Search for non-SM Higgs bosons and for BSM decays of the Higgs boson at the ATLAS experiment

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Warwick University,
ATLAS experiment

HEPMAD18
On behalf of the ATLAS collaboration

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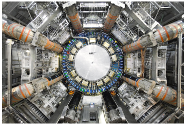
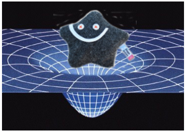
Outline



LHC and ATLAS detector at CERN;

Higgs Models Beyond the Standard Model;



Searches for additional heavy Higgs bosons;

Searches for Exotic decays of the SM Higgs boson;

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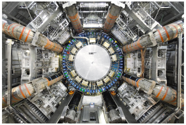

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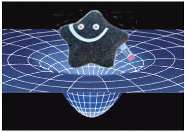

Searches for additional heavy Higgs bosons;

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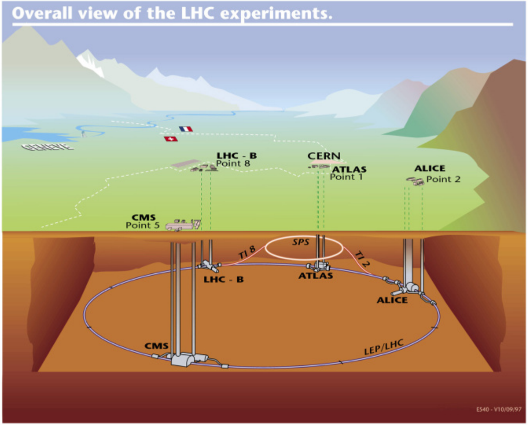
CERN and the Large Hadron Collider

- CERN's Large Hadron Collider, most powerful particle accelerator, located at the border between France and Switzerland;
- LHC is 27 km long, 100 m underground;
- Largest experiments located at the 4 interaction points: ATLAS, CMS, LHCb, ALICE.

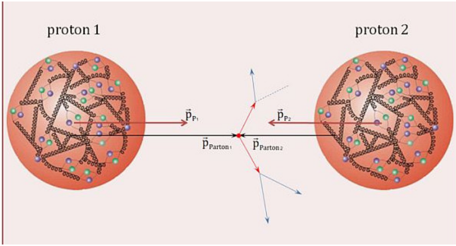


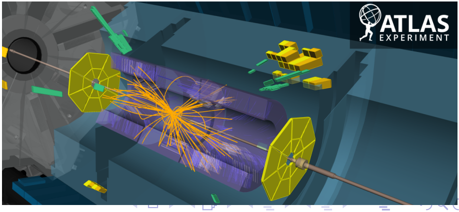
- Superconducting magnets cooled to 1.9 K with 96 tons of liquid helium and generate 8 T magnetic field;

Physics of Proton-Proton Collisions

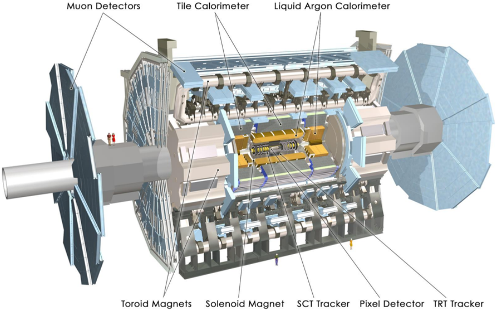
- LHC accelerates protons to an energy of 6.5 TeV;
- Proton mass is 1 GeV - they are accelerated to energies 6500 times their mass;
- Protons collide at a center-of-mass (CoM) energy of 13 TeV;
- Protons made of quarks and gluons (partons); 6.5 TeV energy shared among them;
- Hard (high energy) collisions are very rare: $\sim$ 1 Higgs or $\sim$ 2000 Zs in a billion collisions;
- Particles created according to Einstein's formula $E = mc^2$;

6.5 TeV corresponds to the kinetic energy of a 2 mg mosquito flying at a speed of 1m/s;





ATLAS (A Toroidal LHC Apparatus)



- 44 m long, 25 m in diameter, weights 7000 tons.

Inner Detector (ID)

- Measurement of charged particle trajectories, momentum, electric charge, vertices.

Calorimeters

- Liquid-Argon and Scintillating Tile calorimeters for energy measurements of electrons, photons and hadrons.

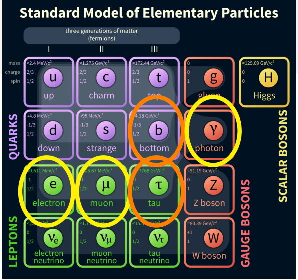
Muon Spectrometer

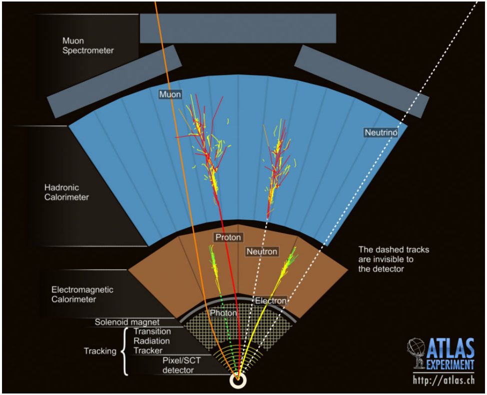
- High precision tracking chambers;
- 3 hits per muon track.

Magnet Systems

- Solenoid and toroid magnets bend charged particle trajectories for momentum measurements.

Particle Detection in ATLAS





Muons

Tracks in the **ID** matched to tracks in the **Muon Spectrometer**;

Jets

Topological clusters in the **calorimeters** using Anti-k_T algorithm; **b-tagging**: tag jets with b-quarks;

Taus

Hadronically decaying taus appear as **narrow jets**; matched to 1-3 tracks in the **ID**;

Electrons

Tracks in the **ID** matched to energy deposits in the **EM calorimeter**;

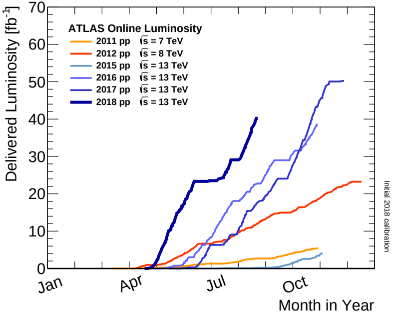
Photons

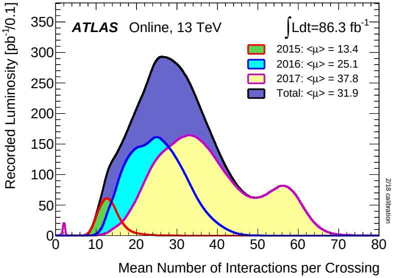
Energy clusters in the **EM calorimeter**;

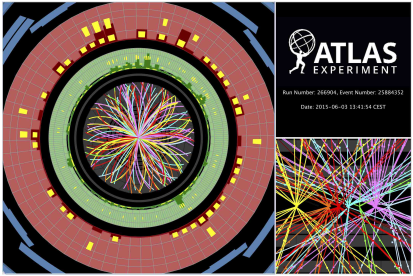
Missing Transverse Energy E_T^{miss}

Vectorial sum of p_T of identified objects from a single vertex.

ATLAS operation in Run-2

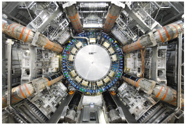






- ATLAS collected 80 fb^{-1} in 2015-2017 and 38 fb^{-1} in 2018;
- $\sim$ 50000 Higgs bosons per 1 fb^{-1};
- Multiple interactions per bunch crossing: pile-up *(top right)*;
- Event display *(bottom right)* from 2015 shows dense track environment;

Outline



LHC and ATLAS detector at CERN;

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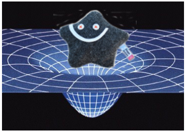
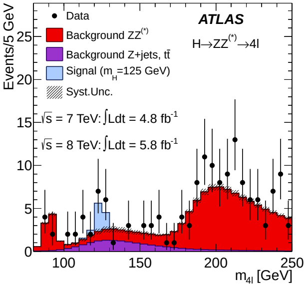


Searches for additional heavy Higgs bosons;

Searches for Exotic decays of the SM Higgs boson;

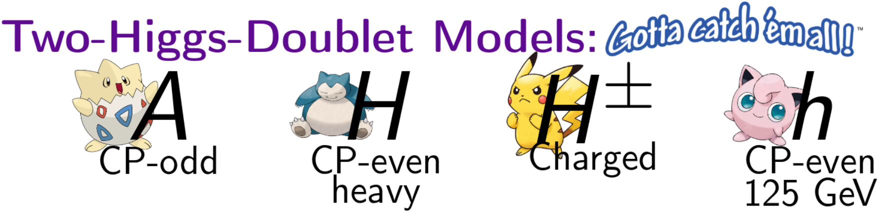
- **A Higgs boson** of mass 125 GeV was discovered in 2012 by ATLAS and CMS;
- All measurements agree with **Standard Model** (SM) predictions: Higgs boson couples to other particles proportionally to their masses;
- However, the discovered Higgs boson could be part of an **extended scalar sector**;
- E.g. Multiple Higgs bosons, one of which is a 125 GeV SM-like Higgs boson;
- Or, SM Higgs boson with couplings to non-SM particles like dark matter;



2 Higgs Doublet Models (2HDM)

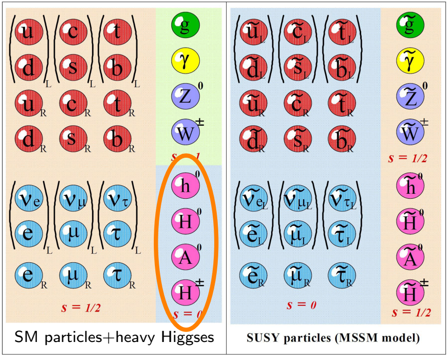
- The most straightforward way to extend the Higgs sector with one additional doublet;

- Variety of different ways to couple Higgs doublets to fermions;
- Outcome is 4 types: Type-I (fermiophobic), Type-II, Lepton-specific, Flipped.
- 2 doublets have 8 degrees of freedom: 3 generate masses for W and Z bosons;
- **5 physical Higgs bosons**: light and heavy h and H; pseudoscalar A and charged $H^{\pm}$.



Minimal Supersymmetric Standard Model (MSSM)

- Additional Higgs bosons also appear in Supersymmetry;
- **Supersymmetry (SUSY)** - a symmetry that relates bosons to fermions.
- **MSSM** is an extension to the **SM with imposed SUSY**, and contains minimum required particle content;
- In the MSSM, Higgs coupling structure is similar to Type-II 2HDM:
  - same 5 physical states of Higgs bosons.



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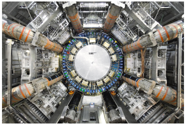

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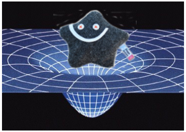

Searches for additional heavy Higgs bosons;

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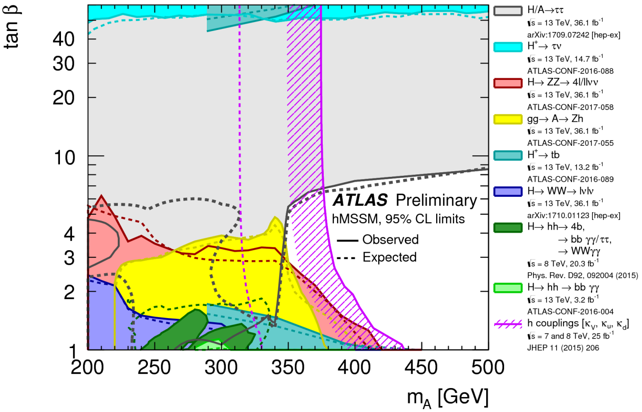
hMSSM Interpretation [1]

- Mass of the light Higgs is fixed to $m_h \approx 125\,\text{GeV}$;
- Every point corresponds to specific cross sections and branching ratios of the $H/A/H^{\pm}$;
- Search channels target different regions of this parameter space;
- Measurements of SM Higgs couplings also exclude hMSSM parameters;



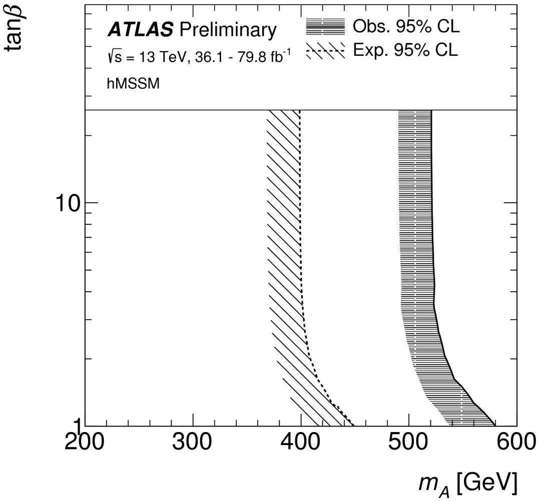
source: CombinedSummaryPlots/HIGGS

hMSSM Interpretation [2]

ATLAS-CONF-2018-031

- ATLAS Combined Higgs coupling measurement exclude $m_A \lesssim 530\,\text{GeV}$;
- gluon-gluon fusion ggF, Higgsstrahlung VH, vector boson fusion VBF, top-associated $tH + ttH$ production modes;
- $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb decay modes;
- h coupling modifiers in hMSSM (α related to M_A):

$$c_V = \sin(\alpha - \beta)$$
$$c_t = \frac{\cos\alpha}{\sin\beta}$$
$$c_{b,\tau} = -\frac{\sin\alpha}{\cos\beta}$$

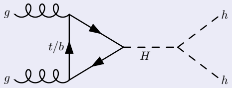


- Fit values of Higgs couplings translate into allowed values of $[\tan\beta, M_A]$;

Searches for Heavy Higgs bosons [1]

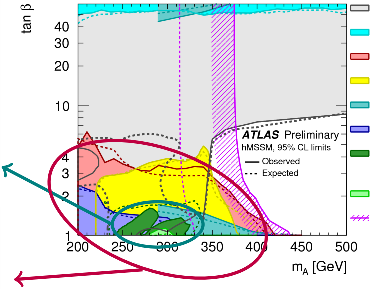
Heavy Higgs boson decay to SM Higgs boson pair

- 1804.06174[hep-ex] $H \to hh \to bbbb$
- 1808.00336[hep-ex] $H \to hh \to bb\tau\tau$
- 1807.08567[hep-ex] $H \to hh \to WW^*\gamma\gamma$
- 1807.04873[hep-ex] $H \to hh \to bb\gamma\gamma$



Heavy Higgs boson decay to gauge boson pair

- 1712.06386[hep-ex] $H \to ZZ \to 4l/ll\nu\nu$
- 1708.09638[hep-ex] $H \to ZZ/ZW \to llqq/\nu\nu qq$
- 1710.01123[hep-ex] $H \to WW \to e\nu\mu\nu$
- 1707.04147[hep-ex] $H \to \gamma\gamma$
- 1805.01908[hep-ex] $H \to Z/W/h + \gamma$

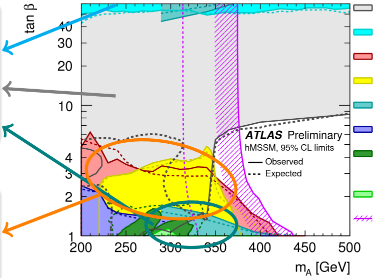


Higgs boson decay to fermions

- 1807.07915[hep-ex] $H^{\pm} \to \tau^{\pm}\nu_{\tau}$
- 1709.07242[hep-ex] $H/A \to \tau^{+}\tau^{-}$
- 1808.03599[hep-ex] $H^{+} \to tb$

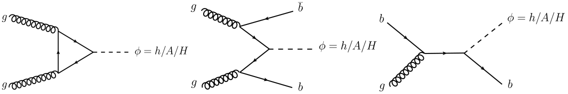
Pseudoscalar Higgs boson

- 1712.06518[hep-ex] $A \to Zh \to \nu\nu bb/llbb$
- 1804.01126[hep-ex] $A \to ZH \to llbb$

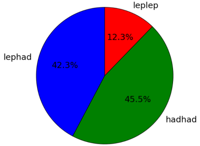


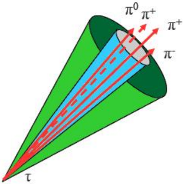
Search for heavy neutral $H/A \to \tau^+\tau^-$ [1]

1709.07242[hep-ex]

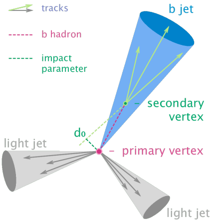


- **Gluon-gluon-fusion** and **b-associated** production modes; Higgs decay to a pair of taus;
- Higgs **couplings** to down-type fermions are **enhanced** at high values of $\tan\beta$;
- Leads to higher branching fraction to taus, and higher production cross section in association with b-quarks;
- Two decay channels of taus: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- *b*-tag and *b*-veto categories to increase sensitivity to b-associated production;





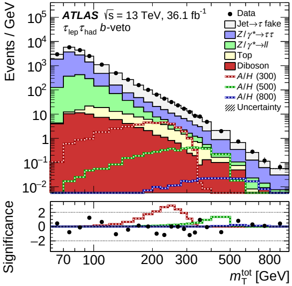
Hadronic tau



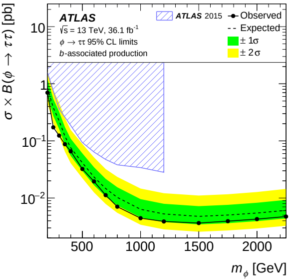
b-tagging

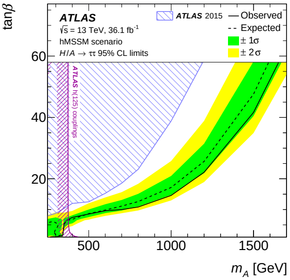
Search for heavy neutral $H/A \to \tau^+\tau^-$ [2]

1709.07242[hep-ex]



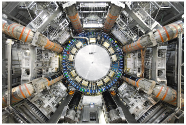
$\tau_{lep}\tau_{had}$ transverse total mass spectrum.





- Transverse total mass used as a discriminating variable;
- Limits placed on cross-section times branching-fraction of a generic scalar;
- Results are interpreted in *hMSSM* scenario;
- Excluding high values of tan β;

Outline



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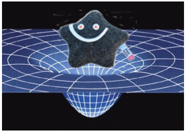
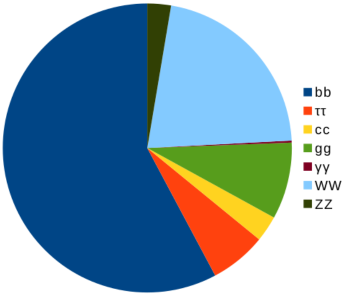


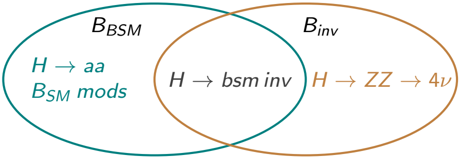
Searches for additional heavy Higgs bosons;

Searches for Exotic decays of the SM Higgs boson;

Exotic decays of the SM Higgs boson

- The Higgs boson could have interactions with non-SM particles;
- **non-SM branching ratio** B_{BSM} of the Higgs boson can be inferred from visible decay channels:
  - E.g. New ATLAS Run-2 measurement with 80 fb^{-1} puts a limit $B_{BSM} < 26\%$ ATLAS-CONF-2018-031;
- Or B_{BSM} can be measured directly in $H \to aa \to ??$ final states;
- Or B_{inv} can be measured directly in searches for Higgs$\to$invisible;
  - ATLAS Run-1 searched for Higgs$\to$invisible in VBF and VH production modes and put a limit $B_{inv} < 24\%$ 1509.00672;





Searches Exotic SM Higgs decays

Decays to light (pseudo)scalars

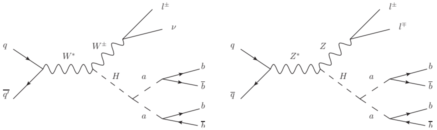
- 1803.11145[hep-ex] $H \to aa \to \gamma\gamma jj$
- 1807.00539[hep-ex] $H \to aa \to bb\mu\mu$
- 1806.07355[hep-ex] $H \to aa \to 4b$

others

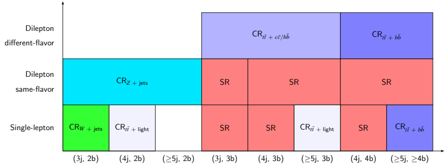
- 1802.03388[hep-ex] $H \to ZX/XX \to 4l$
- 1708.09624[hep-ex] $H \to inv$

Search for Exotic Higgs decay $H \to aa \to 4b$

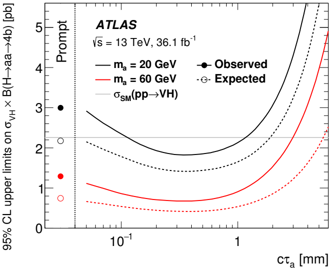
1806.07355[hep-ex]



- Higgs boson produced in association with a vector boson;
- Leptons in the final state provide signature for triggering and background suppression;
- If the a-boson mixes with the Higgs and inherits its Yukawa couplings, decays $a \to b\bar{b}$ are expected to be dominant for $m_a > 2m_b$
- In some models the proper length of the a from 10 μm to kilometers;



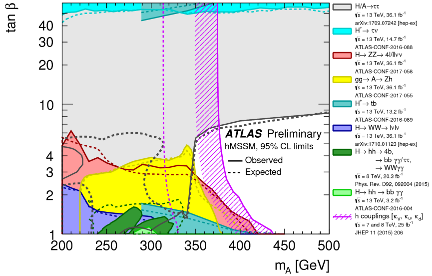
Event Categorization

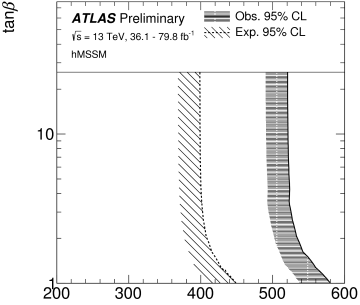


Limits

Summary

- Searches for heavy Higgses put stringent limits on parameters of models;
- Simplest supersymmetric SM model hMSSM exclude additional Higgses below $\sim 530\,\text{GeV}$;
- Invisible Higgs decays constrained to $B_{inv} < 24\%$;
- BSM Higgs decays constrained to $B_{BSM} < 26\%$;
- More analyses with 80 fb^{-1} data are under way;





BACKUP

Relevant parameters

We don't know much information:

- Masses of heavy Higgses are not predicted my the models: m_H, m_A, $m_{H\pm}$;
- Mixing angle of the two CP-even Higgses: α;
- Ratio of vacuum expectation values: $\tan\beta = \frac{v_2}{v_1}$, where

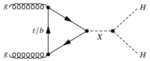
$$\langle 0|H_u^{0\dagger} H_u^0|0\rangle = v_1 \tag{1}$$
$$\langle 0|H_d^{0\dagger} H_d^0|0\rangle = v_2 \tag{2}$$
$$v_1^2 + v_2^2 = v^2 \approx (246\,GeV)^2 \tag{3}$$

Some constraints on the parameters:

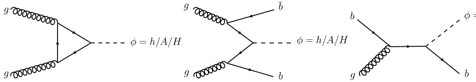
- One CP-even Higgs must have mass 125 GeV;
- In the alignment limit $\cos(\beta - \alpha) \to 0$ the h is SM-like:
    - SM Higgs boson measurements show that we are close to this limit.
- In the alignment limit $m_H \approx m_A \approx m_{H\pm}$;

List of Searches For heavy Higgses

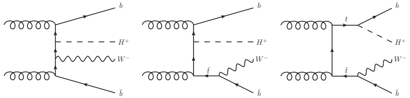
- 1804.06174[hep-ex] $H \to hh \to bbbb$
- 1808.00336[hep-ex] $H \to hh \to bb\tau\tau$
- 1807.08567[hep-ex] $H \to hh \to WW^*\gamma\gamma$
- 1807.04873[hep-ex] $H \to hh \to bb\gamma\gamma$



- 1709.07242[hep-ex] $H/A \to \tau^+\tau^-$



- 1807.07915[hep-ex] $H^\pm \to \tau^\pm \nu_\tau$



- 1808.03599[hep-ex] $H^+ \to tb$
- 1712.06386[hep-ex] $H \to ZZ \to 4l/ll\nu\nu$
- 1708.09638[hep-ex] $H \to ZZ/ZW \to llqq/\nu\nu qq$
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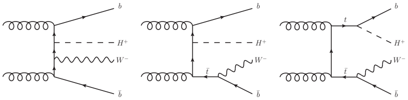
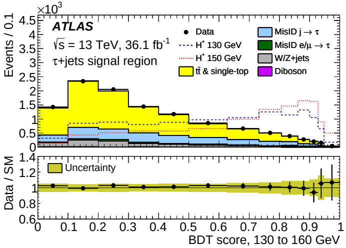
- 1707.04147[hep-ex] $H \to \gamma\gamma$
- 1712.06518[hep-ex] $A \to Zh \to \nu\nu bb/llbb$
- 1804.01126[hep-ex] $A \to ZH \to llbb$
- 1710.09748[hep-ex] $H^{\pm\pm} \to e^\pm e^\pm/e^\pm\mu^\pm/\mu^\pm\mu^\pm$
- 1808.01899[hep-ex] $H^{\pm\pm} \to W^\pm W^\pm$

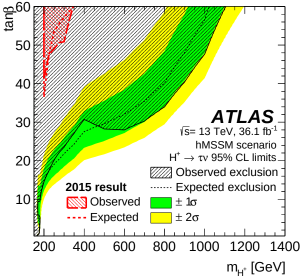
Search for charged $H^{\pm} \to \tau^{\pm}\nu_{\tau}$

1807.07915[hep-ex]



- Higgs produced in top-quark decays or in association with a top-quark;
- For $m_{H^{\pm}} < m_{top}$, double-resonant top-quark production dominates with $t \to bH^{+}$;
- For $m_{H^{\pm}} > m_{top}$, Higgs production with a single-resonant top-quark dominates: $gg \to tbH^{+}$;
- In Type-II 2HDM at large $\tan\beta$ Higgs decay $H^{+} \to \tau\nu$ can reach 15%;
- Sensitive to high values of $\tan\beta$; not as sensitive as $H/A \to \tau^{+}\tau^{-}$
- Depending on how the top decays, leptonically or hadronically, 2 search channels: $\tau_{had} + lepton$ and $\tau_{had} + jets$.

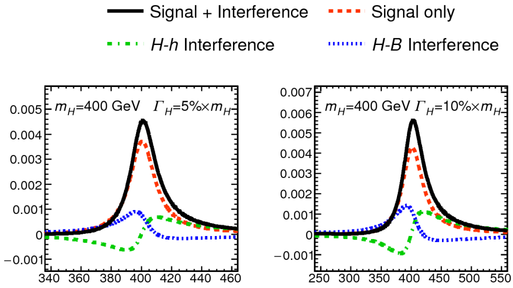


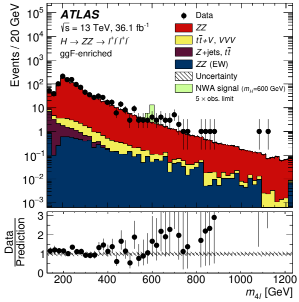


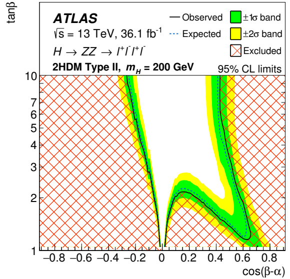
Search for heavy neutral $H \to ZZ \to 4l/ll\nu\nu$

1712.06386[hep-ex]

- Heavy Higgs produced in gluon-gluon fusion or vector-boson fusion and decayed into ZZ;
- Heavy scalar interferes with the SM Higgs and continuum $gg \to ZZ$ background;
- Interference modifies integrated cross section by $\mathcal{O}(10\%)$ for large width resonances;
- Small excess at 700 GeV.



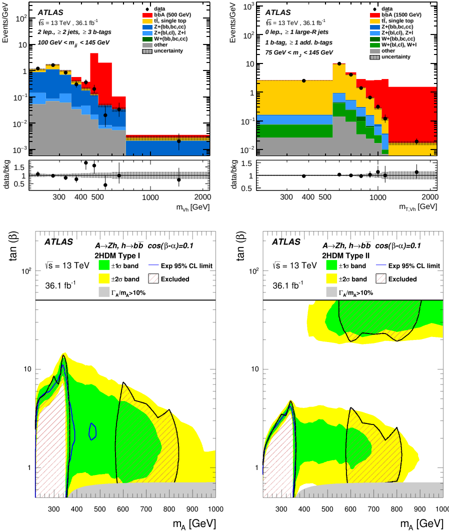




Search for CP-odd $A \to Zh$

1712.06518[hep-ex]

- CP-odd boson A produced in gluon-gluon fusion and b-associated production modes;
- $A \to Zh$ decay mode is relevant at masses below $t\bar{t}$ threshold;
- Search mass range 220 – 2000 GeV;
- Z decays into $\nu\nu$, ee or $\mu\mu$; h decays into b-quarks;
- The Higgs h can have wide range of transverse momenta:
  - at small p_T two b-jets are separated and reconstructed as small-R jets with $R = 0.4$;
  - at high p_T b-jets tend to merge, therefore reconstructed as one large-R jet with $R = 1.0$;



Search for invisible Higgs decays

1708.09624[hep-ex]

- SM Higgs branching ratio to invisible $B_{H \to inv}$ is $\sim 0.1\%$ from $H \to ZZ \to \nu\nu\nu\nu$;
- Higgs decay to WIMPs with a detectable final state $ZH \to ll + inv$;
- Signature of two opposite charge leptons and large E_T^{miss};

	Obs. $B_{H\to\text{inv}}$ Limit	Exp. $B_{H\to\text{inv}}$ Limit $\pm 1\sigma \pm 2\sigma$
ee	59%	$(51\ ^{+21}_{-15}\ ^{+49}_{-24})$ %
$\mu\mu$	97%	$(48\ ^{+20}_{-14}\ ^{+46}_{-22})$ %
$ee + \mu\mu$	67%	$(39\ ^{+17}_{-11}\ ^{+38}_{-18})$ %