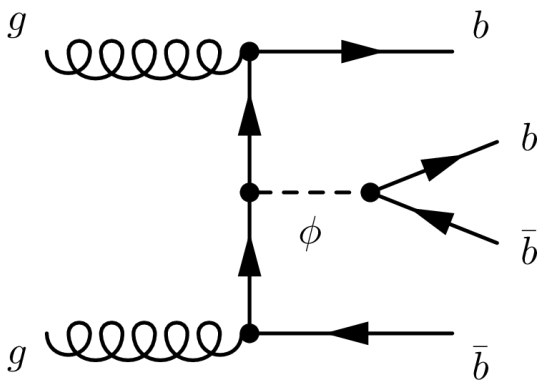




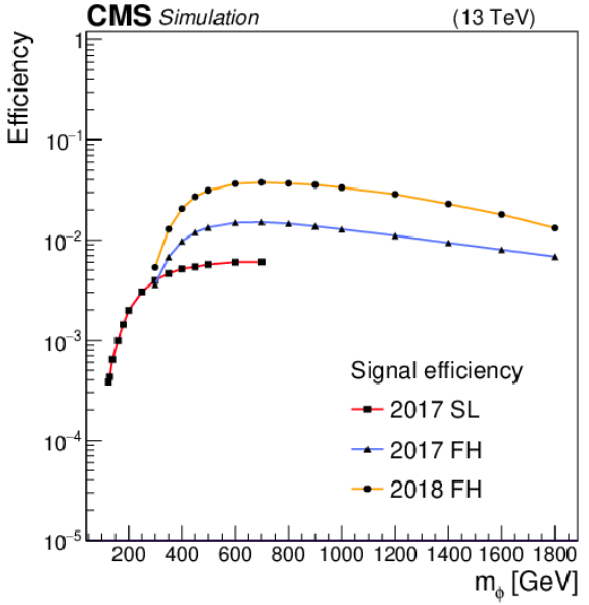
Some CMS results

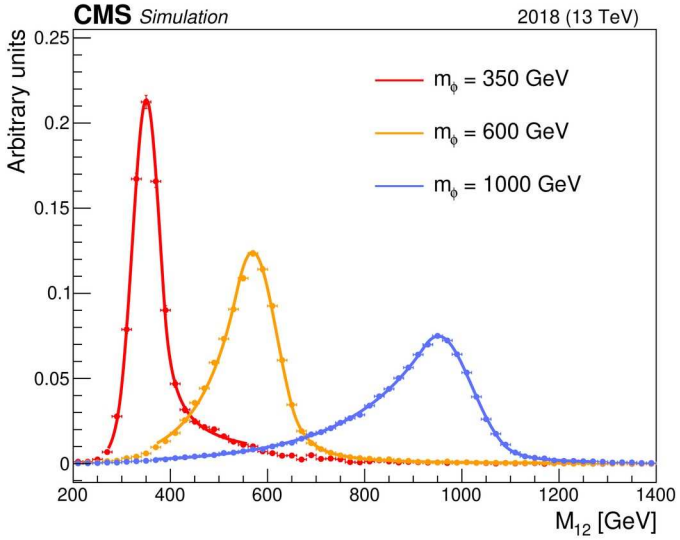
SUS-24-001
Run 2: 36.7–126.9 fb^{-1}

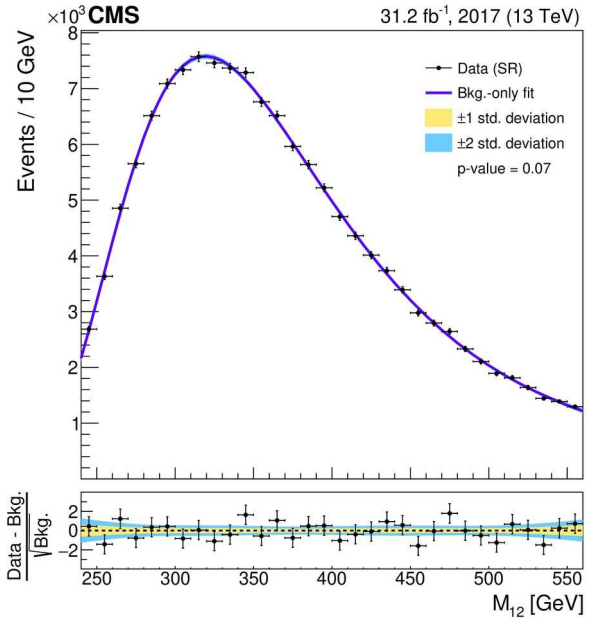
- Heavy Higgs to bb

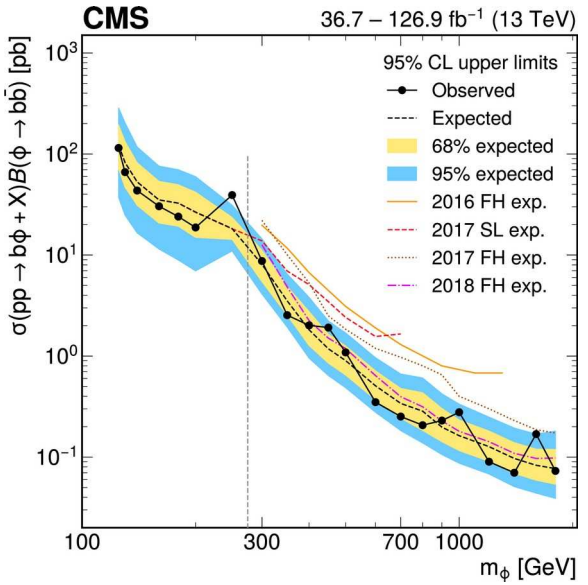


- Challenging to trigger
- at least b-tagged 3 jets are required
- Fully hadronic (FH) and semi-leptonic (SL) channel (muon-in-jet)
- Parametric fit of the mass of the first leading two jets to extract signal
- Results: cross-section limits, MSSM and 2HDM interpretations







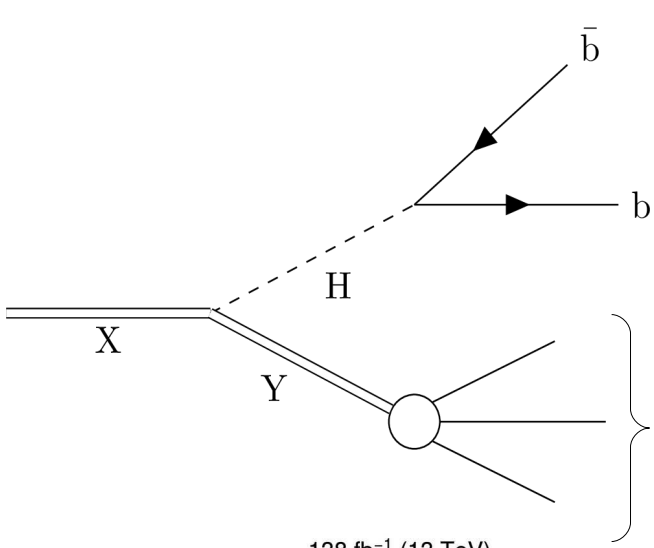


Some CMS results

B2G-24-015

Full Run 2 data

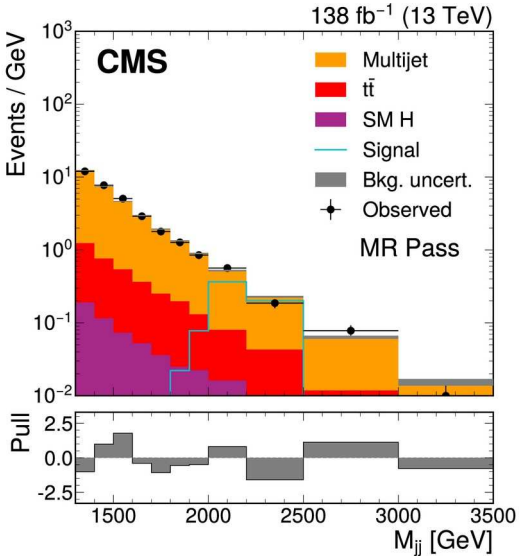
- X → Y h with h → bb

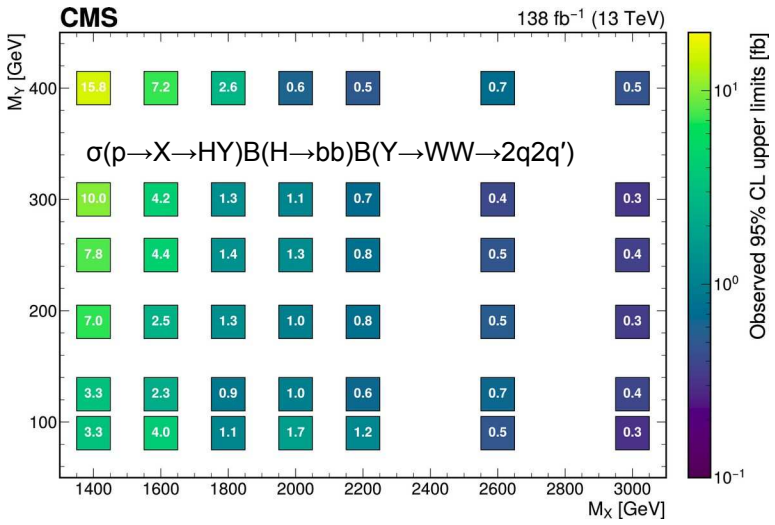


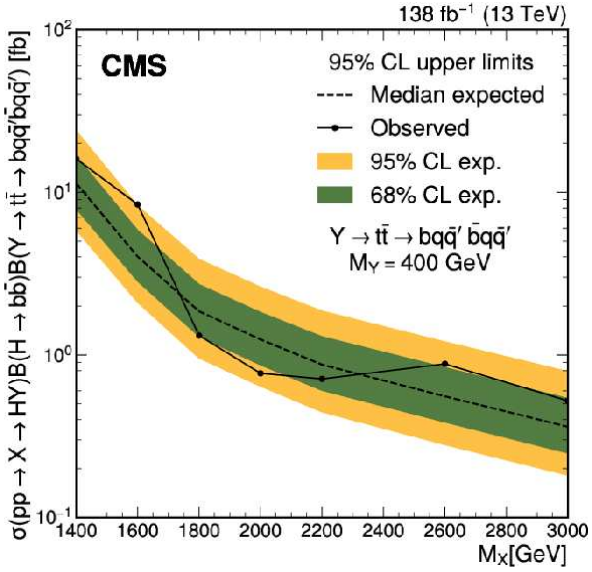
Boosted bb, reco-ed as a single large radius jet

Single large radius jet coming from:
- Y→ WW
- Y→ qq or tt
- Y = top

- Events selected by triggers requiring significant jet activity
- 2 leading jets (300 GeV), mass(jet-jet) > 1300 GeV
- Different multivariate algorithms deal with h(bb) and Y
- signal and control regions based on the algorithm scores, all fitted together for final result







Final words

- Please look at the NMSSM slides (next talk) as well since they include results relevant to Extended scalars as well