Search for Higgs beyond the Standard Model with the ATLAS Detector

ASPEN 2017

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on behalf of the ATLAS Collaboration
Stanford University

Outline

- Introduction
- Beyond Standard Model Higgs theories
- Results for recently published channels
- Conclusion

Introduction

The Higgs boson was discovered in 2012

Need to extend SM to address issues like hierarchy problem, quantum gravity, baryon asymmetry, dark matter/energy, neutrino masses

Look for BSM physics by

- Looking for deviations from the SM in Higgs properties measurements
- Directly searching for beyond SM objects
  - Additional Higgs bosons decaying to SM particles
  - SM Higgs decays to BSM states (eg. invisible decays)

Beyond Standard Model Higgs Theories

SM Higgs doublet + **Additional Field** = **Additional Higgs Bosons**

EWS: Additional EW Singlet Model

SM + one scaler EW singlet =

Neutral CP Even

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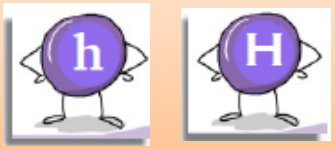
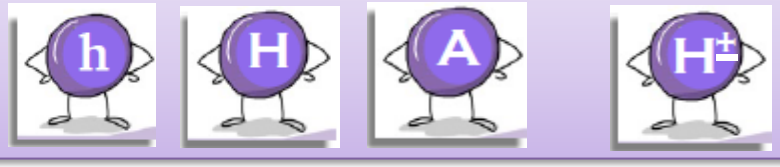


2HDM: Two Higgs Doublet Model
SM + another Higgs doublet =

Neutral **Charged**

CP Even CP Odd



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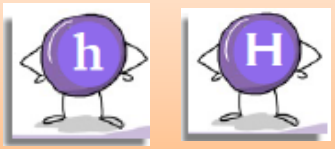
EWS: Additional EW Singlet Model SM + one scaler EW singlet	=			**Neutral CP Even** 
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2HDM + Singlet (complex) Model SM + doublet & singlet	=			**Neutral** CP Even: CP Odd: + 2HDM Higgses

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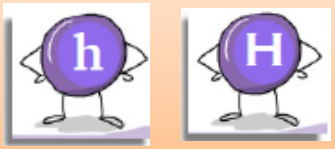
EWS: Additional EW Singlet Model SM + one scaler EW singlet	=	**Neutral CP Even** 
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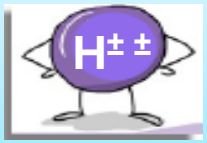
Higgs Triplet Model SM + triplet	=	**Double Charged**  + 2HDM Higgses

Beyond Standard Model Higgs Theories

EWS significantly constrained by Run 1 Higgs measurements

2HDM: two Higgs doublets Φ_1 and Φ_2

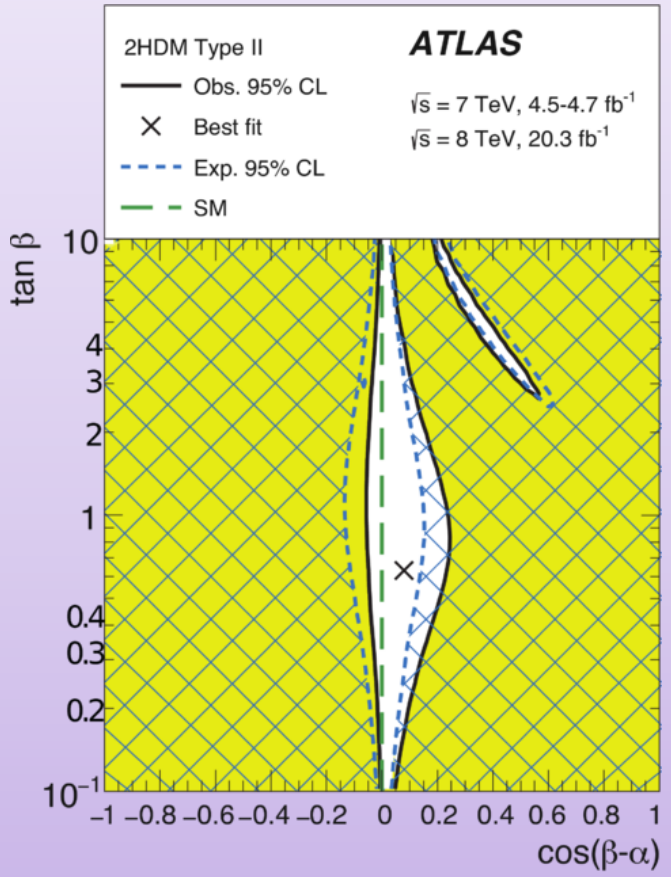
7 parameters:

$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12},\ tan\beta\ ,\ \alpha$

Ratio of VEV of Φ_1 and Φ_2

h & H mixing angle

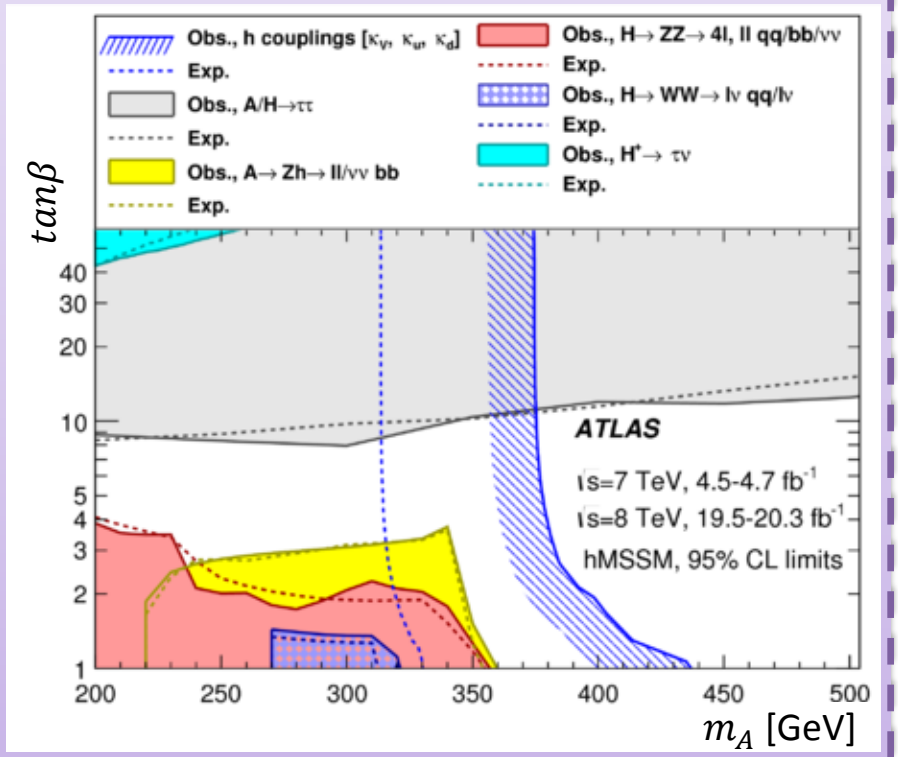
- Models motivated by bounds on FCNC
  - Type I : fermions couple to Φ_2
  - Type II : up type quarks couple to Φ_2, down-type quarks & charged leptons couple to Φ_1. Eg: MSSM
- Run 1 SM Higgs results give big constraints on 2HDM. Data prefers alignment limit: $\cos(\beta-\alpha)\ =\ 0$



Beyond Standard Model Higgs Theories

Minimal Supersymmetric SM (MSSM)

- Simplest extension of SM that includes SUSY
- Beyond tree level more than 2 parameters affect Higgs sector, benchmarks defined:
  - $m_{h,mod}^{\pm}$: m_h is close to 125 GeV
  - hMSSM : measured value of m_h can be used to predict other masses
- In Run 1 excluded many regions of parameter space



Results for all published channels

Neutral Heavy Higgs to bosons	WW → lvlv ZZ → 4l ZV → llqq /vvqq WV→ lvqq X->Zγ
	A→ Zh
	H→4γ H → WH

Neutral Higgs to fermions	A/H/h → ττ A/H/h → tt

Neutral Higgs to di-Higgs	hh → 4b hh → WWγγ
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Charged Higgs	$H^{\pm}$ → τν $H^{\pm}$ → tb $H^{\pm\pm} \rightarrow ll$
	Light $H^{\pm}$ → cs VBF $H^{\pm}$ → WZ

Higgs exotic with MET	H → γγ+MET H → Z (ll)+MET
	VBF h → INV Zh → INV (lep) Vh → INV (had) H → γ+MET H→ ZZ_{dark} H→ INV (1 jet)

Higgs to light res.	h(125) → aa → 4b
	H/h → aa → μμττ

Rare decays/ LVF	h(125) → ϕγ
	h(Z) → J/ψγ h → τμ / τe / eμ

13.2-15.4 fb^{-1} (2015+2016)
3.2 fb^{-1} (2015)
5-20.3fb^{-1} (RUN 1)

Legend

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Will focus on latest results in RED

Updates on these + new channels coming soon

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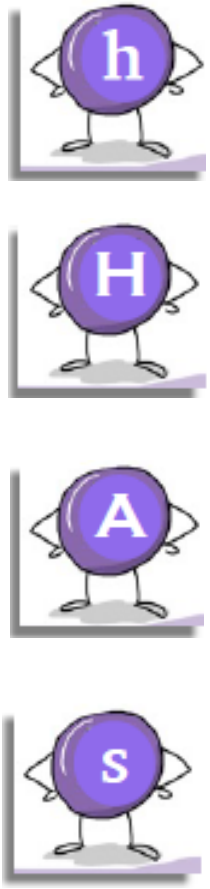

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- Prominent decay is to W/Z in many BSM models

- **Heavy Higgs in Narrow Width Approximation (NWA): Higgs width smaller than experimental resolution (tests EWS, 2HDM, singlet+doublet)**

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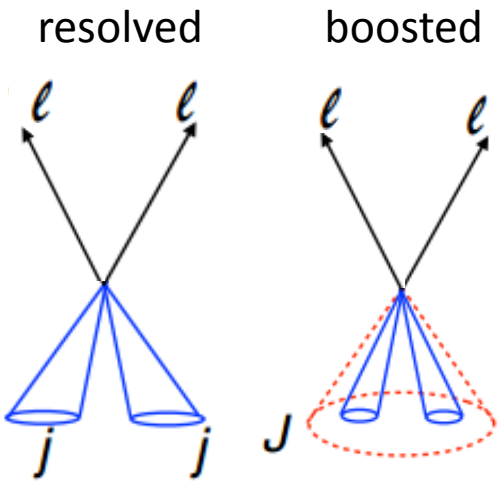
- Other BSM models tested: Spin 1 Z'/W', spin 2: Kaluza-Klein graviton (G_{kk^*})

- Resolved analysis at lower mass: 2 small radius jets (llqq)

- Boosted analysis: when resonance mass higher than W/Z mass 2 jets merge into 1 big radius jet (llqq, vvqq, lvqq)

- Discriminating variable: invariant/transverse mass



ZV → llqq /vvqq

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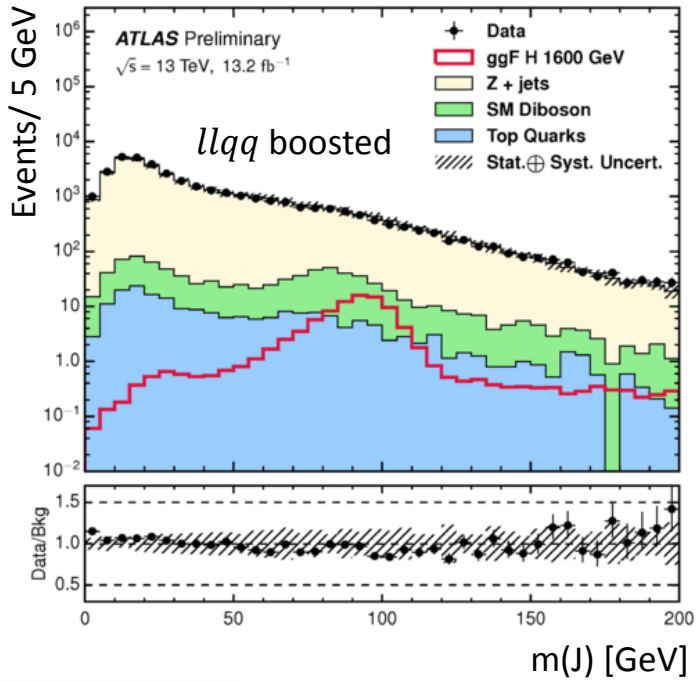
Theories: heavy Higgs in NWA, Z', W', G_{kk^*}

ZZ $\rightarrow (ll/\nu\nu)(qq)$ where $l = e, \mu$

- ggF and VBF studied $llqq$ channel



Excluded $llqq$ channel

H_{ggf} $\sigma \times BR$: 1.28 pb - 6.2 pb

H_{VBF} $\sigma \times BR$: 0.6 pb - 5.2 pb

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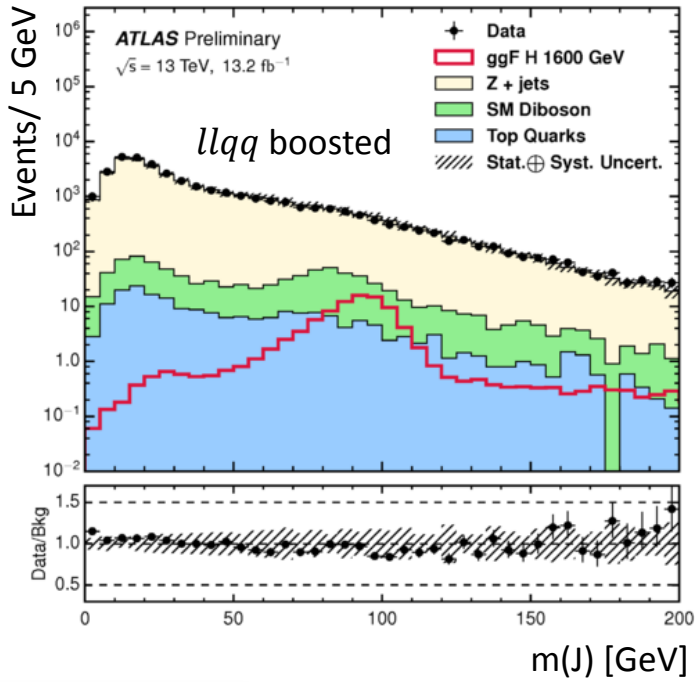

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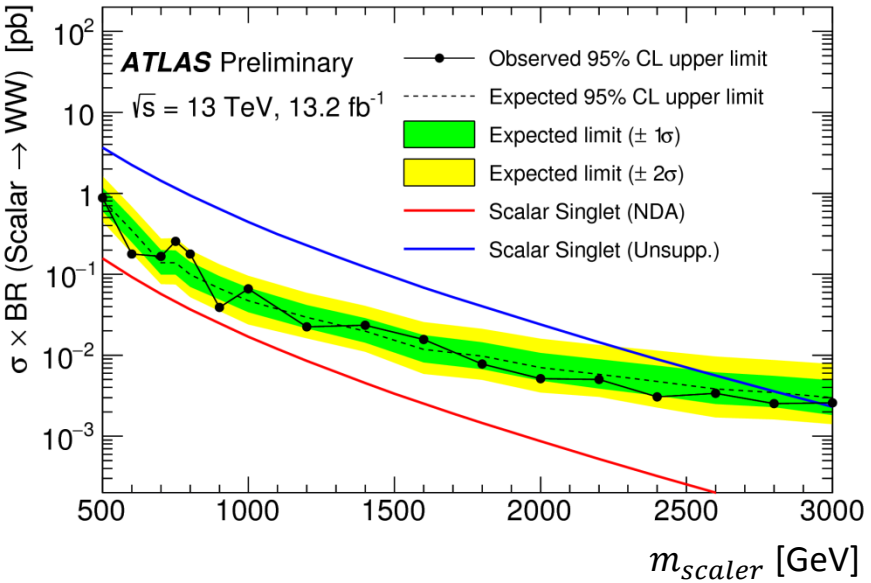
WW $\rightarrow (l\nu)(qq)$, where $l = e, \mu$

- Two CP even scaler singlet models tested predict different BRs of Higgs to WW/gluons



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S (Unsupp.) < 3000 GeV

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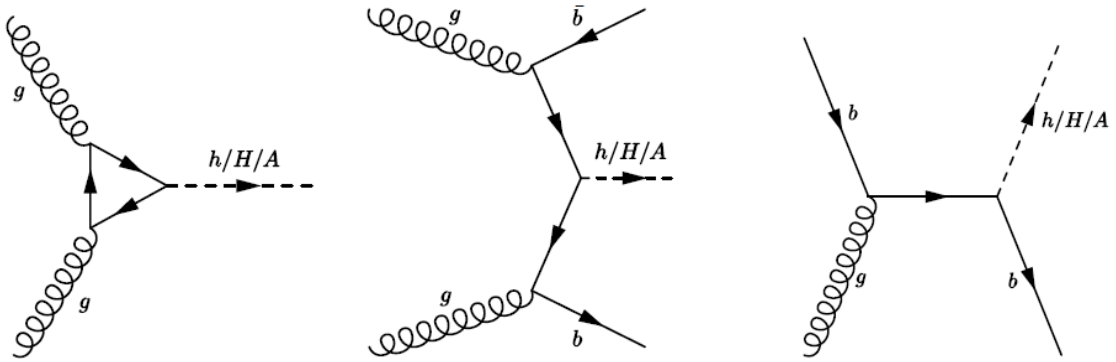

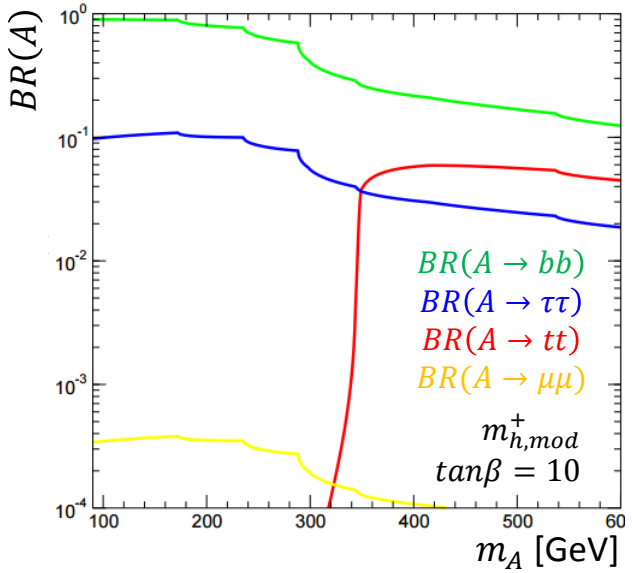

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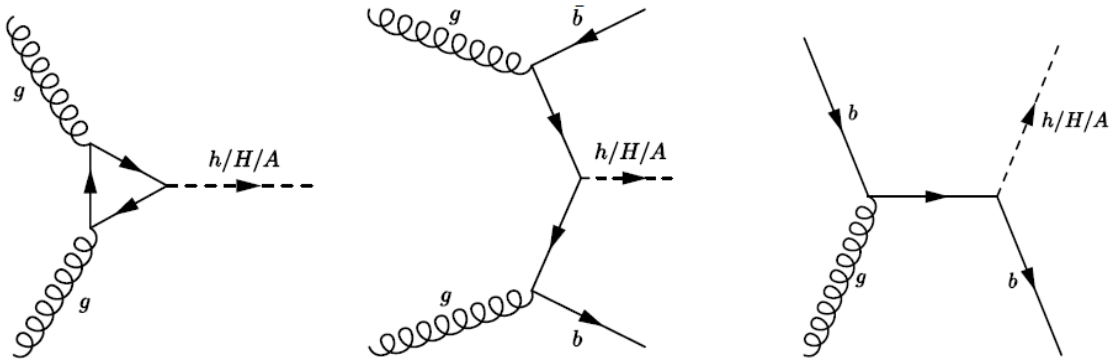
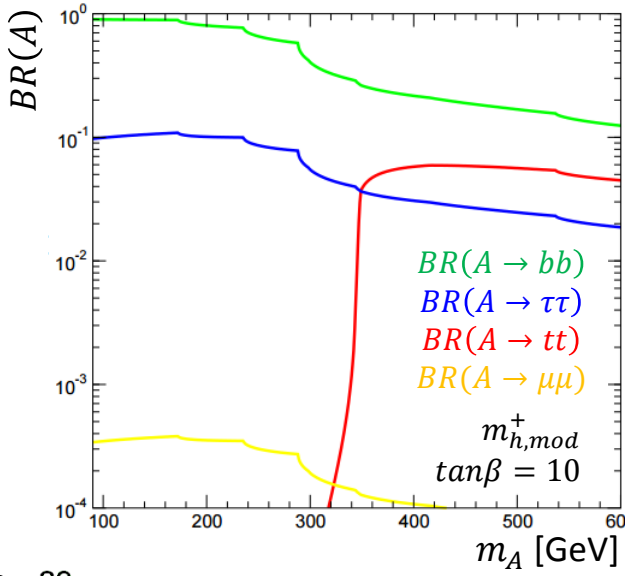


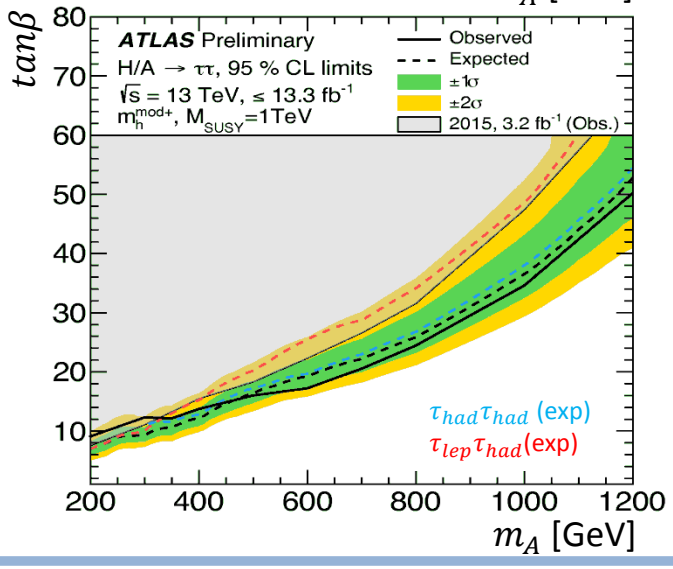


$\tau\tau \to (\mathrm{lep/had})\ (\mathrm{had})$

- Theories: $m^{\pm}_{h,mod}$, hMMSM
- Discriminating variable is transverse mass

Excluded

- $\sigma \times BR$ < 2.0 (2.1) pb - 0.013 (0.014 pb) for $m_{H/A}$ = 200 – 1200 GeV for ggF (b-associated)
- $m^{+}_{h,mod}$: tanβ>9 (50) for $m_A = 0.2$ (1.2) TeV



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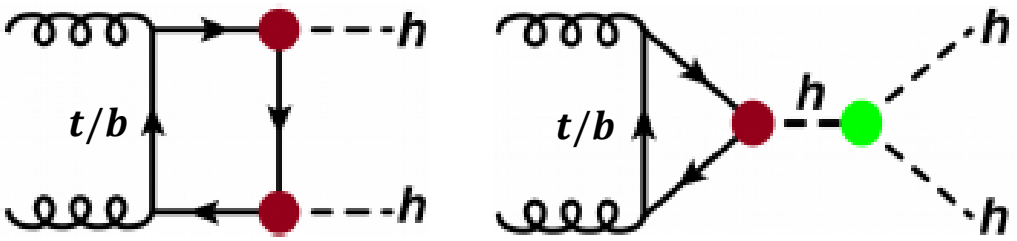
SM Di-Higgs production several orders of magnitude lower than single Higgs production AND destructive interference among diagrams makes it smaller



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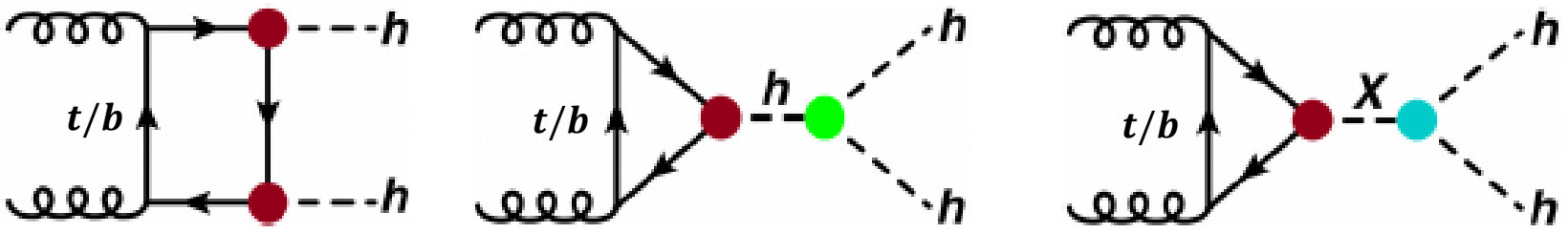

Di-Higgs production enhanced in many BSM models

- Non resonant production: Higgs coupling to t , b , h modified wrt SM values
- Resonant production: Replacing virtual Higgs boson with an intermediate heavy resonance (2HDM, G_{kk^*})

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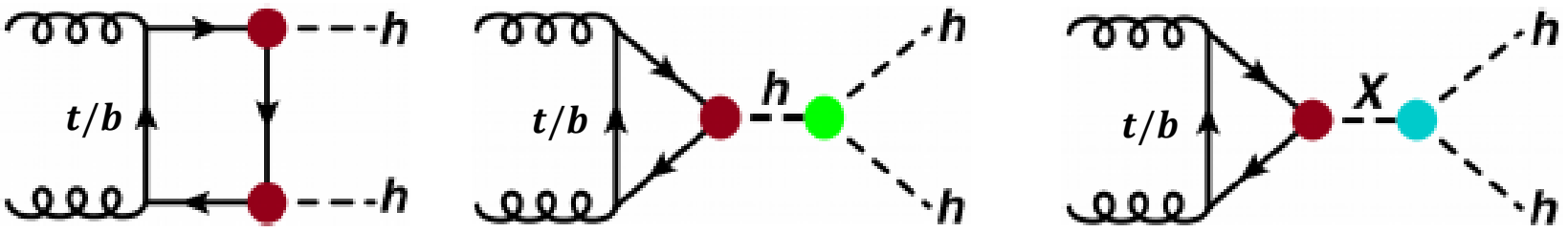

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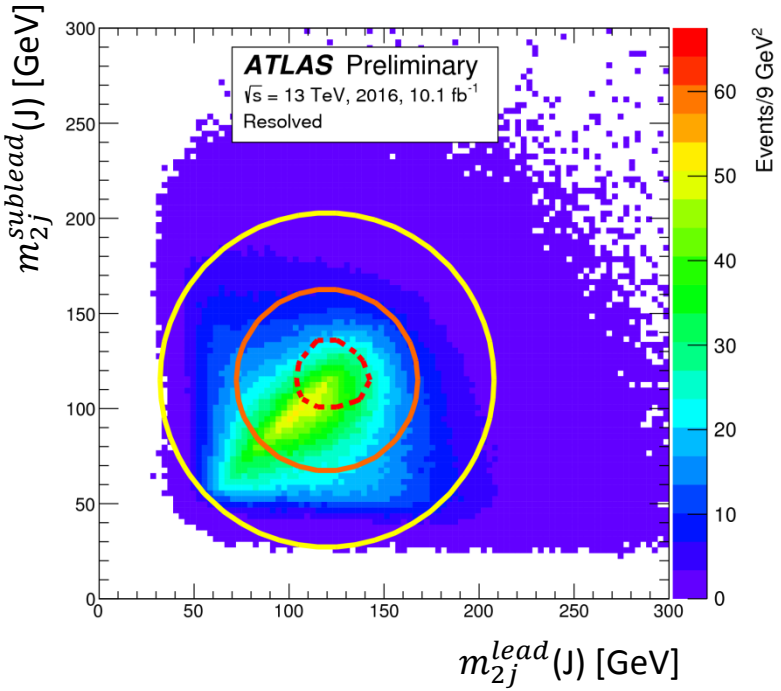
- **hh → 4b:** highest branching ratio
- **hh → WWγγ:** clean signature and good di-photon invariant mass that gives good background rejection

BR	bb	WW
bb	**33%**	
WW	25%	4.6%
$\tau\tau$	7.4%	2.5%
ZZ	3.1%	1.2%
$\gamma\gamma$	0.26%	**0.10%**

hh → 4b

- Theories : ggF non-resonant, G_{kK^*}
- Signal selected in 2D plane of jet mass



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Non-resonant: $\sigma \times BR$ < 300 fb
for 300-3000 GeV (SM : $11.3^{+0.9}_{-1.0}$)

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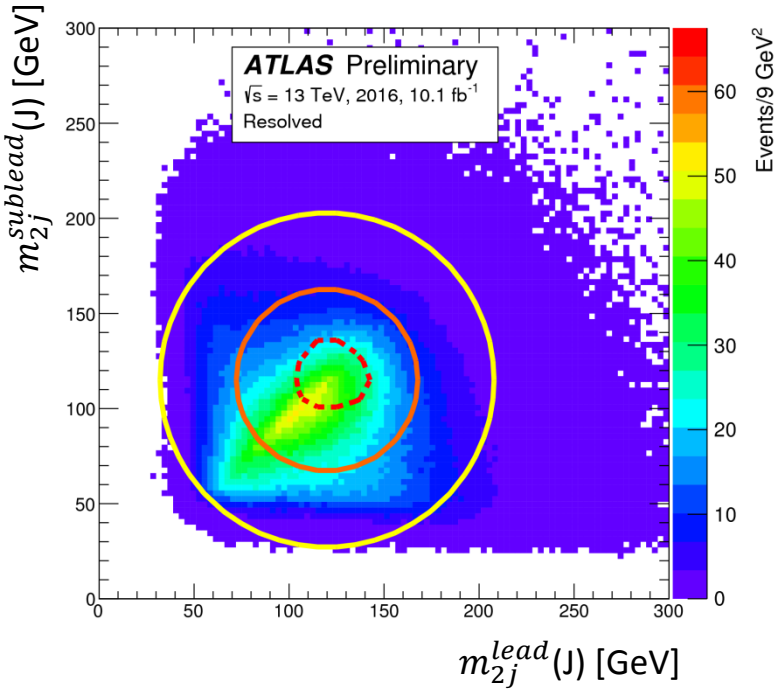

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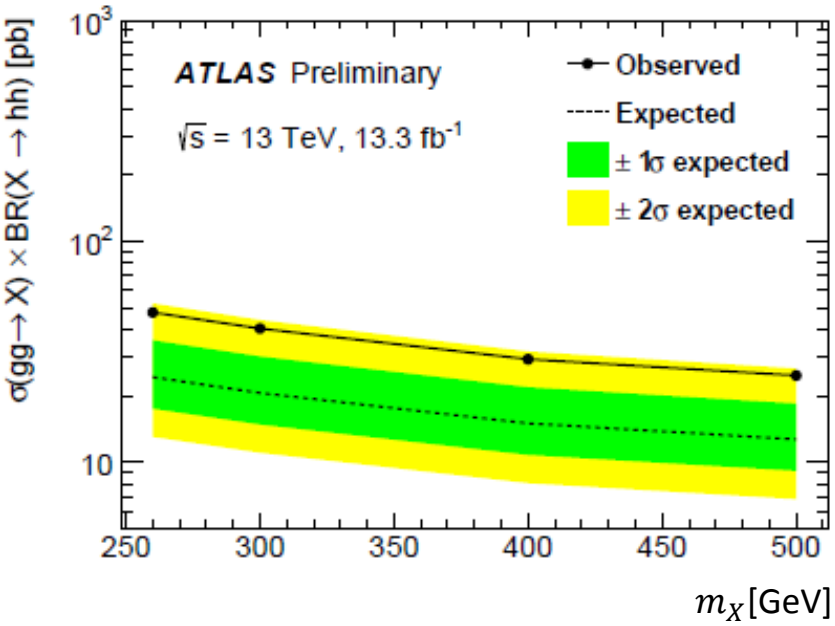
γγWW(→ lν jj)

- Theories : Higgs in NWA, non-resonant
- Counting experiment in signal region



Excluded

Non- resonant: $\sigma \times BR$ < 25.0 pb
Resonant: $\sigma \times BR$ < 47.7pb -24.7 pb

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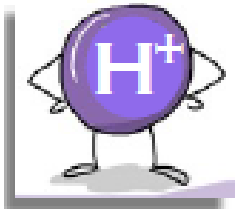
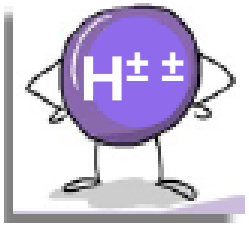
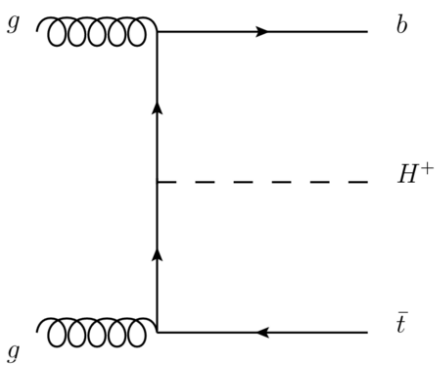
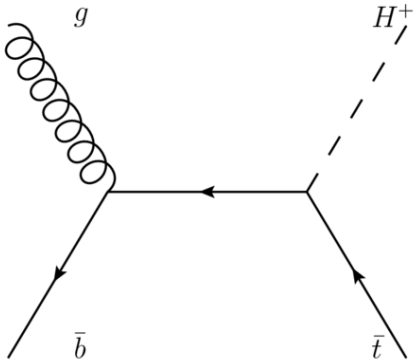




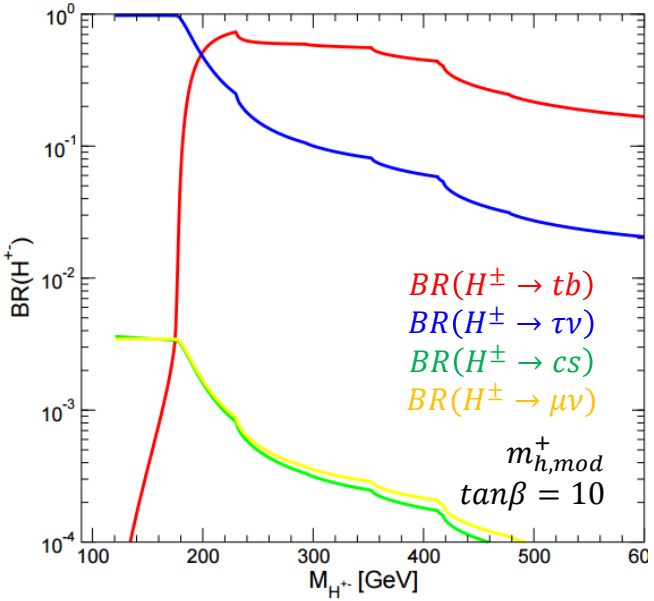
- Charged Higgs bosons appears when doublet/triplet added
- For $m_{H^{\pm}} > (<) m_{top}$ the main production mode of charged Higgs is in association with t (b)
- Decay of $H^{\pm}$ to τν (tb) dominates below (above) top threshold
- Run 1: $H^{\pm} \rightarrow tb$ analysis excess of events above the background-only hypothesis observed (2.4 σ across wide mass range)



4-flavour scheme

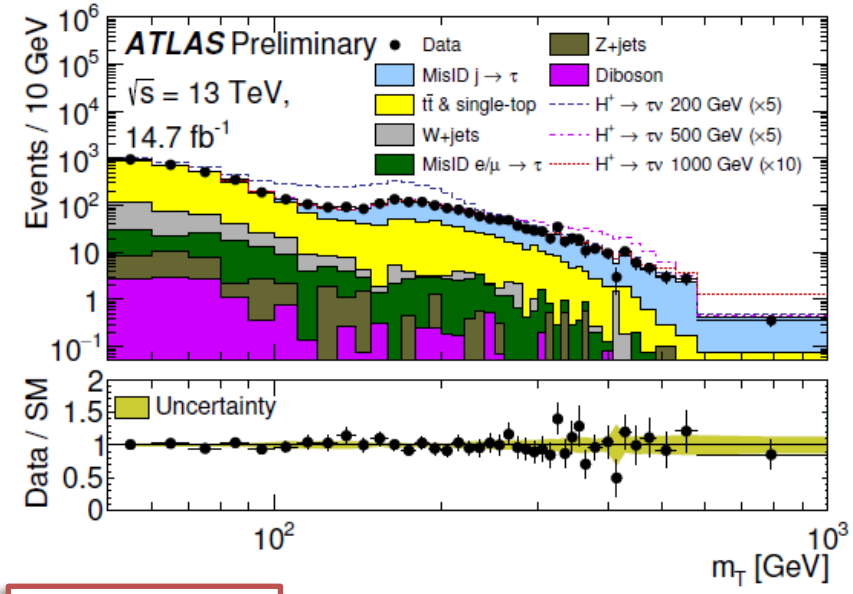


5-flavour scheme



τν (hadronic)

- Theory: hMSSM
- Discriminating variable is transverse mass



Excluded

- $\sigma \times BR < 2.0 \ - 0.008\, pb$

hMSSM

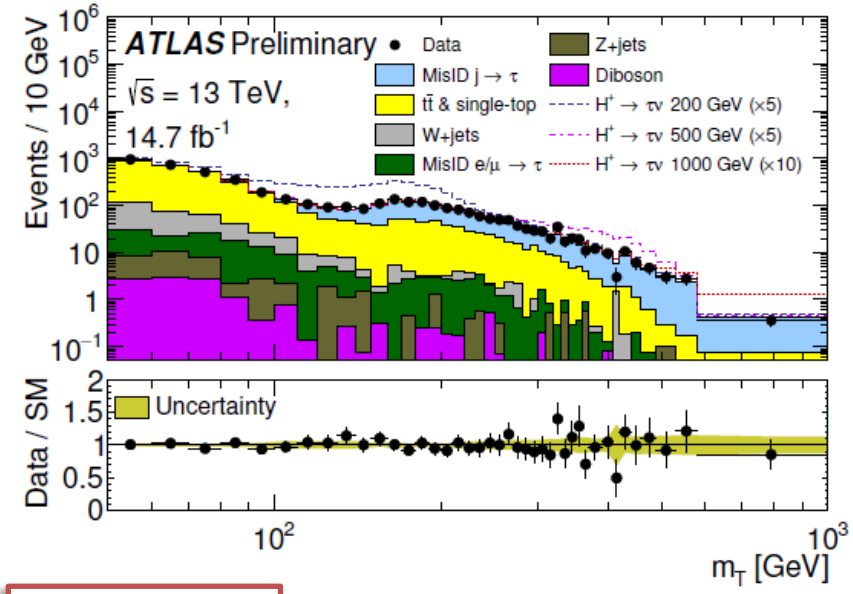
- $42 < \tan\beta < 60$ for $m_{H^{\pm}}$ = 200 GeV
- $m_{H^{\pm}}$ <540 GeV for $\tan\beta = 60$

Heavy Charged Higgs

$H^{\pm} \rightarrow \tau\nu$
$H^{\pm} \rightarrow tb$
$H^{\pm\pm} \rightarrow ll$

τν (hadronic)

- Theory: hMSSM
- Discriminating variable is transverse mass



Excluded

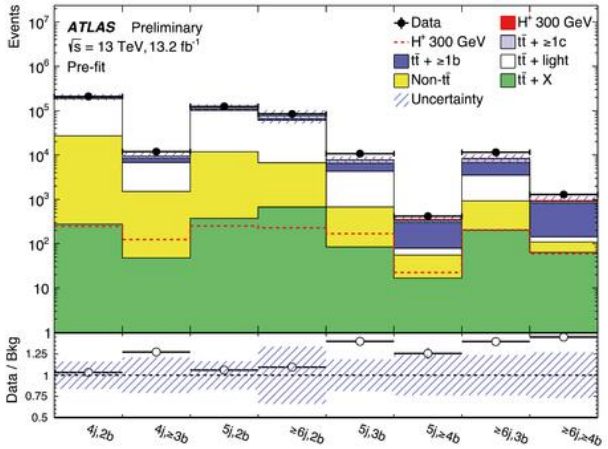
- $\sigma \times BR < 2.0 - 0.008\,pb$

hMSSM

- $42 < \tan\beta < 60$ for $m_{H^{\pm}}$ = 200 GeV
- $m_{H^{\pm}}$ <540 GeV for $\tan\beta = 60$

tb (e/μ from t decay)

- Theory: $m^{\pm}_{h,mod}$
- Events are categorised according to the multiplicity of jets and b-tagged jets
- Multivariate techniques separate signal from background



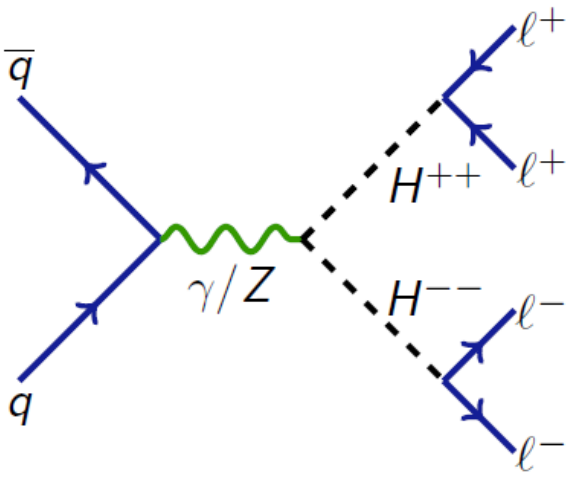
Excluded No big excess above SM

- $\sigma \times BR$ <1.09 -0.18

$m^{-}_{h,mod}$

- $0.5 < \tan\beta < 1.7$ for $m_{H^{\pm}}$ = 300-855 GeV
- $\tan\beta > 44$ (60) for $m_{H^{\pm}}$ = 300 (366) GeV

- In SM events with 2 high momenta, same-charge electrons are rare
- $H^{\pm\pm}$ is cleanest signature for triplet models
- $H^{\pm\pm}$ produced via Drell-Yann process



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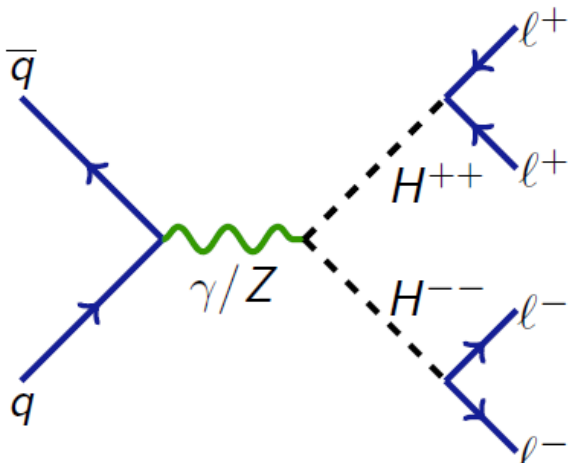
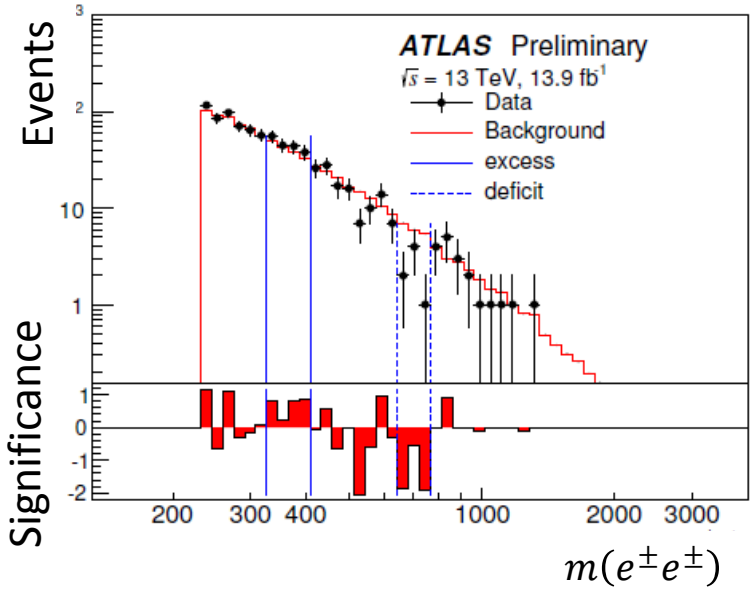


$\ell^{\pm}\ell^{\pm}$ $(e^{\pm}e^{\pm})$

- Theory : left-right symmetric ($H_L^{\pm\pm}$, $H_R^{\pm\pm}$)
- Require same sign electrons > 200 GeV

Excluded

- m of $H_R^{\pm\pm}$ $(H_L^{\pm\pm})$, < 420 (570) GeV,



Results for all published channels

Neutral Heavy Higgs to bosons	WW → lvlv ZZ → 4l ZV → llqq /vvqq WV→ lvqq X->Zγ
	A→ Zh
	H→4γ H → WH

Neutral Higgs to fermions	A/H/h → ττ A/H/h → tt

Neutral Higgs to di-Higgs	hh → 4b hh → WWγγ
	hh → bbγγ
	hh → bbττ

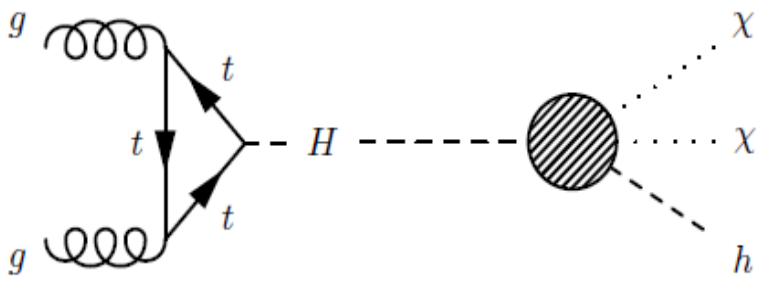
Charged Higgs	$H^{\pm}$ → τν $H^{\pm}$ → tb $H^{\pm\pm}$→ll
	Light $H^{\pm}$ → cs VBF $H^{\pm}$ → WZ

Higgs exotic with MET	H → γγ+MET H → Z (ll)+MET
	VBF h → INV Zh → INV (lep) Vh → INV (had) H → γ+MET H→ ZZ_{dark} H→ INV (1 jet)

- Models with Higgs and missing transverse energy (MET or E_T^{miss}) are motivated by searches for Dark Matter (χ)
- ZZ/ γγ final states can be measured well with relatively low backgrounds

γγ+MET Models

Heavy Higgs scaler H → $\chi\chi h$, parametrized by effective field theory

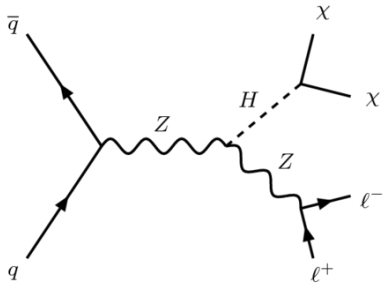


Other BSM theories tested

- Simplified models: vector mediator Z' emits Higgs, then decays to $\chi\chi$

Z (ll) + MET models

- Heavy Higgs decays to ZZ in NWA (encompasses EWS, 2HDM, triplet)
- Production of Z and mediator that decays to $\chi\chi$
- Production of ZH, where H → $\chi\chi$

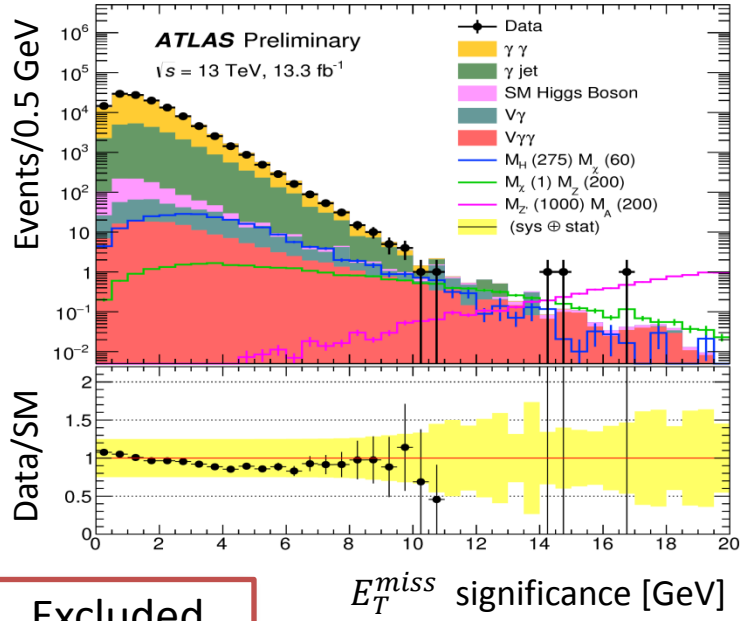


H → γγ+MET

H→ Z (ll)+MET

γγ+MET

- Signal selected 2 or 4 categories defined by (E_T^{miss}) significance and $p_T^{\gamma\gamma}$
- Significance of E_T^{miss} singificance is less sensitive to pileup than E_T^{miss}



Excluded

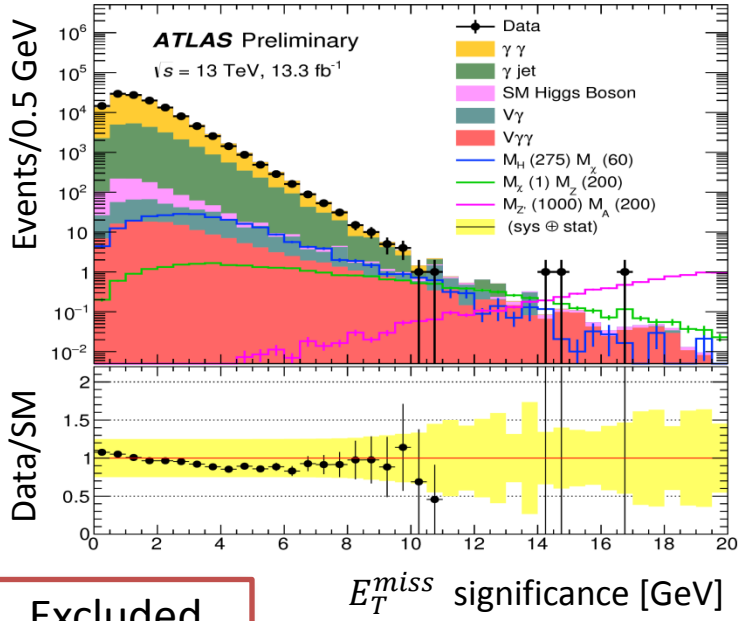
heavy Higgs: $\sigma \times BR < 18.2\ (23.9)$ fb

for $m_{DM} = 50\ (60)\ GeV$

H → γγ+MET
H→ Z (ll)+MET

γγ+MET

- Signal selected 2 or 4 categories defined by (E_T^{miss}) significance and $p_T^{\gamma\gamma}$
- Significance of E_T^{miss} singificance is less sensitive to pileup than E_T^{miss}

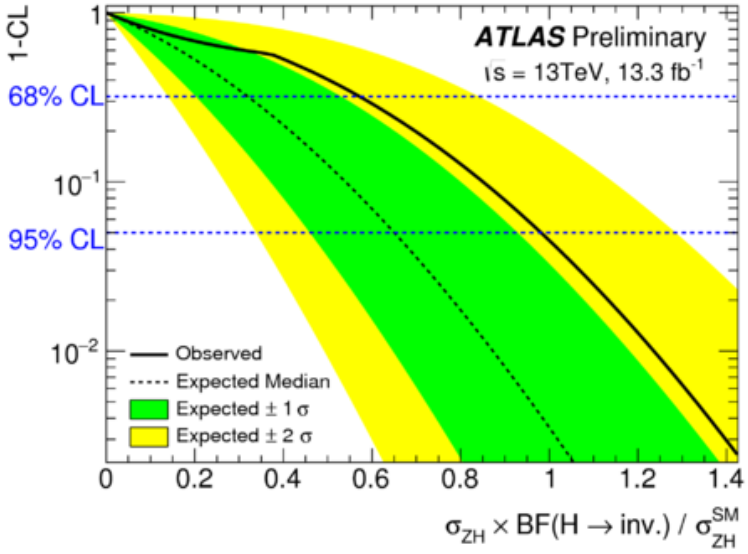


Excluded

heavy Higgs: $\sigma \times BR < 18.2\ (23.9)$ fb for $m_{DM} = 50\ (60)\ GeV$

Z (ll) + MET, where l= e, μ

- Theories: heavy Higgs in NWA, Z+ mediator (→ $\chi\chi$), ZH production with H→ $\chi\chi$, G_{kk^*}



Excluded

heavy Higgs: $\sigma \times BR <$ 67 (37) for m_H= 600 (1000) GeV 67 (37)

Conclusions

- Many ATLAS searches for beyond Standard Model physics were explored
- No discoveries yet of BSM Higgs sector
- Significant excesses not found, but many stringent limits set in several models

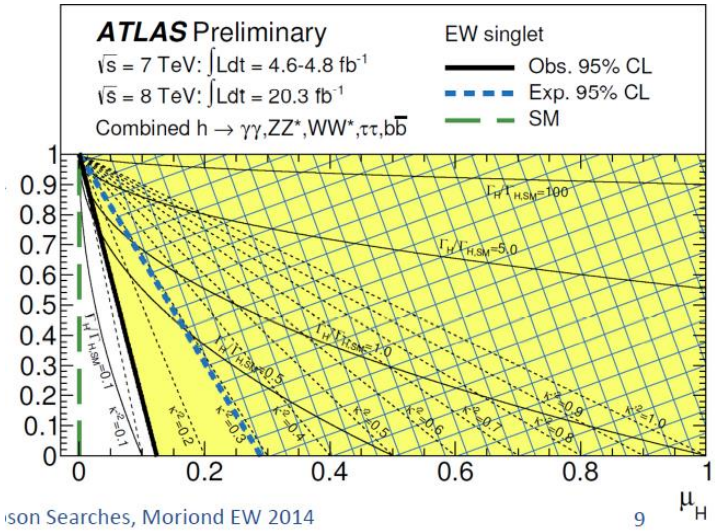
References

- Search for new phenomena in ttbar final states with additional heavy-flavour jets in 13.2/fb of pp collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-104
- Search for charged Higgs bosons in the H+ → tb decay channel in pp collisions at √s = 13 TeV using the ATLAS detector, ATLAS-CONF-2016-089
- Search for charged Higgs bosons in the τ+jets final state with 14.7 fb-1 of pp collision data recorded at √s = 13 TeV with the ATLAS experiment, ATLAS-CONF-2016-088
- A search for new phenomena in events with missing transverse momentum and a Higgs boson decaying to two photons in a 13.3 fb-1 pp collision dataset at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-087
- Search for the Minimal Supersymmetric Standard Model Higgs bosons H/A in the ττ final state in up to 13.3 fb-1 of pp collision data at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-085
- Searches for heavy ZZ and ZW resonances in the llqq and ννqq final states in pp collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-082
- Study of the Higgs boson properties and search for high-mass scalar resonances in the H → ZZ → 4l decay channel at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-079
- Search for a high-mass Higgs boson decaying to a pair of W bosons in pp collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-074
- Search for Higgs boson pair production in the final state of γγWW*(→lνjj) using 13.3 fb-1 of pp collision data recorded at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-071
- Search for diboson resonance production in the lνqq final state using pp collisions at √s = 13 TeV with the ATLAS detector at the LHC, ATLAS-CONF-2016-062
- Search for scalar diphoton resonances with 15.4 fb-1 of data collected at √s = 13 TeV in 2015 and 2016 with the ATLAS detector, ATLAS-CONF-2016-059
- Search for new phenomena in the Z(→ ll) + ETmiss final state at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-056
- Search for doubly-charged Higgs bosons in same-charge electron pair final states using proton-proton collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-051
- Search for pair production of Higgs bosons in the bbbb final state using proton-proton collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-049
- Search for new resonances decaying to a Z boson and a photon in 13.3 fb-1 of pp collisions at √s = 13 TeV with the ATLAS detector, ATLAS-CONF-2016-044
- Constraints on New Phenomena via Higgs Boson Couplings and Invisible Decays with the ATLAS Detector, arXiv:1307.1347

Backup

Theory

EWS from Run 1

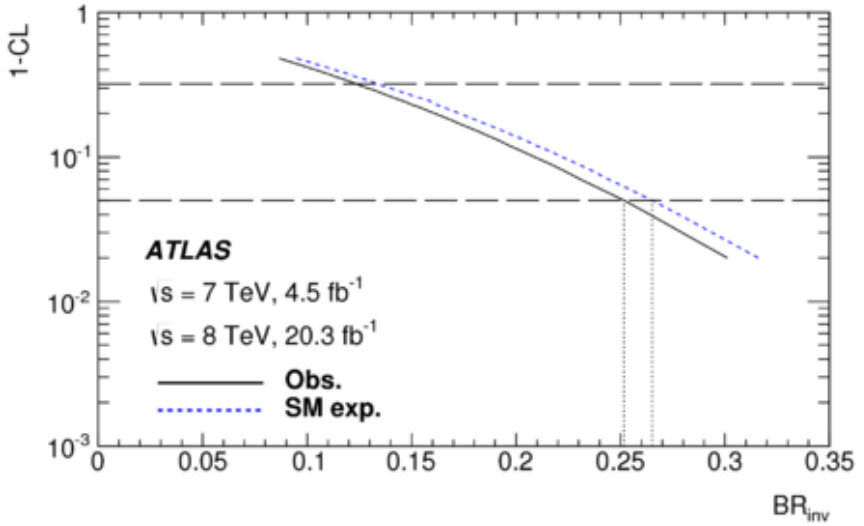


Couplings of h(H) are decreased by factor $\kappa(\kappa')$

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

Run 1 Higgs to Dark Matter



Theory

2HDM

Type	Description	up-type quarks couple to	down-type quarks couple to	charged leptons couple to
Type I	Fermiophobic	Φ_2	Φ_2	Φ_2
Type II	MSSM-like	Φ_2	Φ_1	Φ_1
X	Lepton-specific	Φ_2	Φ_2	Φ_1
Y	Flipped	Φ_2	Φ_1	Φ_2
Type III		Φ_1, Φ_2	Φ_1, Φ_2	Φ_1, Φ_2

Wikipedia

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hMSMM

Mass matrix of neutral CP-even Higgs bosons, h and H is below, with radiative corrections in M_{ij} matrix

$$\mathcal{M}_\Phi^2 = \begin{bmatrix} m_Z^2 \cos^2\beta + m_A^2 \sin^2\beta & -(m_Z^2 + m_A^2)\sin\beta\cos\beta \\ -(m_Z^2 + m_A^2)\sin\beta\cos\beta & m_Z^2 \sin^2\beta + m_A^2 \cos^2\beta \end{bmatrix} + \begin{bmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{bmatrix} ,$$

Simplified approach to study of MSSM, known as hMMS consists of neglecting M11 and M12 terms.

Neutral Heavy Higgs to bosons

ZV → llqq /vvqq
WV→ lvqq

$ZV \rightarrow (ee, \mu\mu, \nu\nu)(qq)$ 300- 5000 GeV

ZZ->llqq
21% of Zqq have 2 bjets – events divided into categories with 2 btagged jets and fewer than 2

Boson tagging for boosted: fat jet tagged using D2 (ration of energy correlation functions of subjet), jet mass to be around V window
vvqq only merged

High purity vs low purity regions depends on weather jet substructure requuirementpassed
ZV →vvqq uses only boosted selection

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T},J} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T},J} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

$$E_{\mathrm{T},J} = \sqrt{m_J^2 + p_{\mathrm{T},J}^2}.$$

Excluded

G_{kk^*} < 1035 GeV for llqq / < 1100 for vvqq
W'< 2225 for llqq/ <2400 for vvqq

$WV \rightarrow (e/\mu + \nu)$(hadrons) 500 – 5000 GeV

Only boosted

Two benchmark models: c3 is set via dimensional analysis to be (1/4pi)^2 and cH=0.9, and another in which coupling to gluons is unsuppressed and c3=1/8pi with ch =0.5. c3 determines sigma of decay width to gluons and decays to W/Z account for remaining width . In unsuppressed BR to WW is 60-73%, in NDA BR is 99%

Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
$W \rightarrow \ell\nu$ selection	Number of signal leptons	1		
	Number of vetoed leptons	0		
	Number of vetoed leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 100\,GeV$		
	$p_{\mathrm{T}}(\ell\nu)$	$> 200\,GeV$		
$W/Z \rightarrow J$ selection	Number of large-R jets	≥ 1		
	Passing the $D_2^{(\beta=1)}$ cut	yes (no)	yes (no)	yes (no)
	$\lvert m_{W/Z} - m_J \rvert$	< 15 GeV	> 15 GeV	< 15 GeV
Topology cuts	$p_{\mathrm{T}}(\ell\nu)/m_{WV}$ $p_{\mathrm{T}}(J)/m_{WV}$	> 0.4		
Top-quark veto	Number of b-tagged jets	0		≥ 1

S < 3000 GeV

Excluded

G_{kk^*} < 1240 GeV
Z' (W') < 2500 -2810 (2400 - 2540) GeV

Neutral Higgs to fermions

A/H/h → ττ

$\tau\tau \rightarrow (\mathrm{lep/had})\ (\mathrm{had})$ 200- 1200 GeV

- Extends previous results for mA > 350 GeV
- Require at least one hadronic τ decay:
- $\tau\ \tau$ (lephad)
  - b-veto and b-tag categories (lepton trigger)
  - High MET category – New in 2016
- $\tau\ \tau$ (hadhad)
  - b-veto and b-tag categories (τhad trigger)

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1) + m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2) + m_{\mathrm{T}}^2(\tau_1, \tau_2)},$$

mT(a,b)=[2pT(a)pT(b)(1-cosΔϕ(a,b)]1/2

For m(H+/-)<mtop, t→bH+ production dominated
For m(H+/-)>mtop, t associated production dominated

Heavy Charged Higgs

$H^{\pm} \rightarrow \tau\nu$
$H^{\pm} \rightarrow tb$

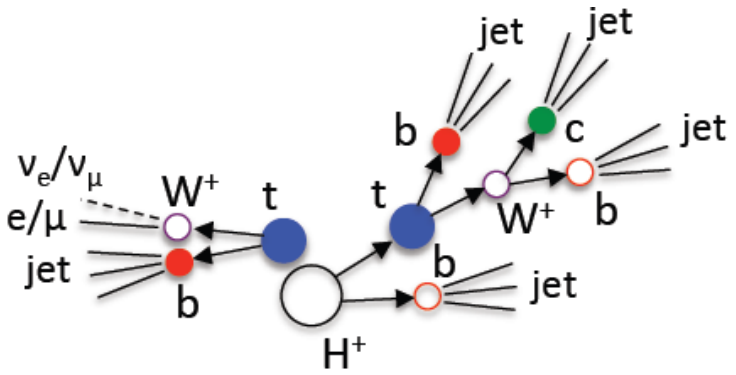
$H^{\pm} \rightarrow \tau\nu$: 200 to 2000 GeV

Search for:
(b)t H± → (b)(j jb)(τhad ν)

Event selection:
- MET trigger, MET > 150 GeV
- Hadronically decaying τ, no high-pT e, μ
- N(jets) ≥ 3, N(b-tag) ≥ 1

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\tau}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi_{\tau,\mathrm{miss}})}$$

$H^{\pm} \rightarrow tb$: 300 to 1000 GeV



Single lepton trigger, 1 lepton, ≥ 4 jets (≥ 2 b-tag)
- Signal/control regions defined by N(jets) and N(b-tag)
- Fits done using : BDT in the signal region, sum of the pT of the selected jets in CRs

Neutral Higgs to di-Higgs

hh → 4b
hh → WWγγ

hh → 4b : search 300-3000 GeV

- Large multi-jet background

Resolved analysis: non-resonant / low-mass hh

- 4 btagged anti-kT jets (R=0.4) jets
- 2 bjets to make Higgs candidate
- Invariant mass of two Higgs candidates

Boosted analysis (for G search only):

- Higher mass resonant hh systems
- Two b-jets merge due to the high boost
- ≥2 anti-kT jet (R=1.0)
- 2/3/4 4 b-tagged track jets
- Invariant mass of the two large-R jets

$Excluded$: G_{kK^*} < 860 GeV

γγWW(→ lν j j) 260 GeV – 500 GeV

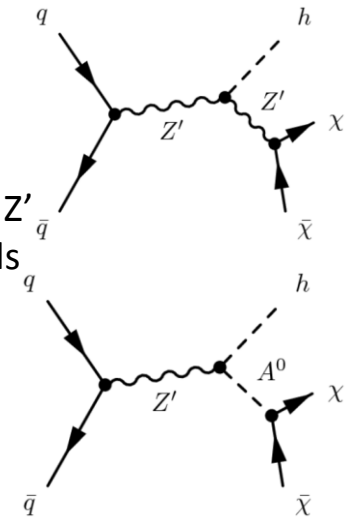
Given a slight excess of events in the data, the difference between expected and observed limits is expected.

Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.00224
Observed		15

Higgs exotic with MET

H → γγ+MET
H→ Z ($\ell\ell$)+MET

γγ+MET
IN FIT:
- 2 categories in high di-photon momenta and MET significance for Z'
- 4 categories for heavy higgs models (MET not as good discriminant)
EFT for heavy Higgs



$$S_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}}.$$

Category	$S_{E_{\mathrm{T}}^{\mathrm{miss}}}$ [$\sqrt{\mathrm{GeV}}$]	$p_{\mathrm{T}}^{\gamma\gamma}$ [GeV]
High $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$, high $p_{\mathrm{T}}^{\gamma\gamma}$	> 7	> 90
High $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$, low $p_{\mathrm{T}}^{\gamma\gamma}$	> 7	≤ 90
Intermediate $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$	> 4 and ≤ 7	> 25
Rest	-	> 15

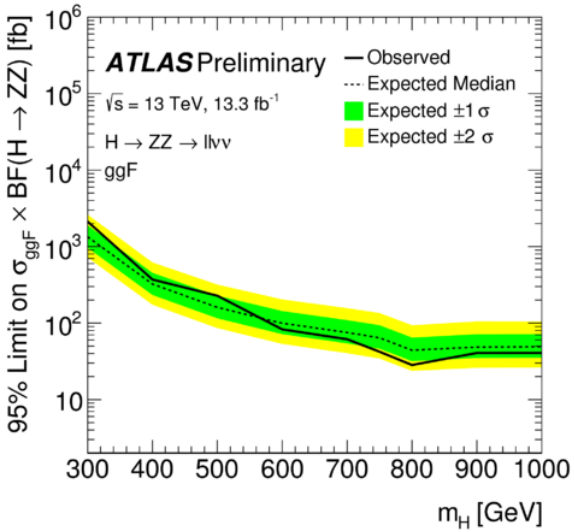
Excluded

Z_b': $\sigma \times BR < 3$ fb for $m_{Z_b'} = 59\ GeV, m_{DM} = 1\ GeV$

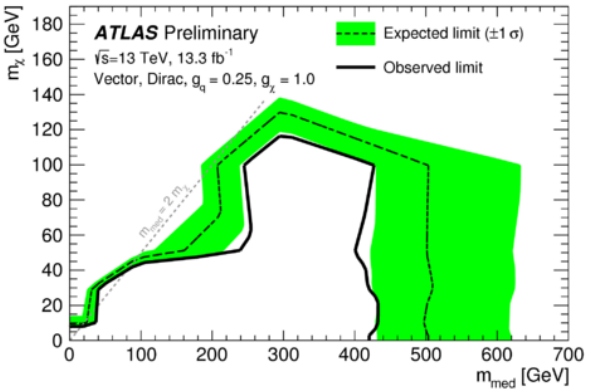
Z' 2HDM: plot in paper

heavy Higgs: $\sigma \times BR < 18.2(23.9)$ fb for $m_{DM} = 50\ (60)\ GeV$

Z ($\ell\ell$)+MET, $\ell = e, \mu$



Heavy Higgs NWA

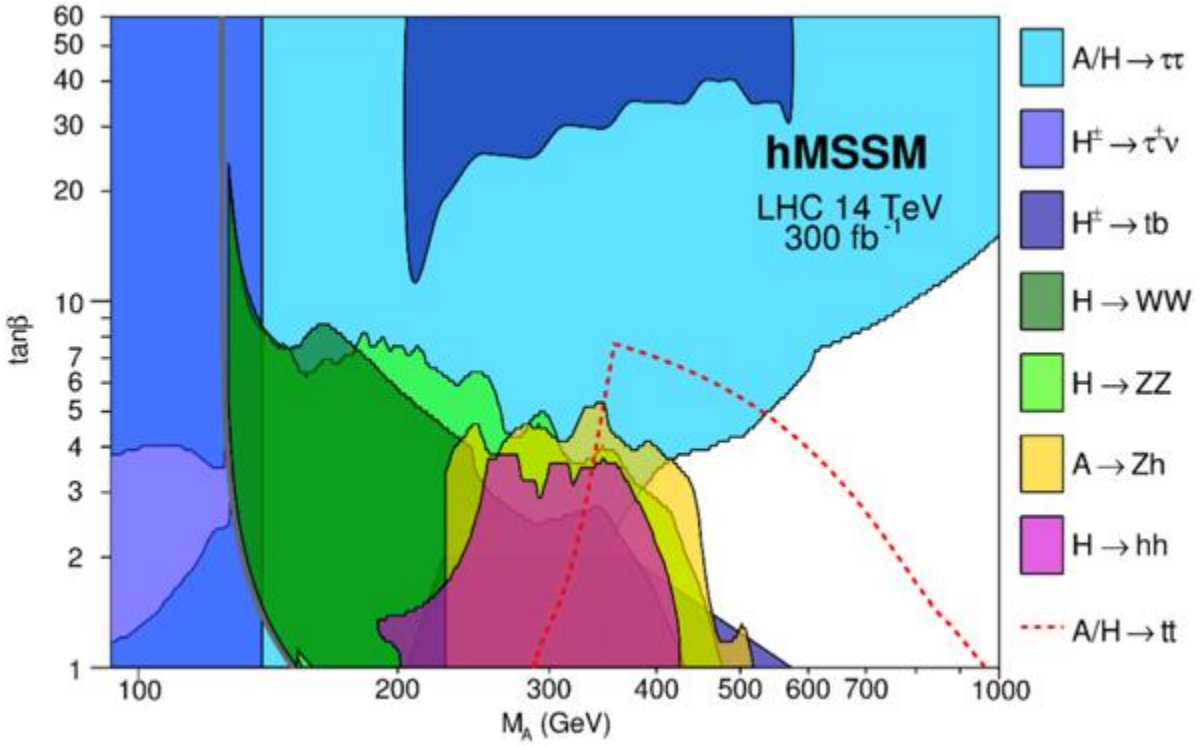


Production of Z and mediator (mediator to DM) Interpreted in simplified models where additional BSM vector particle mediates interaction between WIMP and SM

Excluded

G_{kk^*} < 1.03 TeV

Theory projections (2σ sensitivity)



Djouadi, A., Maiani, L., Polosa, A. et al.
JHEP 06 (2015) 168