BSM Higgs Searches at LHC

Lianliang MA

Shandong University

CLHCP 2020 workshop (online)

Nov. 6-9, 2020

Outline

- Brief introduction to signal models
- Neutral Higgs searches
- Charged Higgs searches
- Precision constraints
- Summary

Not full list of searches

Only selected latest results

ATLAS physics results

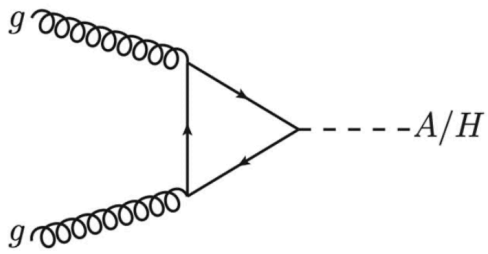
CMS physics results

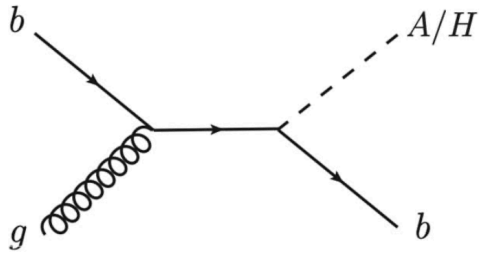
Benchmark Model for BSM Higgs

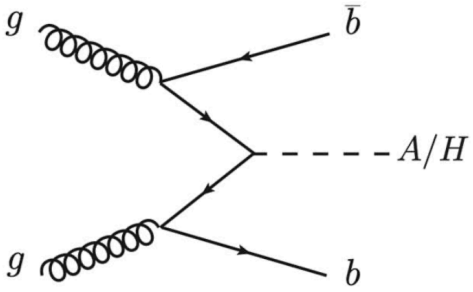
- Resonances in theory models: NWA, LWA, RS graviton, 2HDM, ….
  - NWA: narrow width approximation; LWA: large width assumption
  - RS: the bulk Randall–Sundrum (RS) model
- The two-Higgs-doublet models (2HDM), the simplest extension
  - 5 Higgs: *h/H (CP even), A (CP odd),* $H^{\pm}$
  - α: mixing angle between the two CP-even Higgses
  - tanβ: ratio of the two vacuum expectation values (v2/v1).
  - m^2_{12}: for a soft breaking of the $\mathcal{Z}_2$ symmetry (avoid tree-level FCNC)
  - Type-I, only Φ_2 couples to all quarks and leptons
  - Type-II, Φ_1 couples to down-type quarks and leptons and Φ_2 to up-type quarks.
- To explain the neutrino mass in 2HDM (arXiv:1904.07883v1)
  - Type I seesaw: Majorana mass term added for right-handed neutrinos
  - Type II seesaw model: a scalar triplet, with a neutral scalar that is responsible for generating neutrino masses at the eV scale
    - 7 scalar bosons: $H^{\pm\pm}$, $H^{\pm}$, A^0 (CP odd), H^0 and h^0 (CP even)

BSM Higgs Production

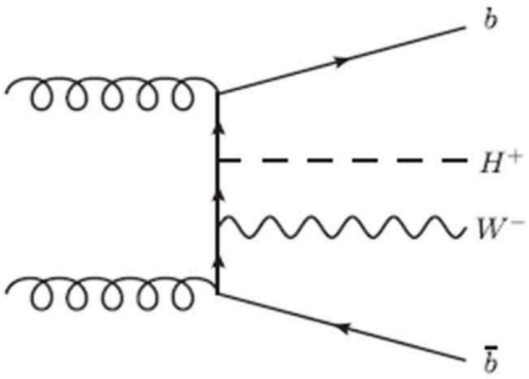
Neutral Higgs production A/H

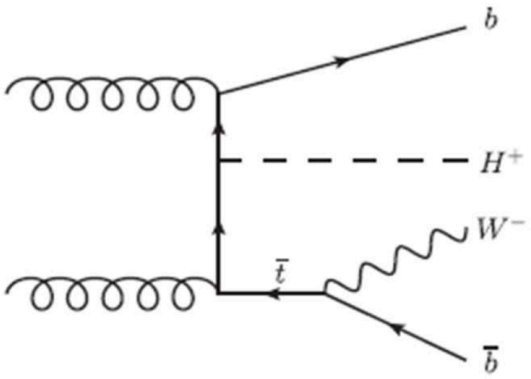


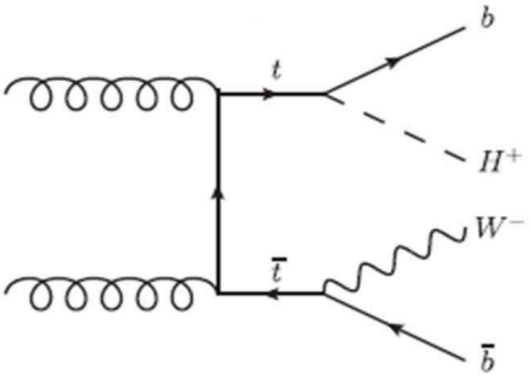




Charged Higgs production $H^{\pm}$







Searches at LHC

Neutral Higgs
√ $H/A \to \tau\tau$
$H/A \to bb$
$H/A \to tt$
$H/A \to \mu\mu$
√ $H/A \to \gamma\gamma$
√ $A \to Zh$
$A \to ZH$
√ $H \to WW$
√ $H \to ZZ$
$H \to ZA$

Charged Higgs
$H^+ \to \tau\nu$
√ $H^+ \to tb$
√ $H^+ \to cs$
$H^+ \to WZ$

Double Charged Higgs
√ $H^{++} \to W^+W^+$
$H^{++} \to \ell^+\ell^+$

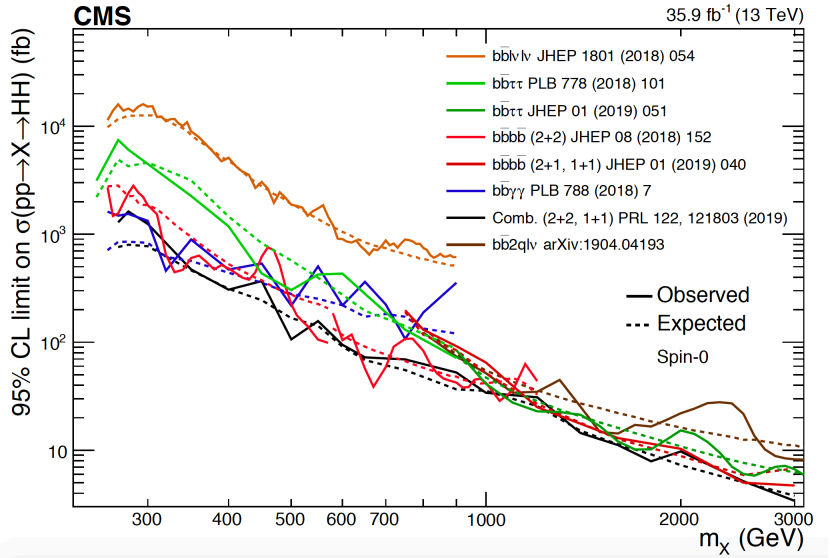
Di-Higgs Resonance Searches

WWWW, WWγγ, WWbb,

bbττ, γγττ, bbbb

Higgs exotic decays

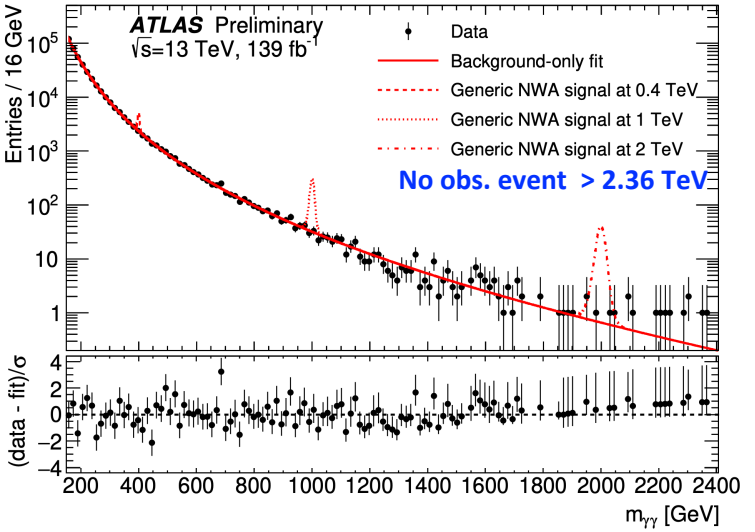
NOT included

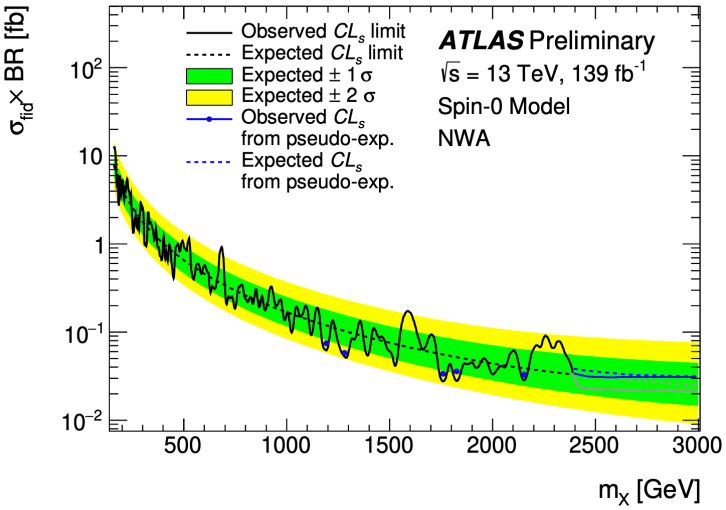


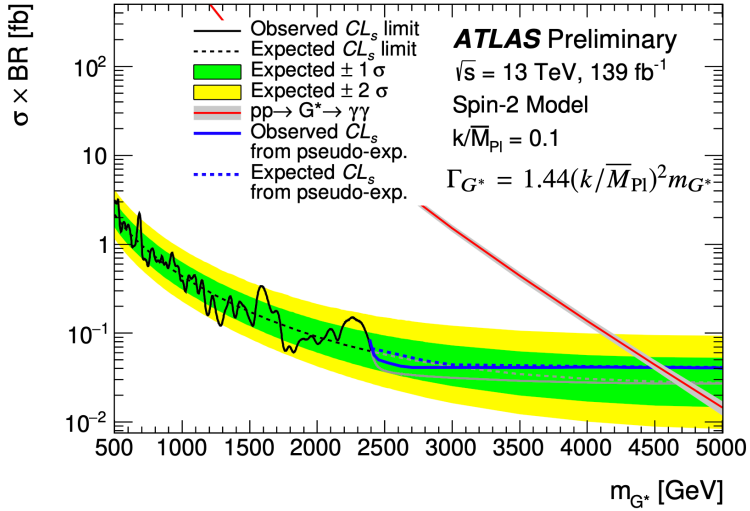
ATLAS-CONF-2020-037

Search for Heavy Resonance in γγ

- Search for high mass resonance for spin-0 resonant and spin-2 graviton
- Signal: double-sided crystal ball
- Background: power-law function
- Largest excess: 3.3σ at 684 GeV (1.3σ)





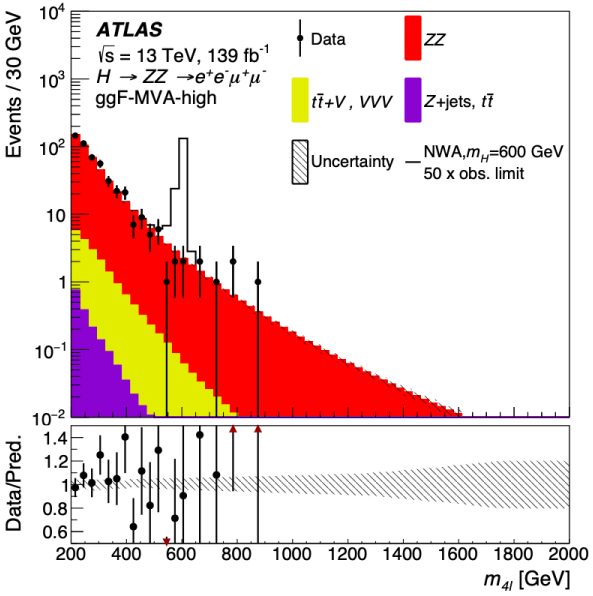


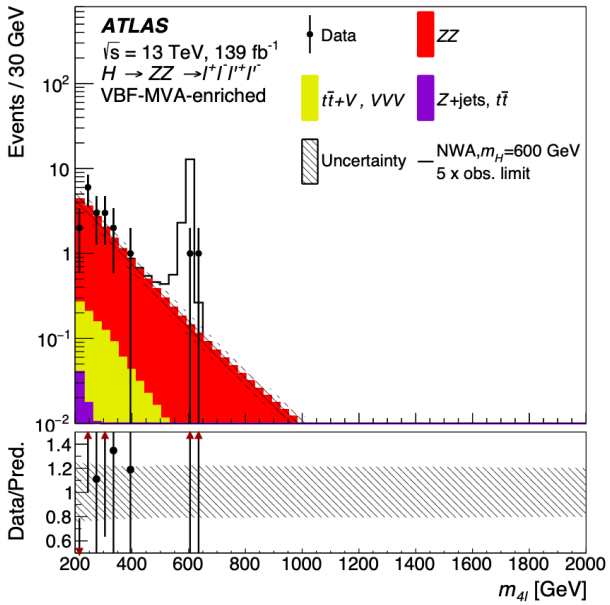
Spin-0		
m_X	400 GeV	2800 GeV
NWA	1.1 fb	0.03 fb
Γ_X/m_X= 2%	2.5 fb	0.03 fb
Γ_X/m_X= 6%	4.4 fb	0.03 fb
Γ_X/m_X= 10%	8.3 fb	0.03 fb
Spin-2		
m_{G^*}	500 GeV	5000 GeV
$k/\overline{M}_{Pl}$= 0.01	1.9 fb	0.04 fb
$k/\overline{M}_{Pl}$= 0.05	2.3 fb	0.04 fb
$k/\overline{M}_{Pl}$= 0.1	3.2 fb	0.04 fb

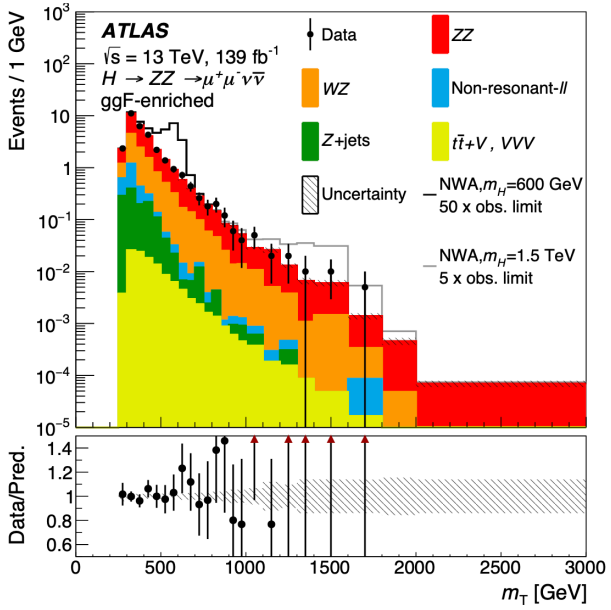
H→ZZ→4l and llvv

arXiv:2009.14791

- Narrow width approximation: ggF and VBF production modes
- Large width assumption: 1%, 5%, 10%, and 15%, with the consideration of interference effects with background
- 4-lep with 5 SRs in m_{4l}: VBF-high, ggF-high in 4e, 4μ, 2e2μ, ggF-low-4l
- 2l2v with 4 SRs in m_T: (2e2v, 2μ2v) ⊗(ggF, VBF)

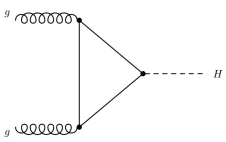


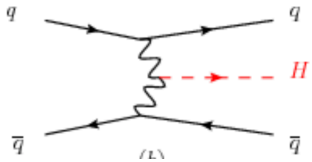




H→ZZ→4l and llvv

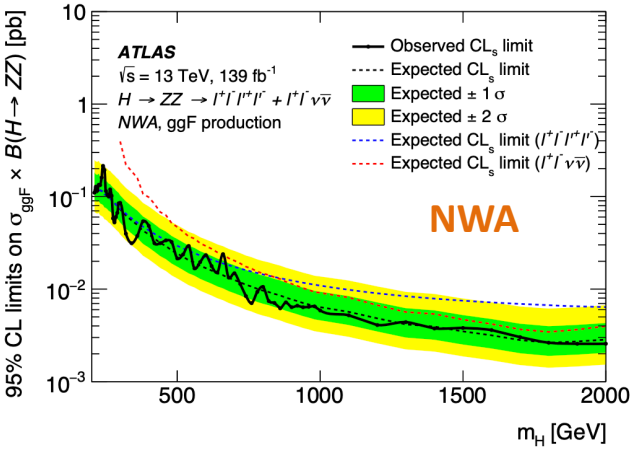
arXiv:2009.14791

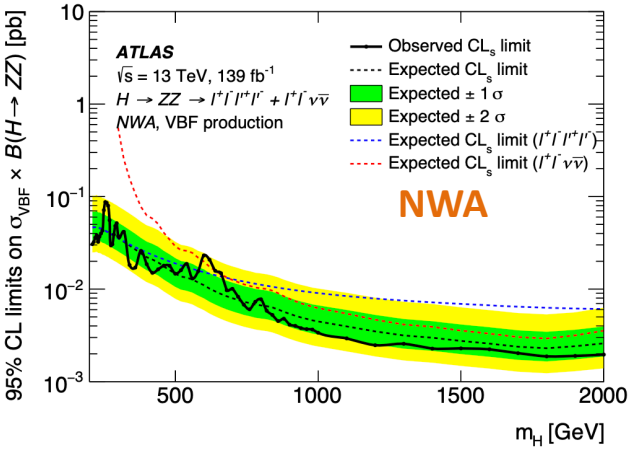


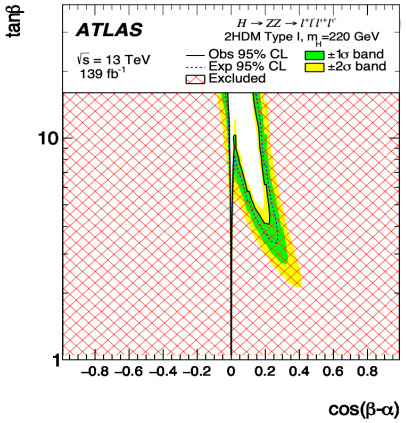


Largest excess:

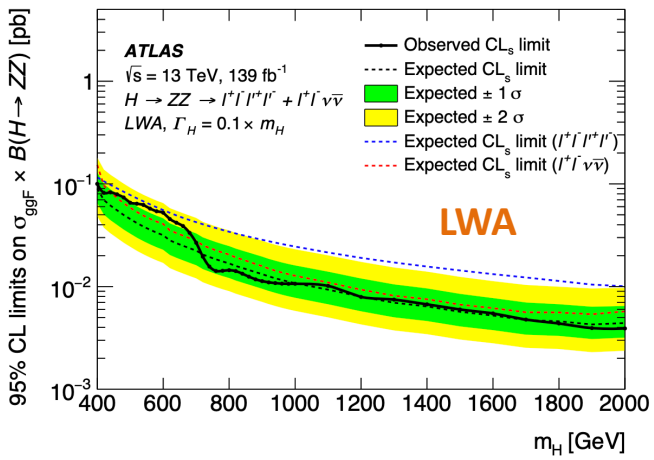
- ggF@240 GeV: 2.1σ (0.5σ)
- VBF@660 GeV: 2.6σ (1.2σ)

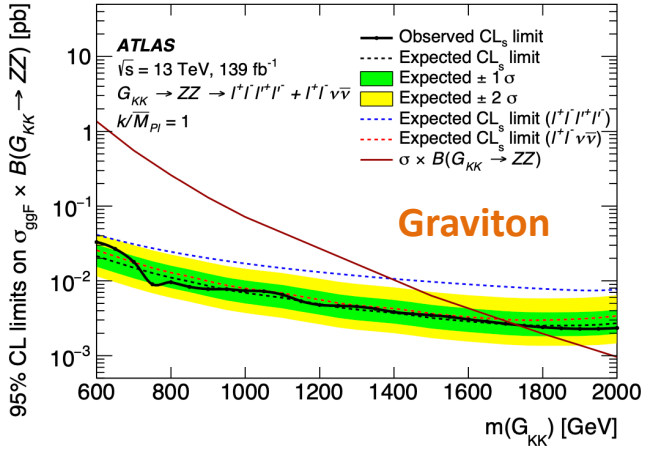


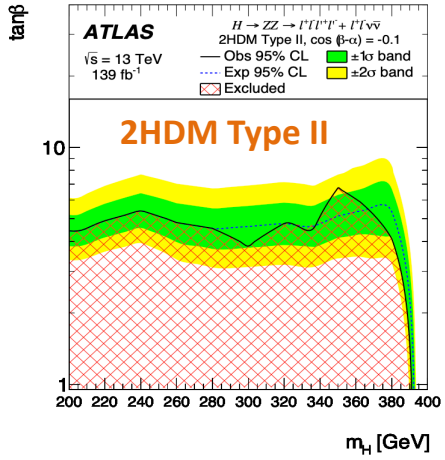




2HDM Type I



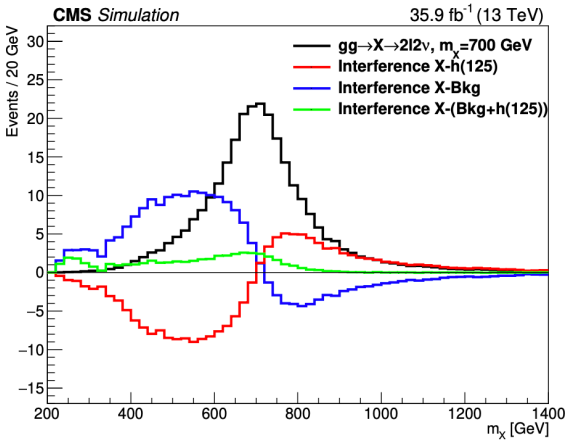




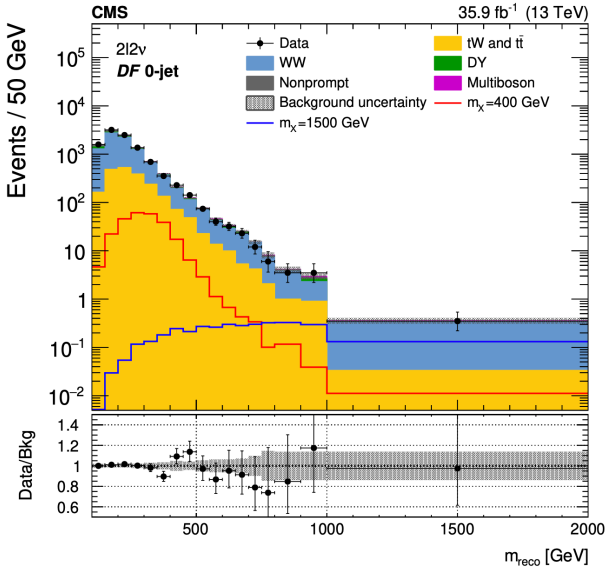
H →WW→lvlv and lvqq

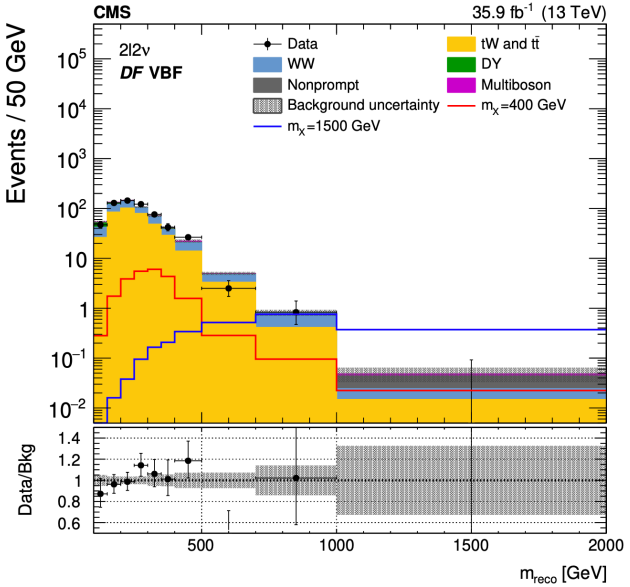
JHEP03 (2020) 034

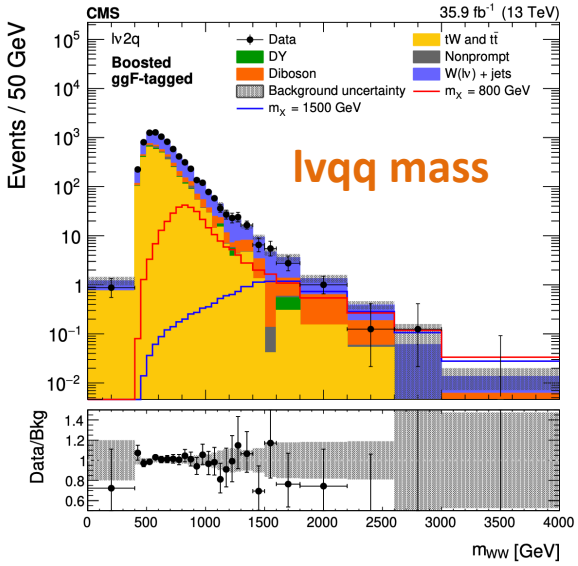
- Heavy resonance in ggF and VBF modes
- 2l2v: eμ in 0J, 1J, VBF, and ee/μμ in VBF
- lvqq: (resolved, boosted) ⊗(VBF, ggF, untagged)
- Interference considered for both ggF and VBF



$$m_{\mathrm{reco}} = \sqrt{(p_{\ell\ell} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\ell\ell} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}$$



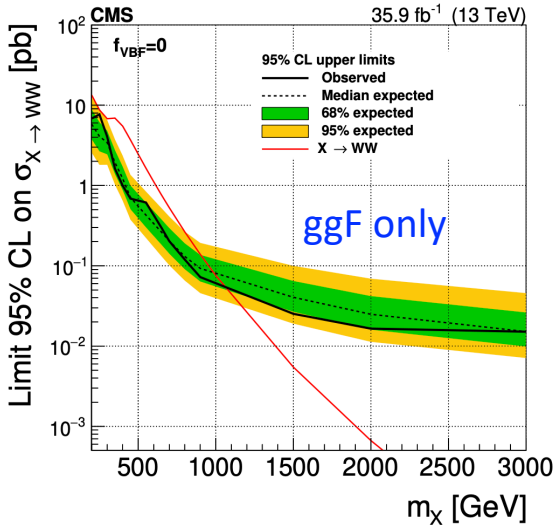


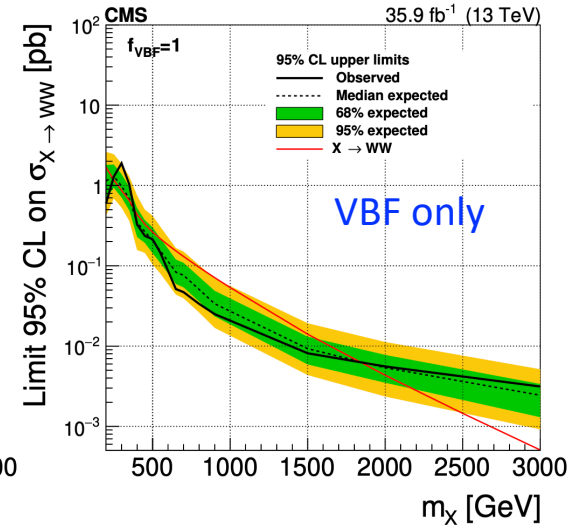


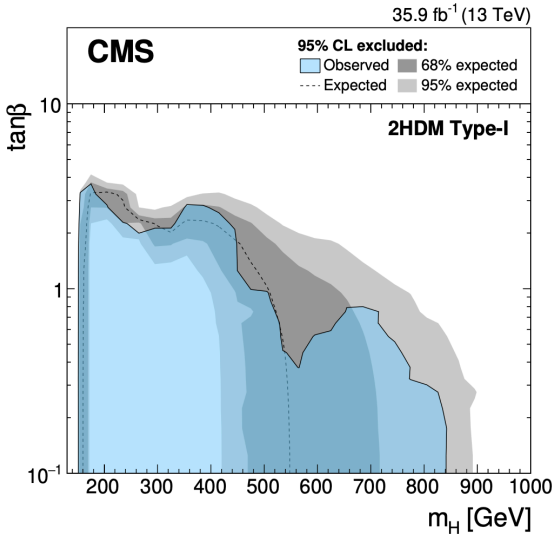
H →WW→lvlv and lvqq

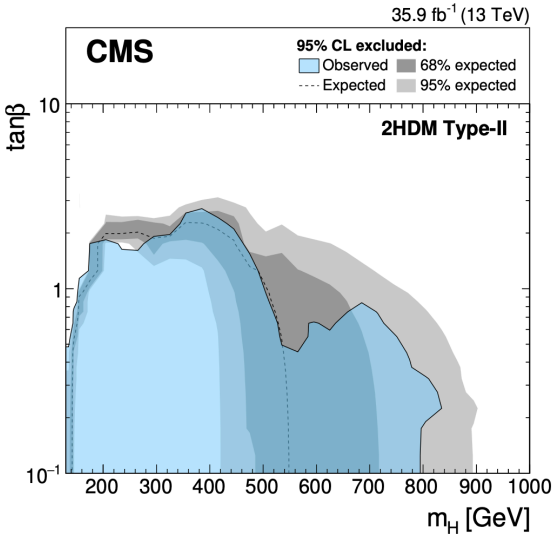
JHEP03 (2020) 034

- A simultaneous fit on done all 2l2v and lvqq SRs and CRs (1bin) for WW, top, DY, W+jets
- No excess observed, limits set on σxBr, or m_H vs tanβ
  - lvlv sensitivity: DF dominates for <800 GeV, similar for higher
  - lvqq sensitivity: resolved dominates at mass <400 GeV
  - lvlv dominiates for mass <400 GeV, lvqq more sensitive at high masses



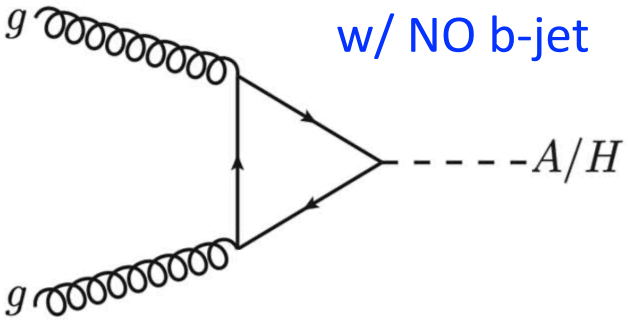




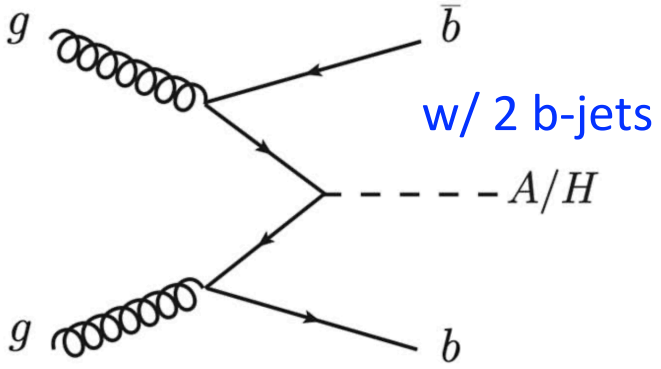


A/H→ττ

[Phys. Rev. Lett. 125 (2020) 051801]



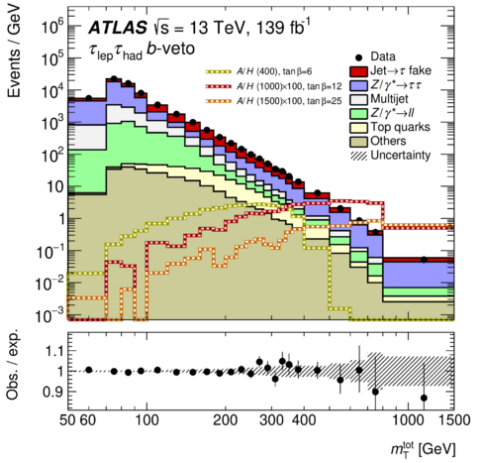
w/ NO b-jet

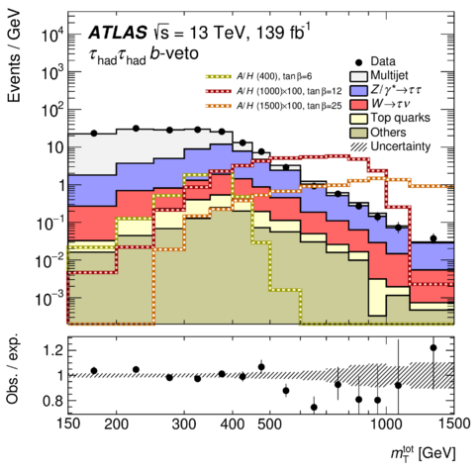


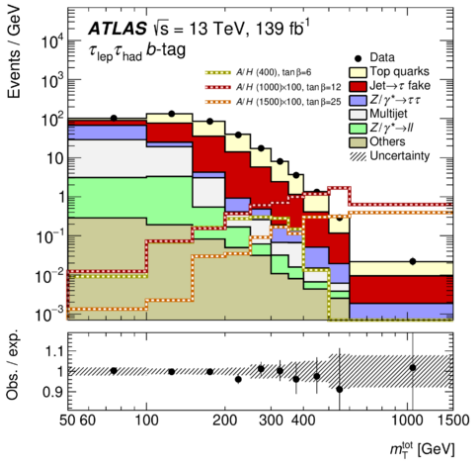
w/ 2 b-jets

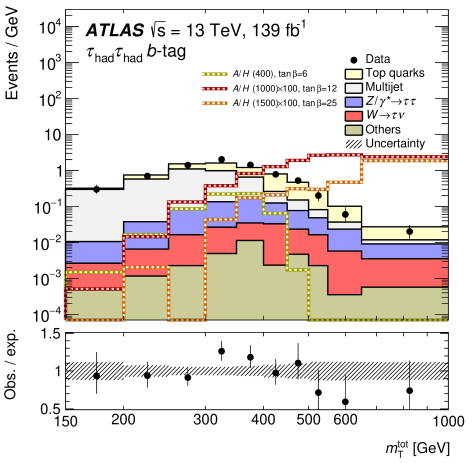
b-veto regions in lep-had and had-had

b-tagged regions in lep-had and had-had





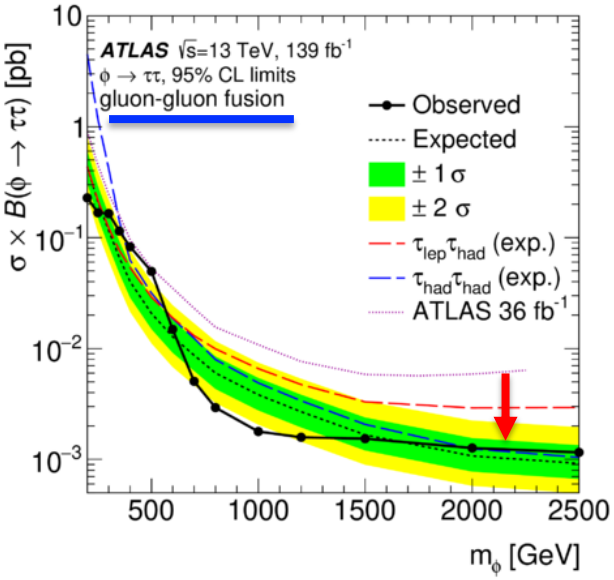


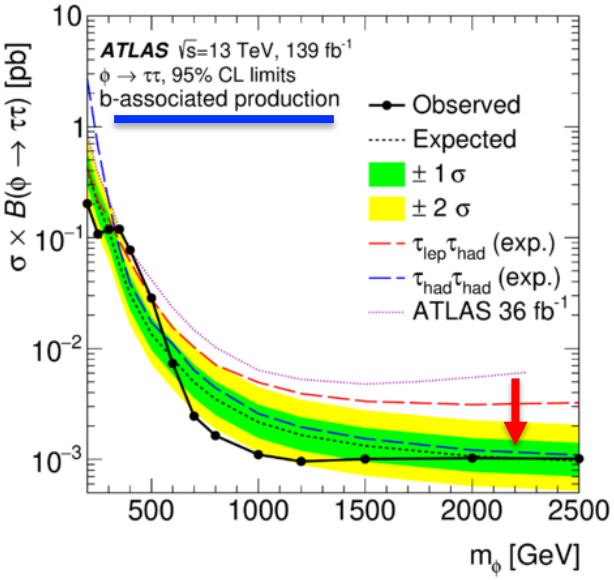


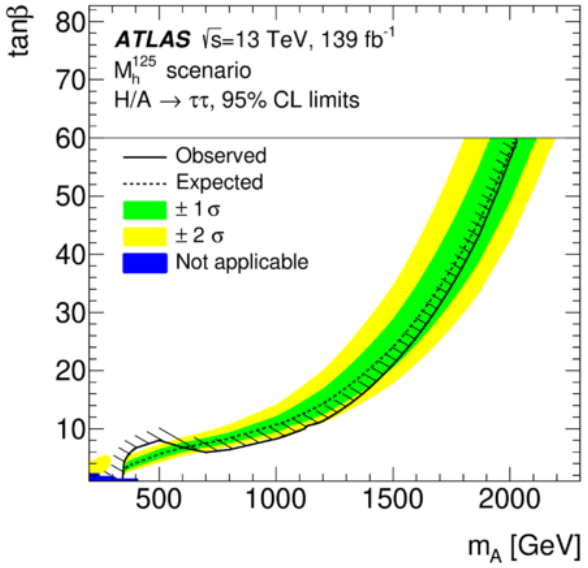
$$m_T^{\text{tot}} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\text{miss}})^2 - (\boldsymbol{p}_T^{\tau_1} + \boldsymbol{p}_T^{\tau_2} + \boldsymbol{E}_T^{\text{miss}})^2}$$

A/H→ττ

Phys. Rev. Lett. 125 (2020) 051801





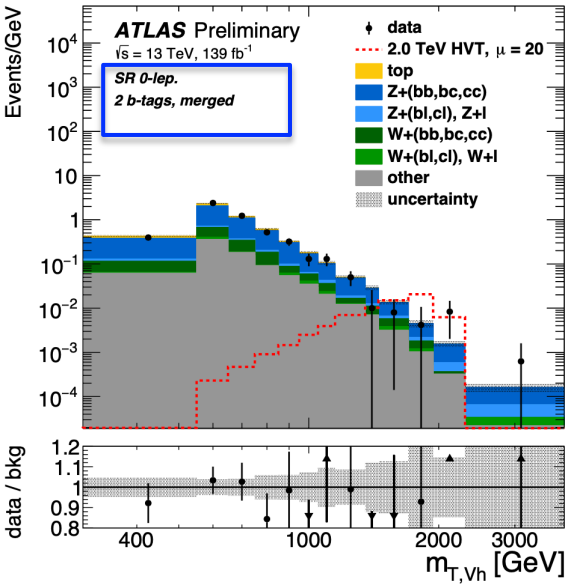


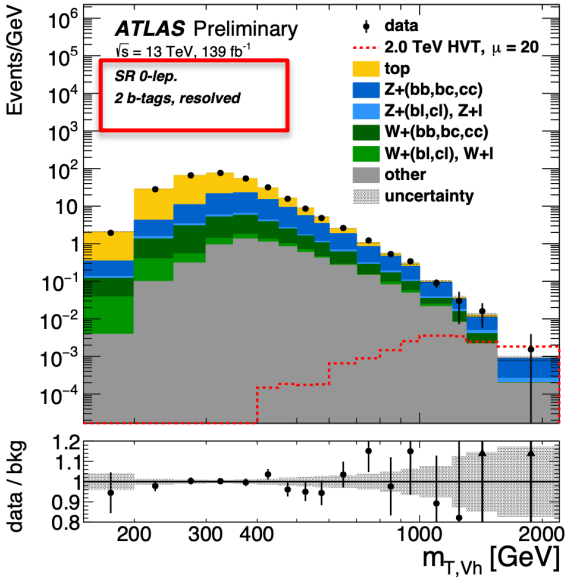
- No significant excess in the mass range of 0.2-2.5 TeV
- Lep-had dominates at the low masses, but had-had at the high masses
- Larger improvement than 36.1 fb^{-1} results, especially for high mass
- Largest excesses at 400 GeV: 2.2σ at ggF, 2.7σ for bbH

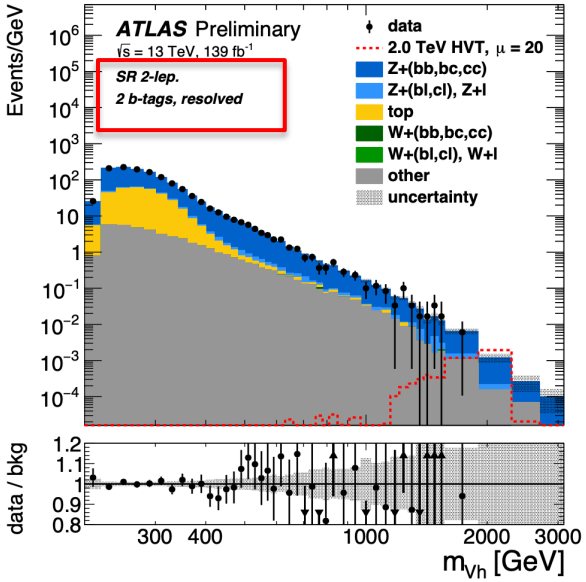
Z'/A→Zh, h→bb

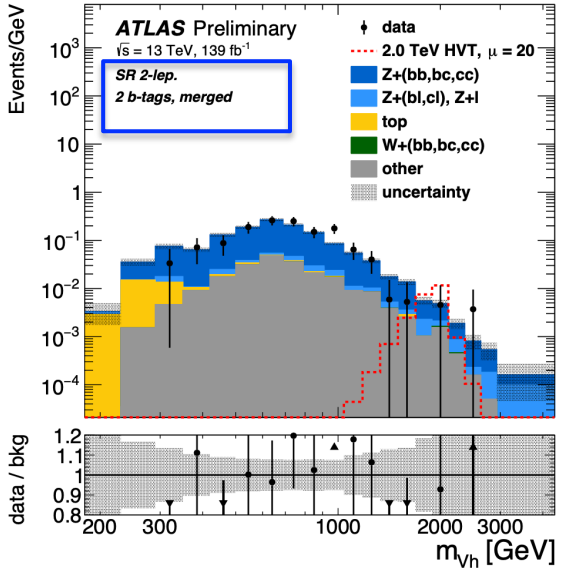
ATLAS-CONF-2020-043

- Search for heavy vector boson Z', or a heavy CP-odd scalar boson A
- 8 signal regions: (0-lep, 2-lep)⊗(1b-tag, 2b-tag) ⊗(resolved, merged)
- Control regions: (1b-tag, 2-btag) ⊗(resolved, merged) for 0-lep, and 1 top CR in eμ for 2-lep





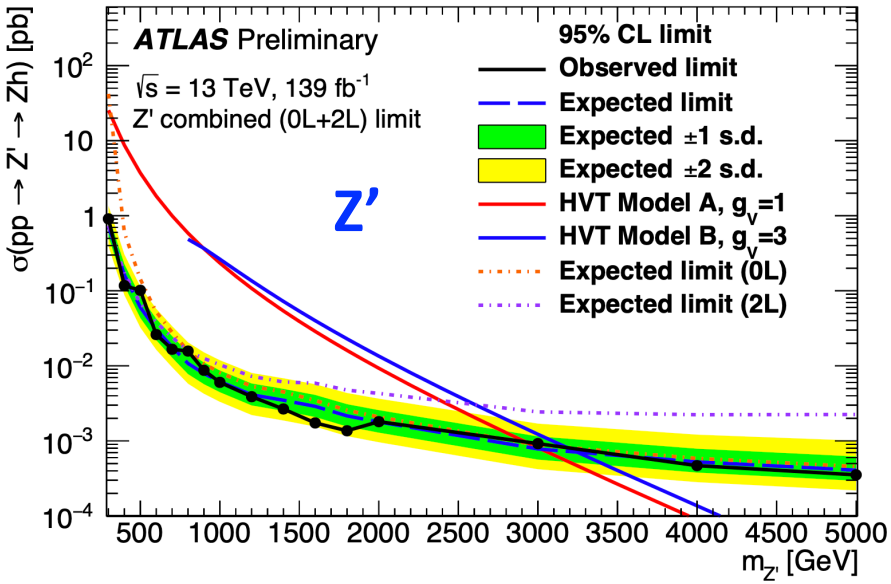


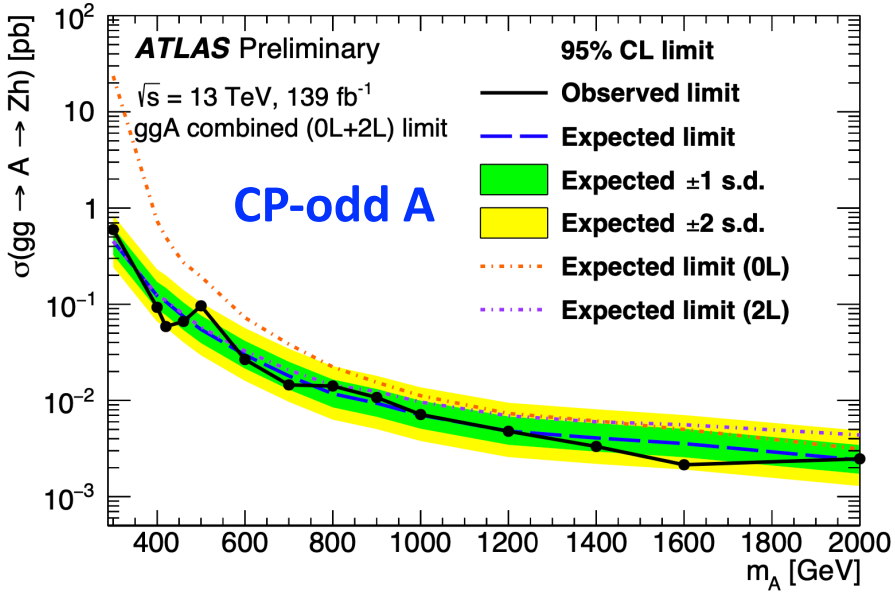


Z'/A→Zh, h→bb

ATLAS-CONF-2020-043

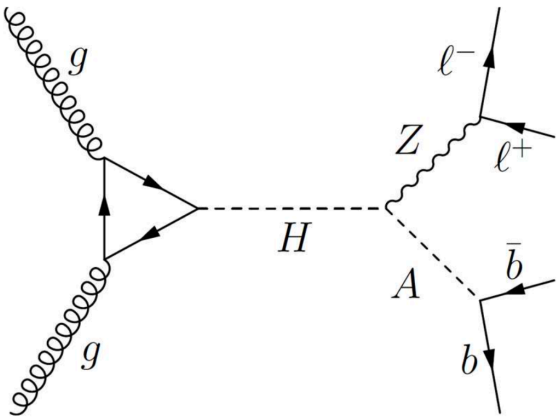
- Search for heavy vector boson, Z', or a heavy CP-odd scalar boson A
- For Z' signal,
  - Model A: ferminoic coupling comparable with bosonic coupling,
  - Model B: fermionic coupling suppressed
- Largest excess: 1.6σ at 500 GeV in 2-lepton channel





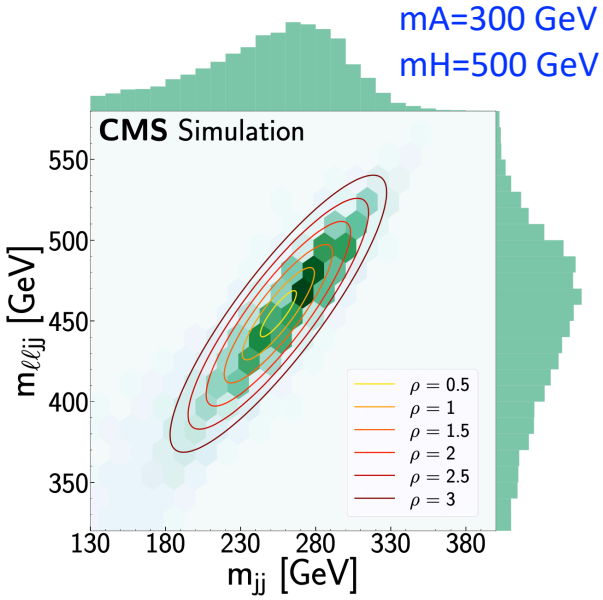
H→ZA→llbb

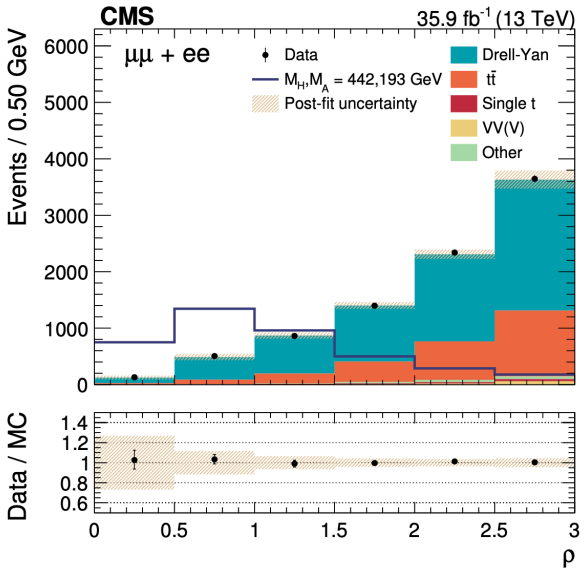
JHEP03(2020)055

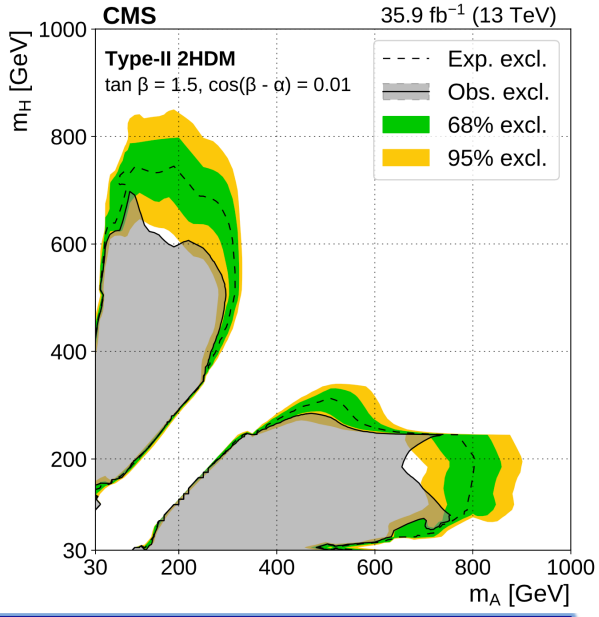


- Interesting channel in several scenarios such as 2HDM when cos(β-α)→0 (SM-like h)
- Mlljj vs mjj plane binned into elliptical regions

with ρ=*i*, containing roughly the fraction of signal events expected within *i* standard deviations in the 2D distribution



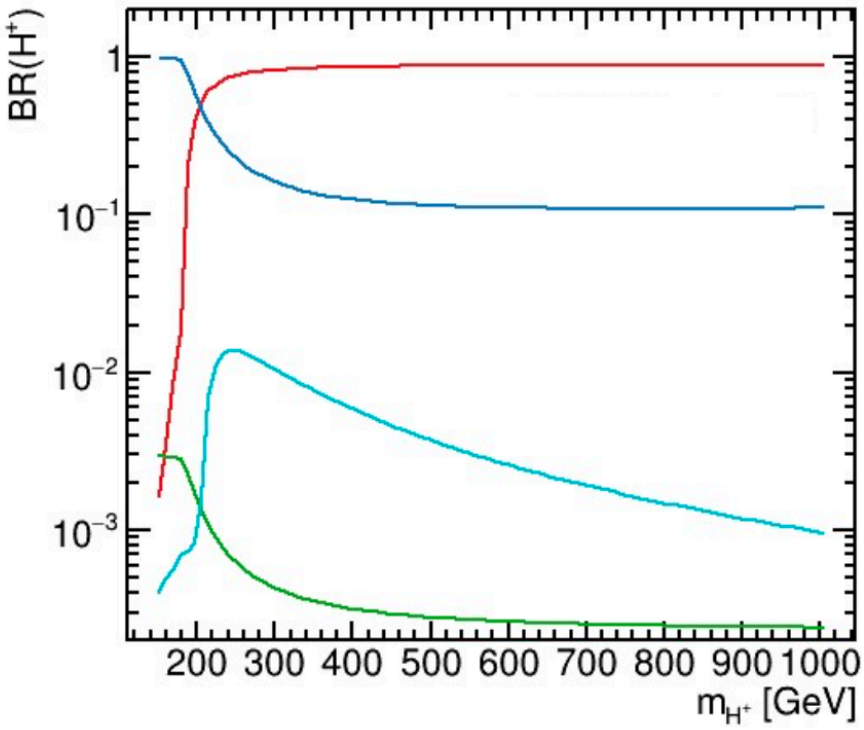




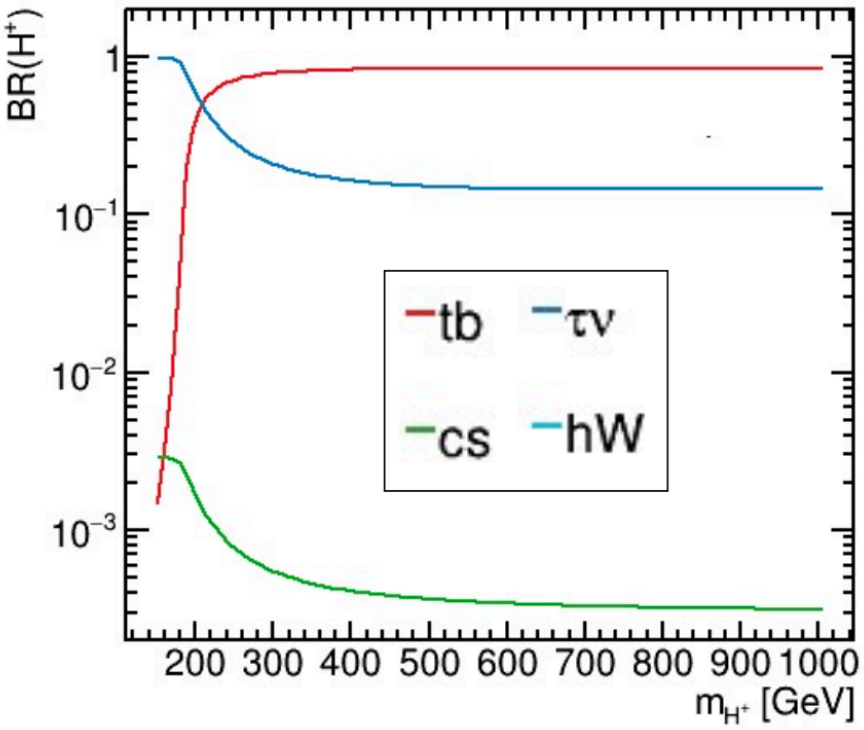
Charged Higgs

Example benchmark hMSSM

tanβ = 10



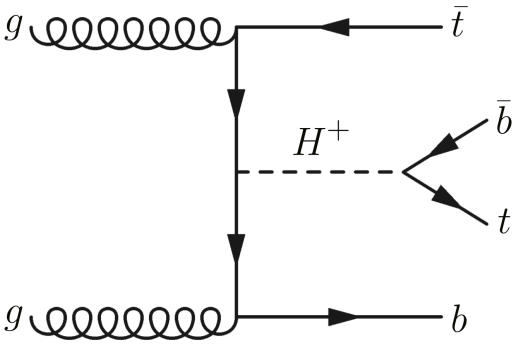
tanβ = 50

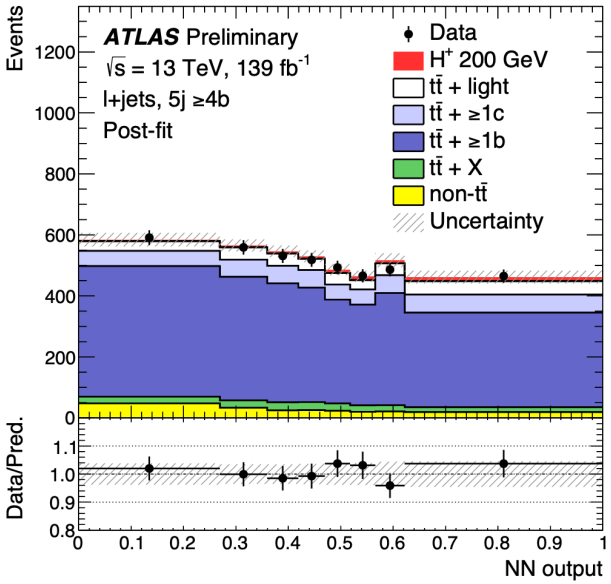


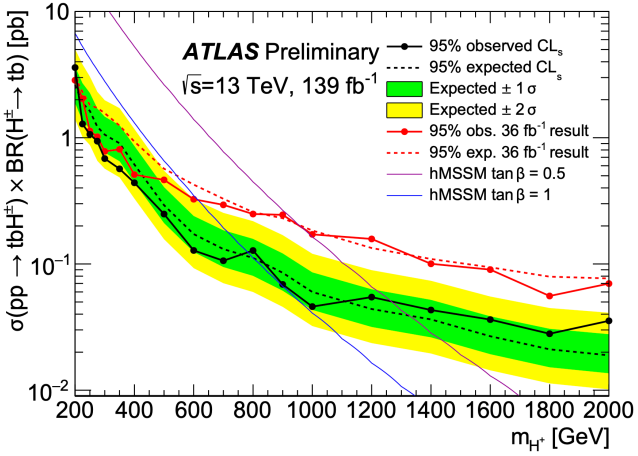
$H^+ \rightarrow tb$ in the 1 Lepton Channel

ATLAS-CONF-2020-039

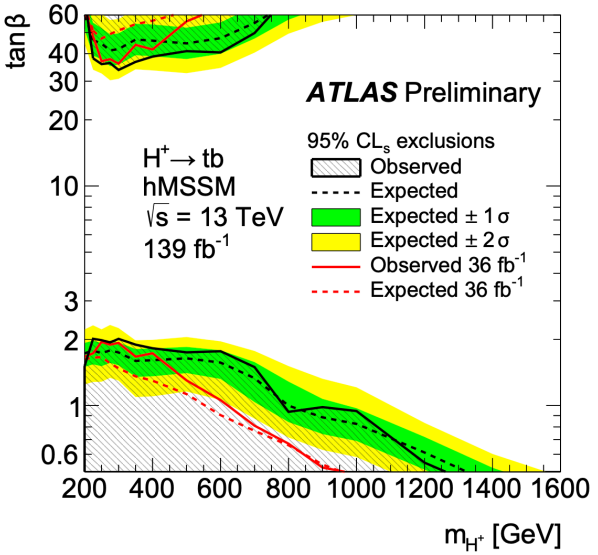
- Key channel in several new physics searches, 2HDM (MSSM) with high H^+ mass
- A neural network algorithm implemented
- Categories: (5j, >=6j) ⊗(3b, >=4b)
- No excess observed, limits set on σxBr





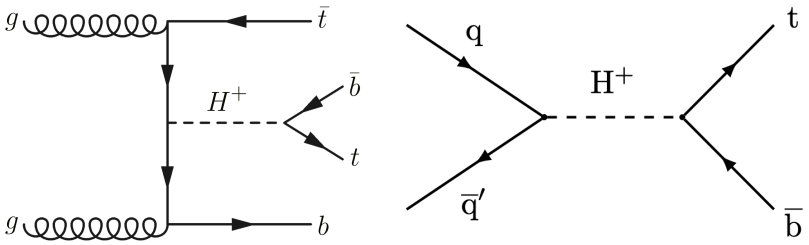


Tighter limits due to larger dataset and improved analysis



$H^+ \rightarrow tb$ in the All-Had Channel

JHEP07(2020)126

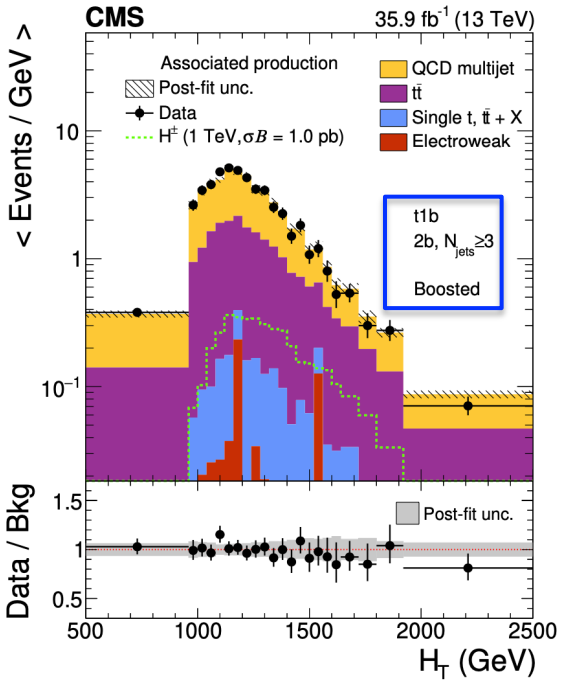


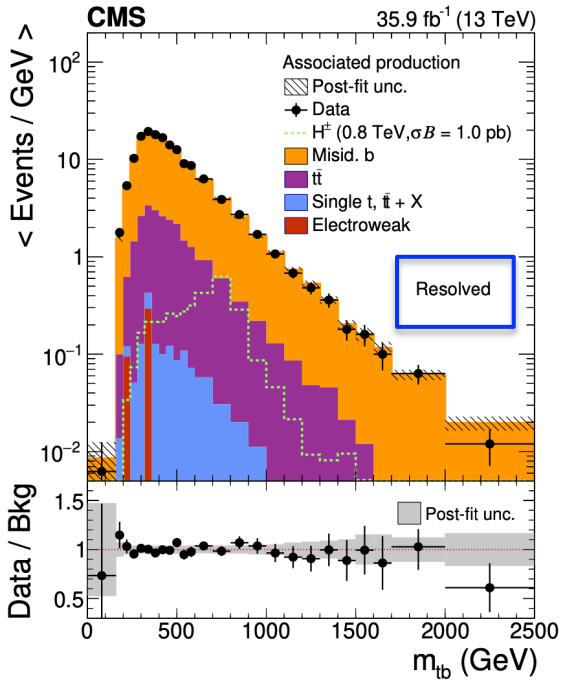
- Triggered with H_T^{trig}>900 (small-R)

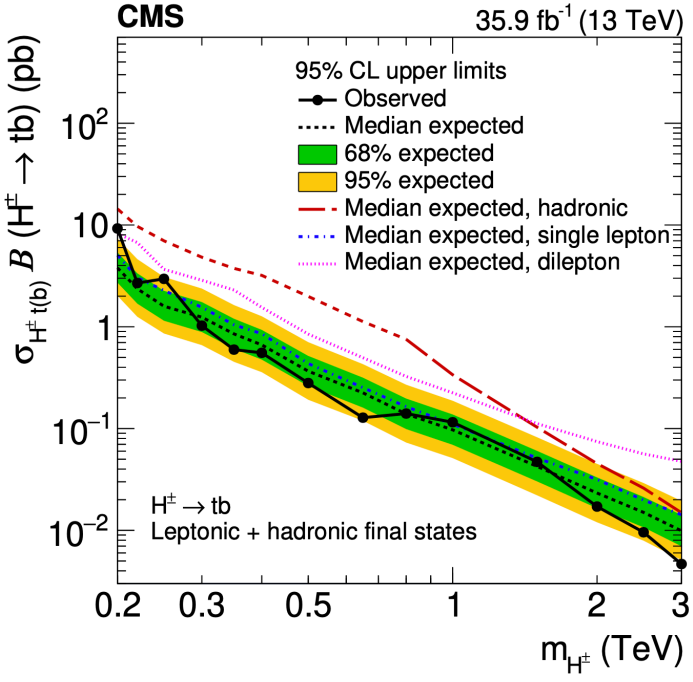
  p_T^{trig}>360 GeV with mass>30 GeV(LR)
- Split in *n*-jets, boosted t/W and *n* b-tags
- Target resolved (m_{tb}) and boosted(H_T)

H_T: scalar p_T sum of all selected jets

$$m_{H^\pm} \gtrsim 5 m_{top}$$



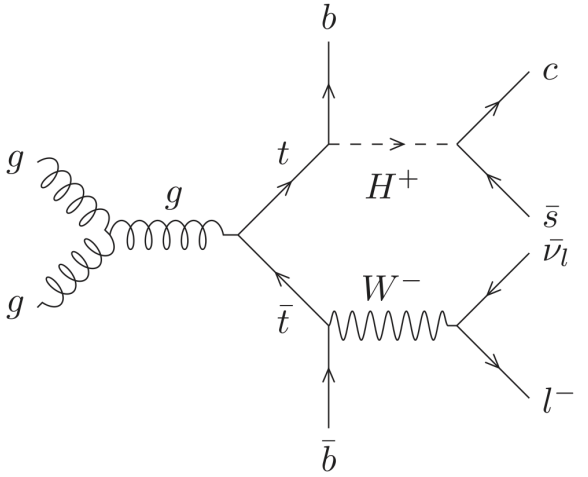


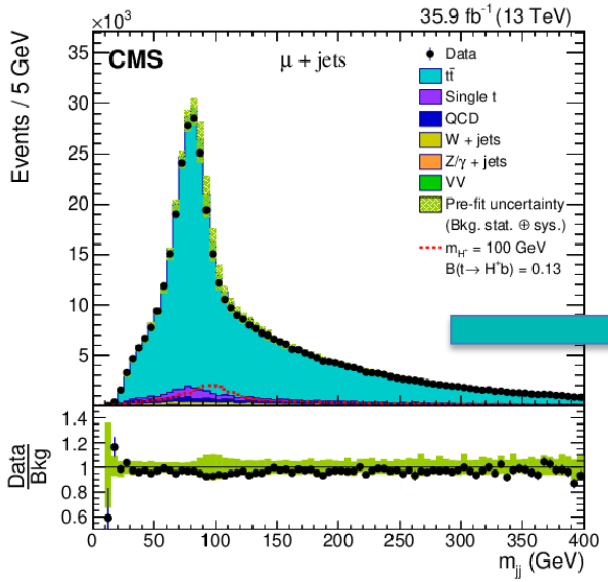


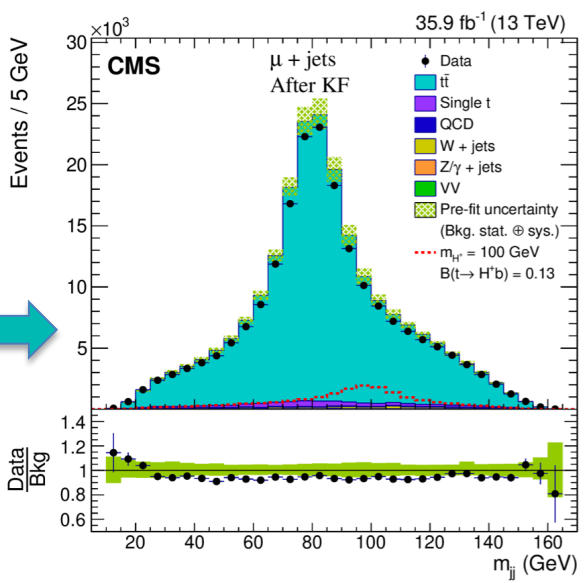
$H^+ \rightarrow cs$ for low H^+ mass

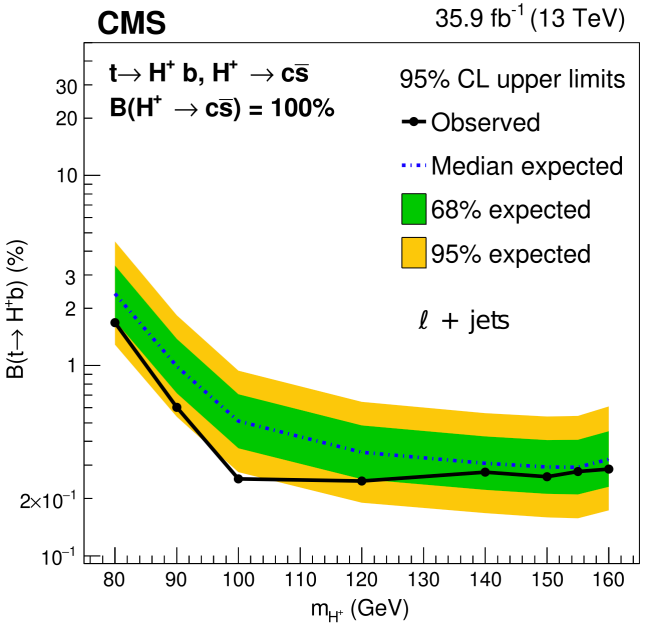
PRD 102 (2020) 072001

- Key channel in low tan β search in tt
  1 e/μ, E_T^{miss}, ≥ 4 jets (2 b-jets)
- Use kinematic fit with constraints on top mass
  mjj of 2 non-b jets as final discriminant
- Categories based on c-tagging (loose, medium, tight)



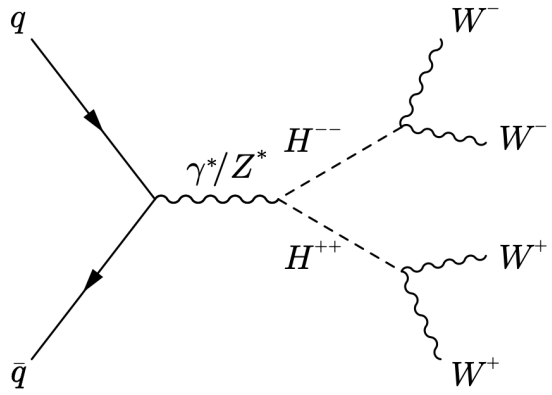






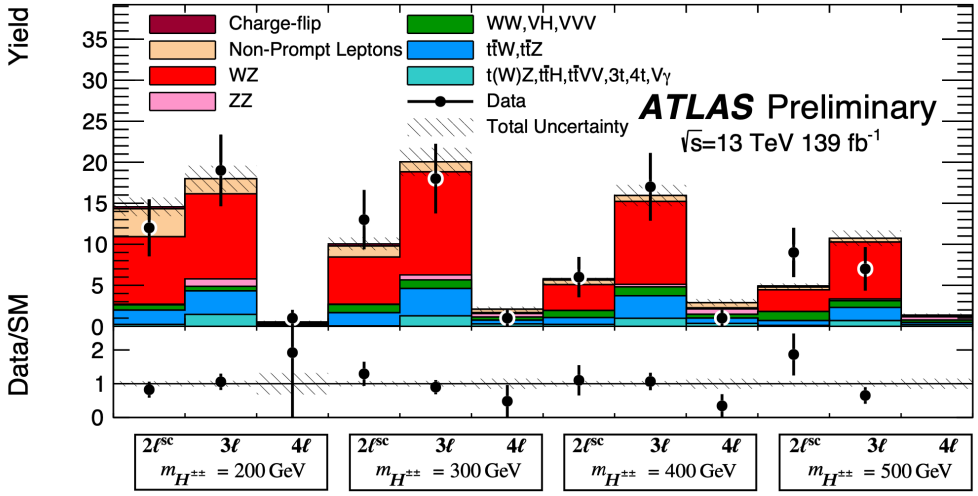
ATLAS-CONF-2020-074

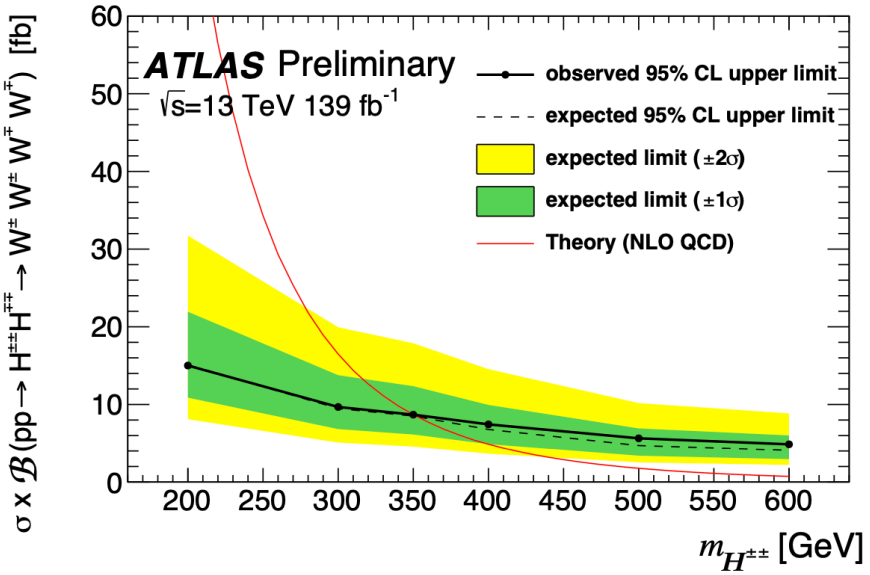
$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ in pair production



- Pair production of doubly charged Higgs
- Three channels: two same-sign charge, three or four leptons
- Prompt lepton backgrounds from MC, non-prompt leptons from data

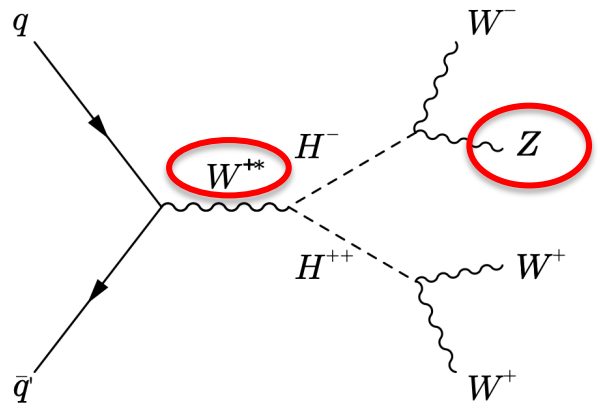
The mass difference between $H^{\pm\pm}$ and $H^{\pm}$ bosons is > 100 GeV





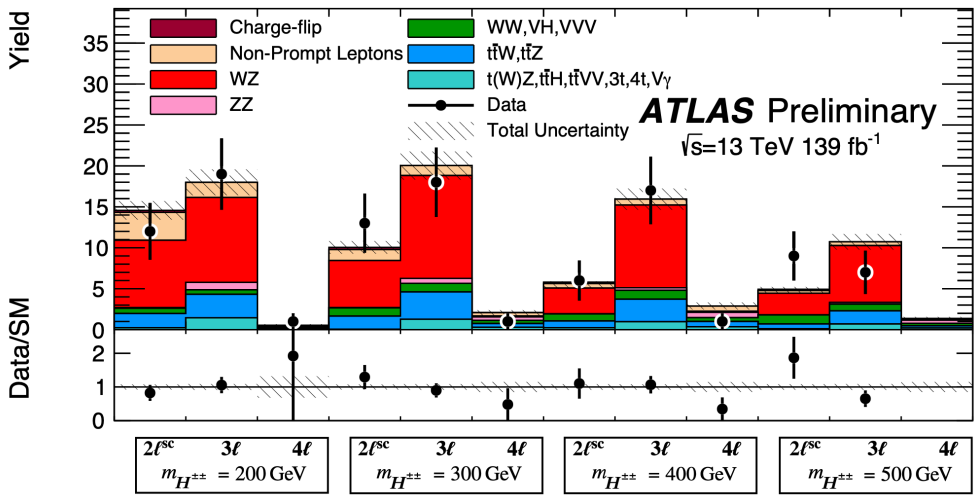
$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ associated $H^{\mp}$

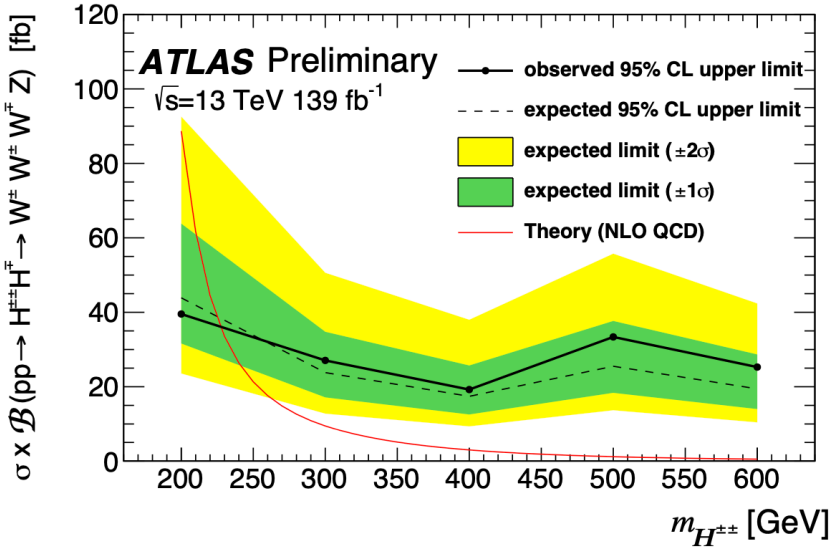
ATLAS-CONF-2020-074



Targets range $|m_{H^{\pm\pm}} - m_{H^{\pm}}| < 5$ GeV

- Associated production of singly charged & doubly charged Higgs bosons
- Three channels: two same-sign charge, three or four leptons
- Prompt lepton backgrounds from MC, non-prompt leptons from data



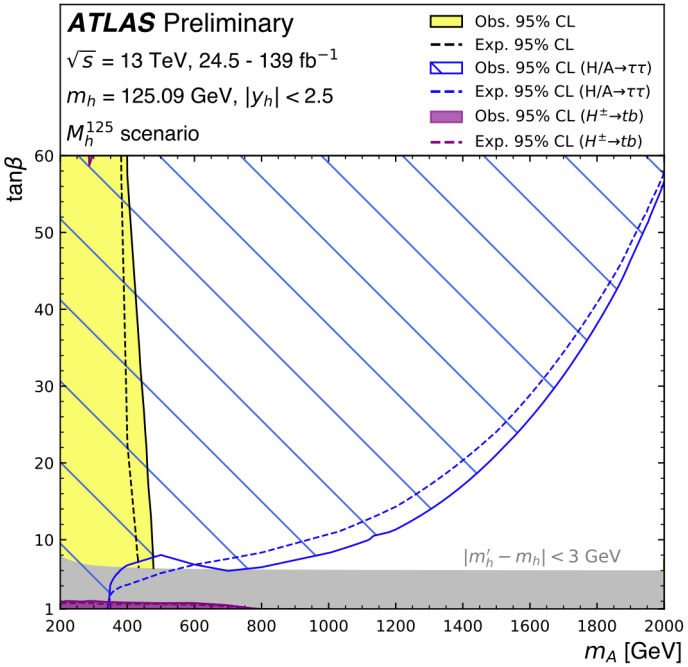


Combined Higgs Measurements

- Reinterpretation of combination of Higgs measurements in several MSSM benchmark scenarios

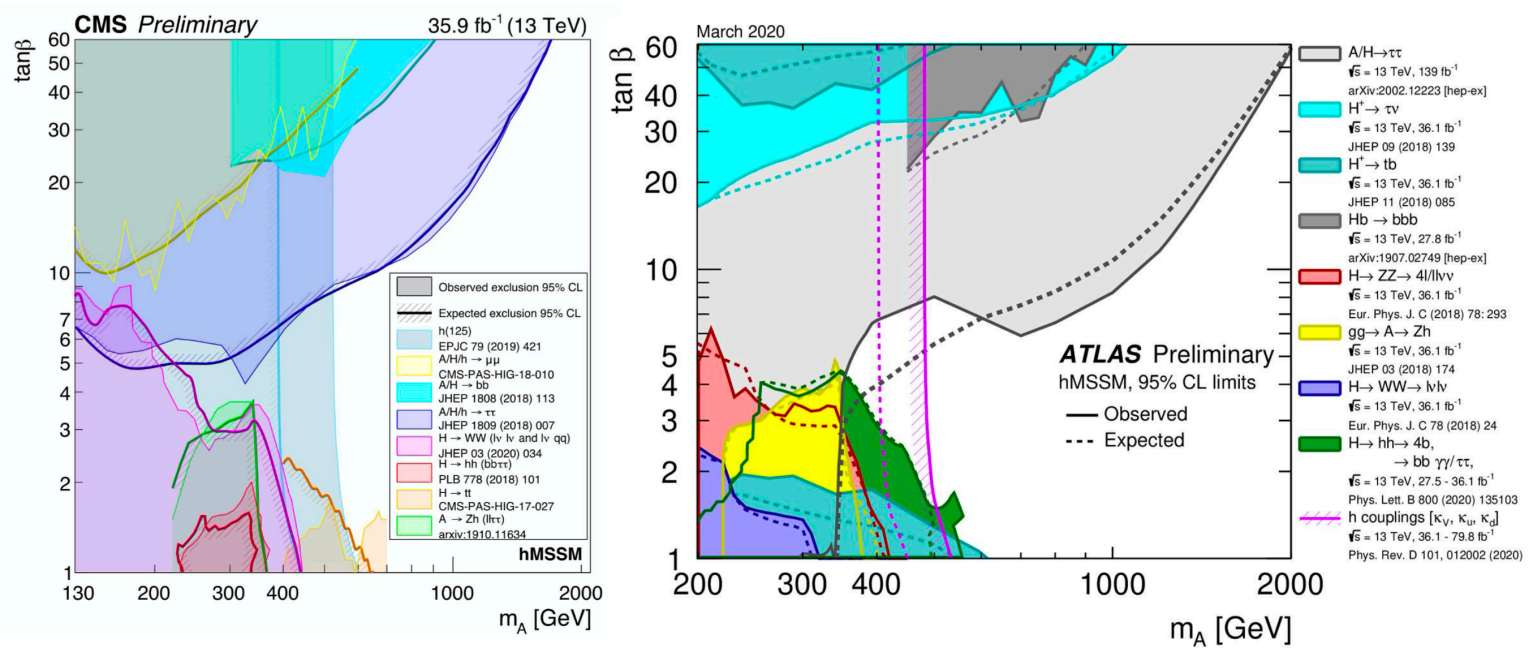
Analysis		Integrated lumi (fb^{-1})
$H \to \gamma\gamma$	(all production modes)	139
$H \to ZZ^* \to 4\ell$	(all production modes)	139
$H \to b\bar{b}$	(VH)	139
$H \to WW^*$	(ggH, VBF)	36.1
$H \to \tau\tau$	(ggH, VBF)	36.1
$H \to b\bar{b}$	(VBF)	24.5 – 30.6
$H \to b\bar{b}$	$(t\bar{t}H)$	36.1
$H \to$ multilepton	$(t\bar{t}H)$	36.1
$H \to \mu\mu$	(all production modes)	139

- M_h^{125} **scenario:**
  1) All superparticles are so heavy that production and decays of the MSSM Higgs are only mildly affected by their presence
  2) The loop-induced SUSY contribution to the couplings of the light CP-even scalar are small
  3) The heavy Higgs bosons with masses up to 2 TeV decay only to SM particles



Summary

- Presented latest results for BSM Higgs searches from the ATLAS and CMS
- No significant excess observed, but some results with a local excess with about 2-3σ significance
- Searches extended to new regimes: higher/low masses, new channels, …

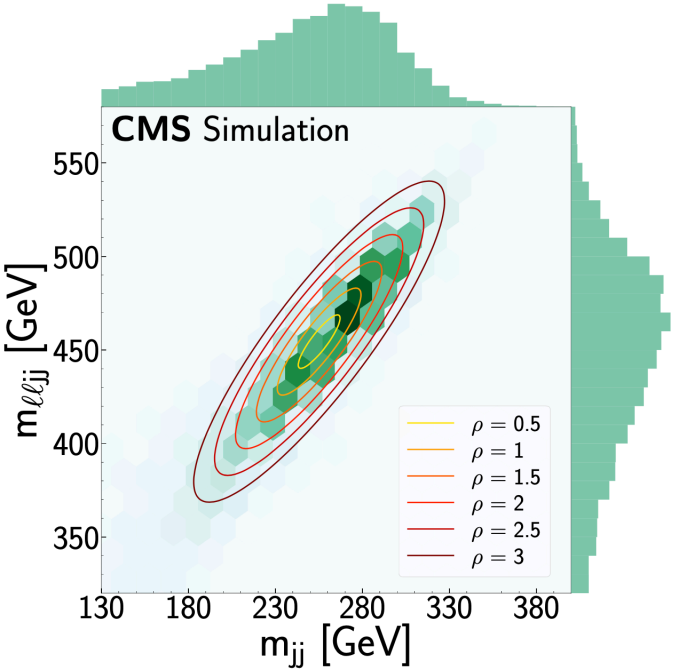


These plots NOT updated to all the latest results

Thank you!

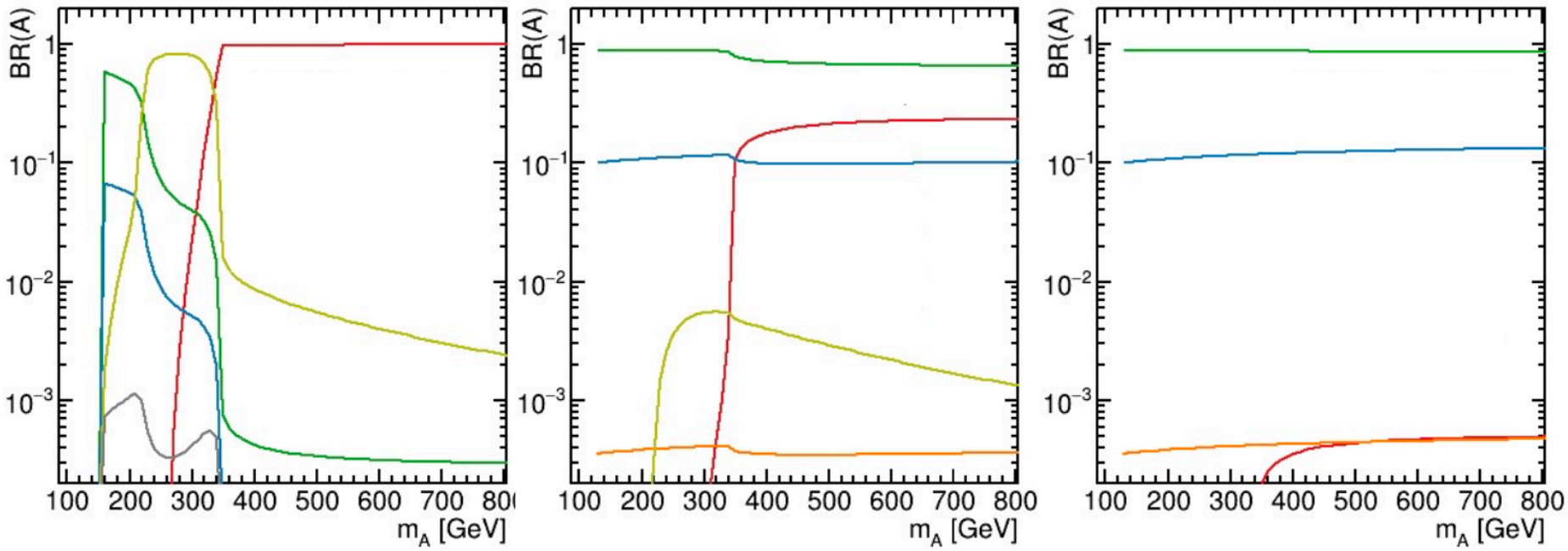
H→ZA→llbb

Since the shape of the signal is not exactly Gaussian, concentric elliptically shaped regions are defined in the parameter space using a parameter called ρ. Specifically, an ellipse with $\rho = i$ contains roughly the fraction of signal events expected within i standard deviations in a 2D distribution. Selected events in the $m_{\ell\ell jj}$ vs. m_{jj} plane are classified in six regions around the center of the ellipse defined for each signal point. The regions are built in ρ steps of 0.5, from 0 to 3, as illustrated in figure 4 (right), and lead to a template containing six bins used to perform the statistical analysis. By construction, the bulk of the signal is located at small values of ρ. The yield in data and the expected yields in simulation are reported in table 1 for each elliptical bin under the mass hypothesis $m_H = 500\,\text{GeV}$ and $m_A = 200\,\text{GeV}$. The ee and μμ categories are summe



Branching Ratio of A(CP odd) Decays

tanβ = 1 tanβ = 10 tanβ = 50



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

Charged Higgs boson mass	$m_{H^{\pm\pm}}$ = 200 GeV	$m_{H^{\pm\pm}}$ = 300 GeV	$m_{H^{\pm\pm}}$ = 400 GeV	$m_{H^{\pm\pm}}$ = 500 GeV or 600 GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S [rad.]	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^\pm\ell^\pm}$ [rad.]	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_T^{miss}}$ [rad.]	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
E_T^{miss} [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^\pm\ell^\pm}$ [rad.]	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
E_T^{miss} [GeV]	>30	>55	>80	>90
$\Delta R_{\ell jet}$ [rad.]	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_T^{leading\ jet}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
E_T^{miss} [GeV]	>60	>60	>60	>60
$p_T^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R^{min}_{\ell^\pm\ell^\pm}$ [rad.]	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R^{max}_{\ell^\pm\ell^\pm}$ [rad.]	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

SR	$2\ell^{sc}$			3ℓ		4ℓ
				Number of same-flavour opposite-charge pairs		
	ee	$e\mu$	$\mu\mu$	0	> 0	
Prompt lepton	1.66±0.28	4.3±0.5	2.30±0.26	1.62±0.20	17.2±1.6	1.69±0.19
Charge-flip	0.17±0.07	0.102±0.034	–	–	–	–
Non-prompt lepton	0.3±0.25	0.65±0.33	0.39±0.19	0.36±0.23	0.9±0.6	0.41±0.25
Total background	2.1±0.4	5.1±0.6	2.69±0.32	1.98±0.29	18.1±1.6	2.10±0.30
Data	4	8	1	1	17	1
n_{95}	6.72	9.21	3.24	3.27	9.52	3.31
$H^{\pm\pm}H^{\mp\mp}$	1.99±0.24	5.3±0.6	3.03±0.35	2.63±0.30	7.6±0.9	1.50±0.17
A_{PP} [%]	0.087	0.233	0.132	0.115	0.333	0.065
$H^{\pm\pm}H^{\mp}$	0.57±0.07	1.43±0.16	0.81±0.09	0.43±0.05	1.35±0.16	0.156±0.020
A_{AP} [%]	0.043	0.109	0.62	0.033	0.103	0.012

$H^+ \rightarrow tb$ in the All-Had Channel

JHEP07(2020)126