Search for neutral and charged BSM Higgs Bosons with the ATLAS detector

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Phenomenology 2017 Symposium

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Motivation

- 125 GeV Higgs discovery in 2012:

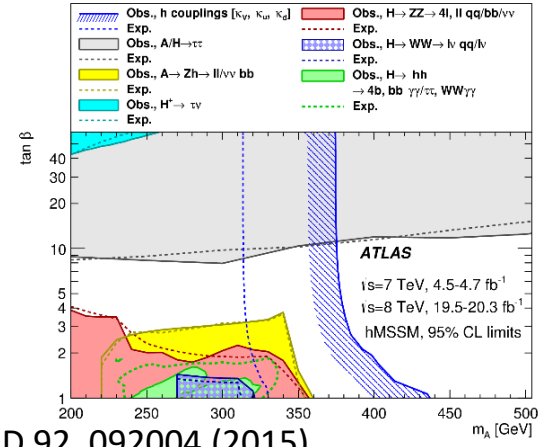
- What's next?
  - Is SM description of EWSB correct?
  - Is this the only one Higgs boson?
- Motivation for BSM physics
  - Solve hierarchy problem, explain dark matter/energy, …

BSM Higgs

- Some BSM extension of SM predict additional Higgs bosons:
  - 2HDM, MSSM: h, H, A, H^+, H^-
  - Electroweak Singlet Model: h, H
  - Higgs Triplet Model, Left-right Symmetry Models : H^{++}
- Results are presented as
  - Limits on production cross section of new Higgs boson
  - Constraints on some benchmark physics scenarios:
    - hMSSM, $m_h^{mod\pm}$, m_h^{max} scinarios of MSSM.
    - 2HDM.

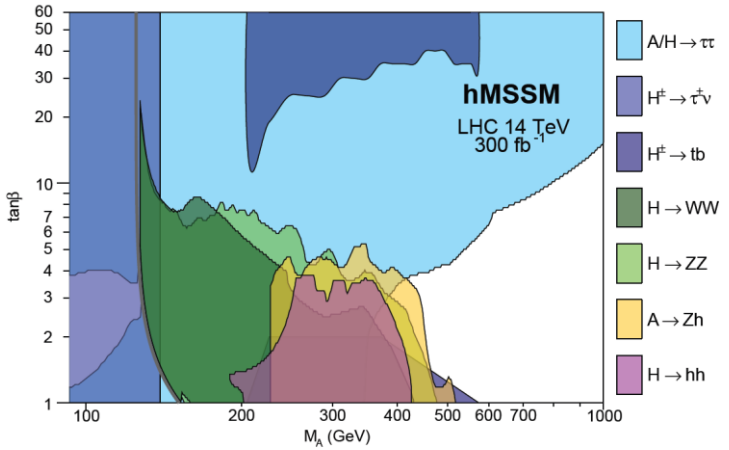
A. Djouadi et al. JHEP06 (2015) 168.

Excluded regions in $(m_A, \tan\beta)$ plane for hMSSM scenario (ATLAS Run1)



Phys. Rev. D 92, 092004 (2015)

2σ sensitivity of LHC at $300\ \mathrm{fb}^{-1}$ in $(m_A, \tan\beta)$ plane for hMSSM scenario



ATLAS 13 TeV results for BSM Higgs

Heavy Neutral Higgs → bosons	$WW \to lvlv$
	$ZZ \to 4l$
	$ZZ \to 2l + E_T^{miss}$
	$\gamma\gamma$
	$Z\gamma$
	$ZZ \to \ell\ell qq/\nu\nu qq$
	$WW \to \ell\nu qq$
	$VV \to JJ$
	$A \to Zh$

Heavy Neutral Higgs → fermions	$A/H \to \tau\tau$
	$A/H \to tt$
Heavy Charged Higgs	$H^{\pm} \to tb$
	$H^{\pm} \to \tau\nu$
Double Charged	$H^{\pm\pm} \to e^{\pm}e^{\pm}$
Heavy Neutral Higgs → hh	$bbbb$
	$\gamma\gamma WW$
	$\gamma\gamma bb$
	$bb\tau\tau$

For dihiggs and Higgs rare decays at ATLAS, see **Jason Veatch**'s talk in BSM Higgs I session.

We focus on channels in red in this talk.

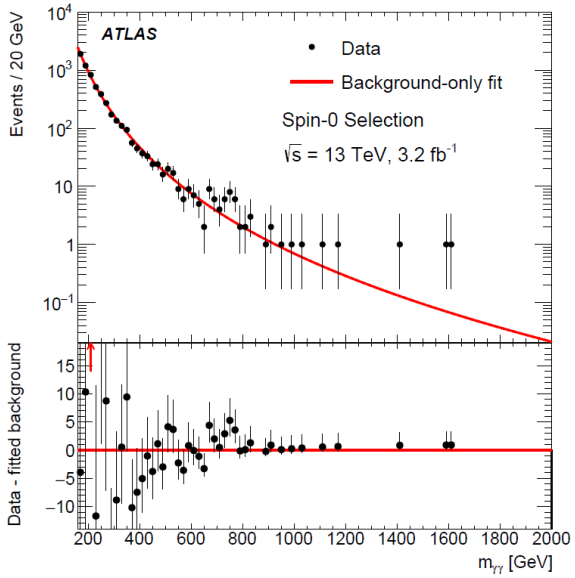
Only 7/8 TeV results so far
3.2 fb $^{-1}$ (2015)
13.2-15.4 fb $^{-1}$ (2015+2016)

Search for $X \rightarrow \gamma\gamma$ in 2016 data

- One of main measurement channels for h(125).
- Can be used to search for high mass BSM particles.
- 2015 data ($\sqrt{s}$=13 TeV, 3.2 fb $^{-1}$) had an excess.
- Event Selection:

$$2\gamma, P_T^1 > 40, P_T^2 > 30 \text{ GeV}.$$
$$P_T^1 > 0.4m_{\gamma\gamma}, P_T^1 > 0.3m_{\gamma\gamma}.$$

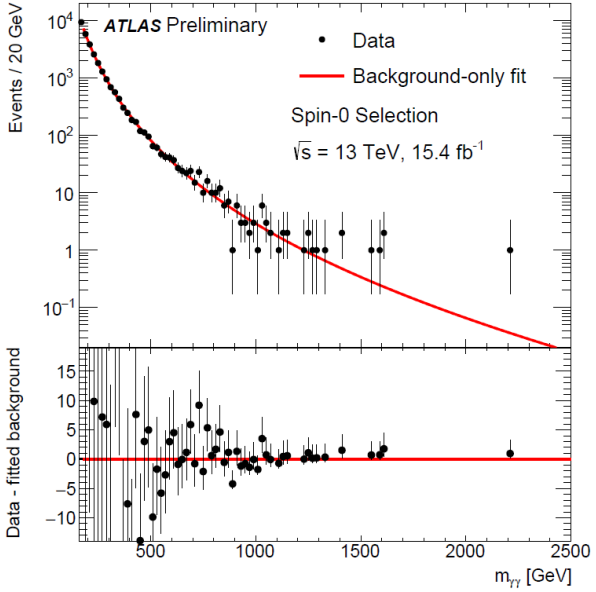
ATLAS 2015 Data: 3.2 fb^{-1}



Excess around $m_{\gamma\gamma} \sim 750 \text{ GeV}/c^2$.

- Local $\sim 3.8\sigma$. / Global $\sim 2.1\sigma$.
- CMS 2015 data had similar excess with local $\sim 3\sigma$.

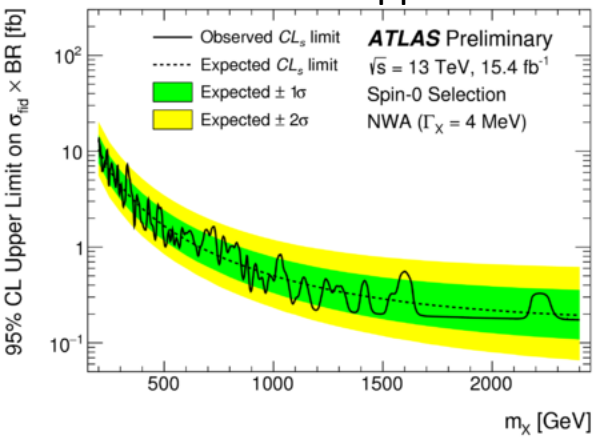
ATLAS 2015+2016 data: 15.4 fb^{-1}



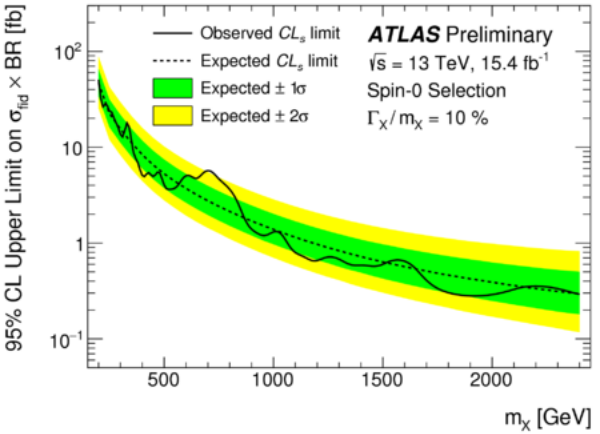
With 2015+2016 combined data, largest local significance in 700-800 GeV was 2.3σ for 710 GeV.

Limits on $\sigma_{fid} \times Br$

Narrow Width Approx.



$\Gamma_X/m_X = 10\%$

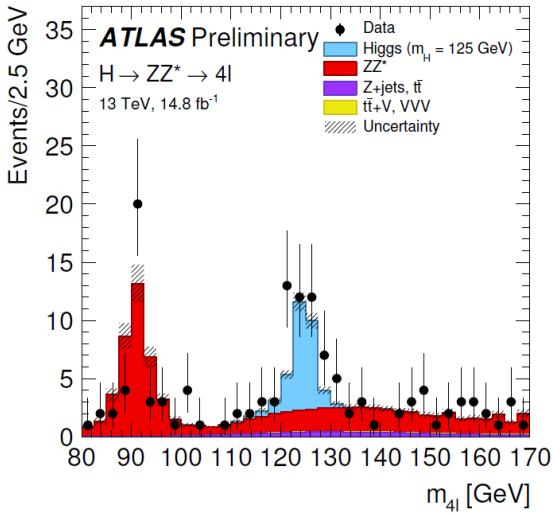


12.2 fb^{-1} of 2016 data in agreement with expected background within 1σ.

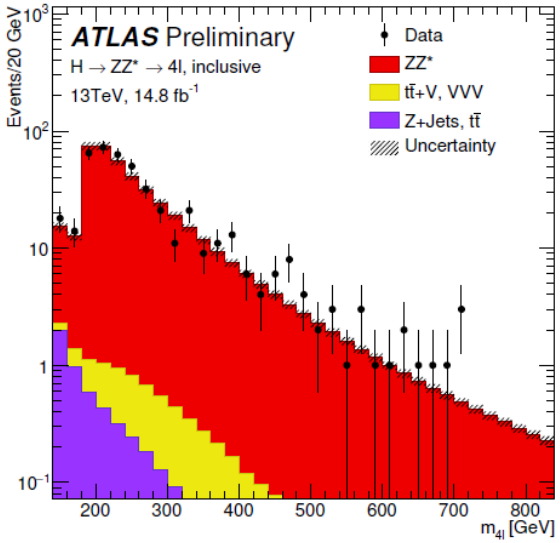
$H \to ZZ \to 4\ell$

- One of main measurement channels for h(125).
  - Mass, spin, ….
  - Clear channel, reliable event reco.
  - Can be used to search for BSM particles.
- Event selection
  - Two pair of OS same flav dilepton
  - $50 < m_{12} < 106\ \text{GeV}, 12 < m_{34} < 115\ \text{GeV}$

H(125) peak in $m(4\ell)$ dist.

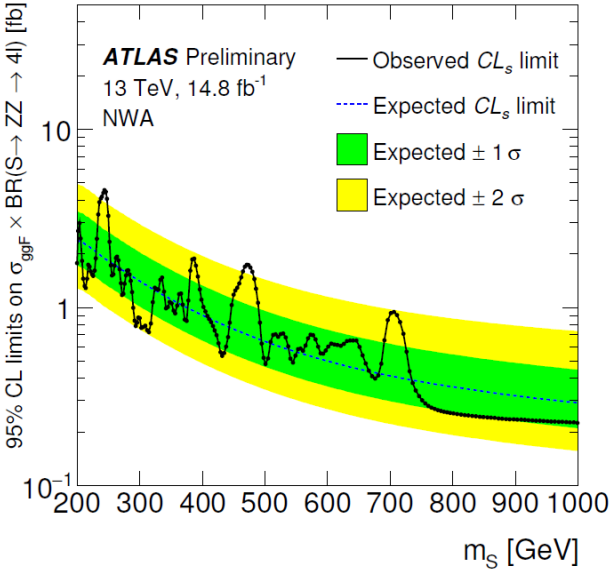


$m(4\ell)$ in high mass region

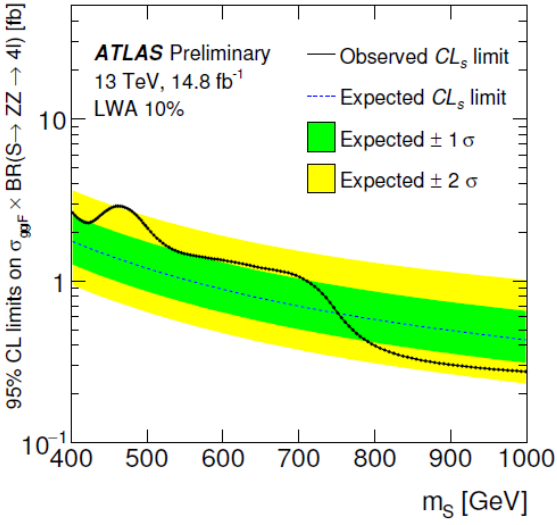


Limit on $\sigma(gg \to H)$ $\times Br(H \to ZZ \to 4l)$

Narrow Width Approx.



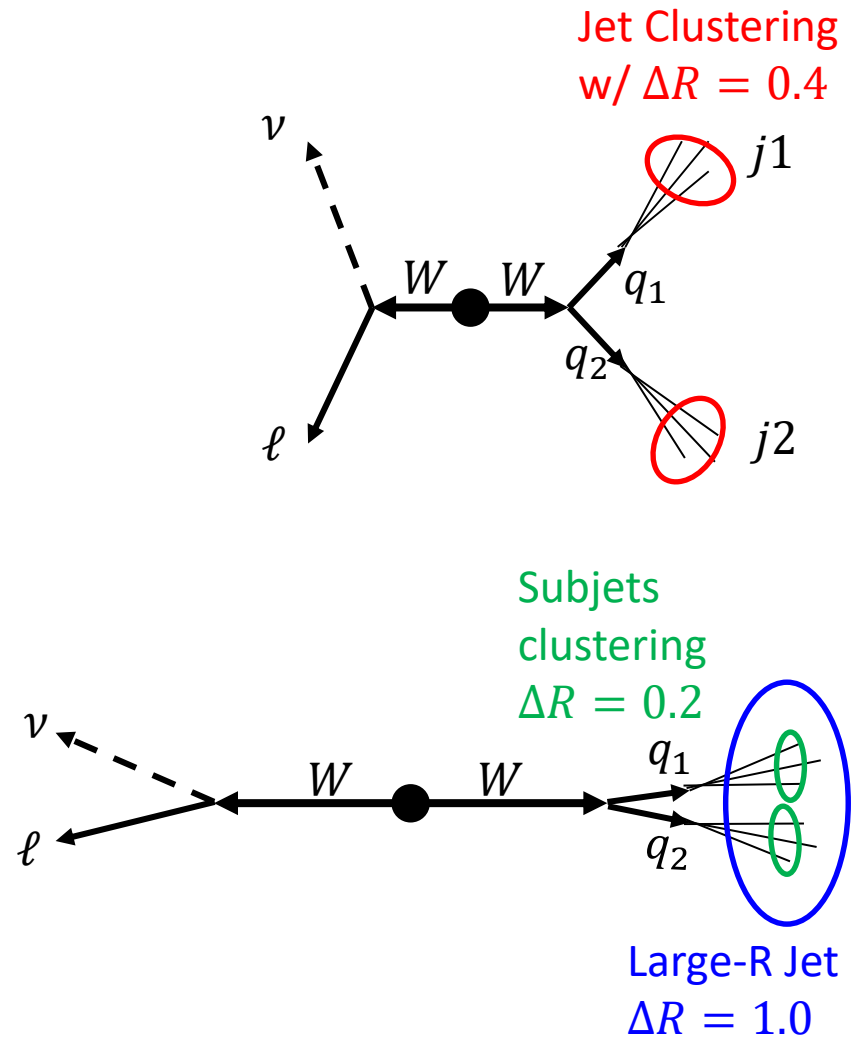
Large WA $\Gamma_H/m_H = 10\%$



$H \rightarrow WW \rightarrow \ell\nu qq$
Boosted Boson Tagging

- Hadronically decaying W
- Traditional analysis:
  - Find two jets clustered $\Delta R = 0.4$.
  - Calculate the dijet mass.

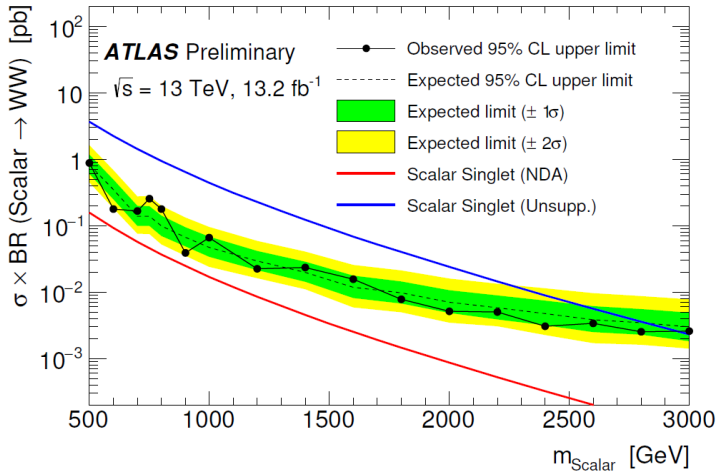
- For large P_T^W :
  - The two jets often merge.
  - Cluster the whole hadronic energies into a large-R jet, with $\Delta R = 1.0$.
  - Analyze the substructure of the large-R jet, and recalculate the jet mass after subtracting pile-up energies.
  - Large-R jet considered to originate from *W* boson, if its mass is consistent with m_W.
  - Substructure of the jet can further used to discriminate against jets of QCD and top origin.



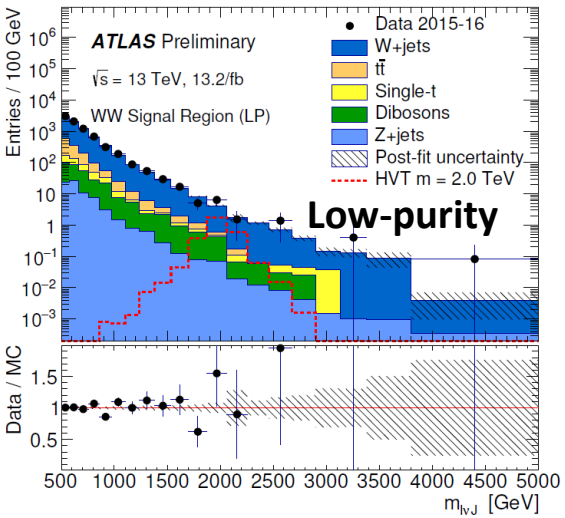
$H \rightarrow WW \rightarrow \ell\nu qq$

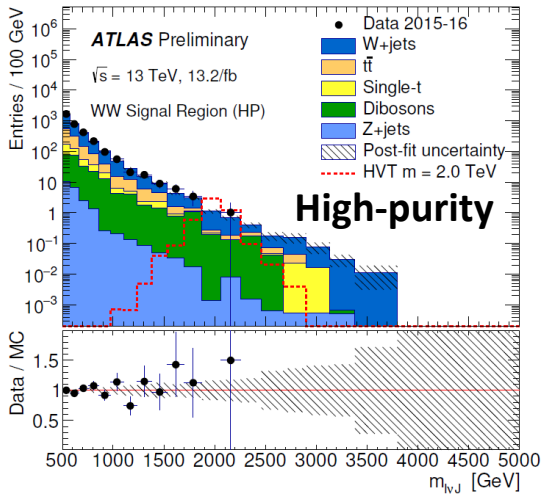
- Event selection:
  - One lepton /w $P_T^e > 27$ ($P_T^\mu > 25$) GeV
  - $E_T^{miss} > 100$ GeV
  - One large-R jet /w $P_T^J > 100$ GeV
  - P_T $(\ell, E_T^{miss}) > 200$ GeV
- P_z^ν determined by solving equation $m(\ell, \nu) = m_W$.
- Subdivision into High/Low-purity regions by jet substructure $D_2^{(\beta=1)}$.

Limit on $\sigma(gg \rightarrow H) \times Br(H \rightarrow WW)$



$m_{\ell\nu J}$ Distribution

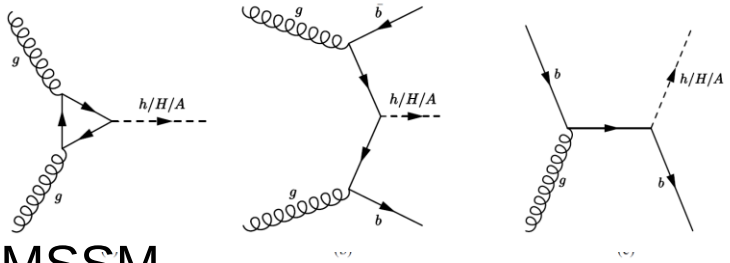




Results compared to CP-even scalar singlet model with

$(c_3, c_H) = \left(\left(\frac{1}{4\pi}\right)^2, 0.9\right), \left(\frac{1}{8\pi}, 0.5\right)$

$H/A \to \tau\tau$



- Promising search mode for high $\tan\beta$ in MSSM.
- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels
  - τ_{had} identified by shower shape and track multiplicity.
- Events are subcategorized by presense of b-tagged jets.
  - Separate gg fusion and b-associated production.
- Final discriminant:

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

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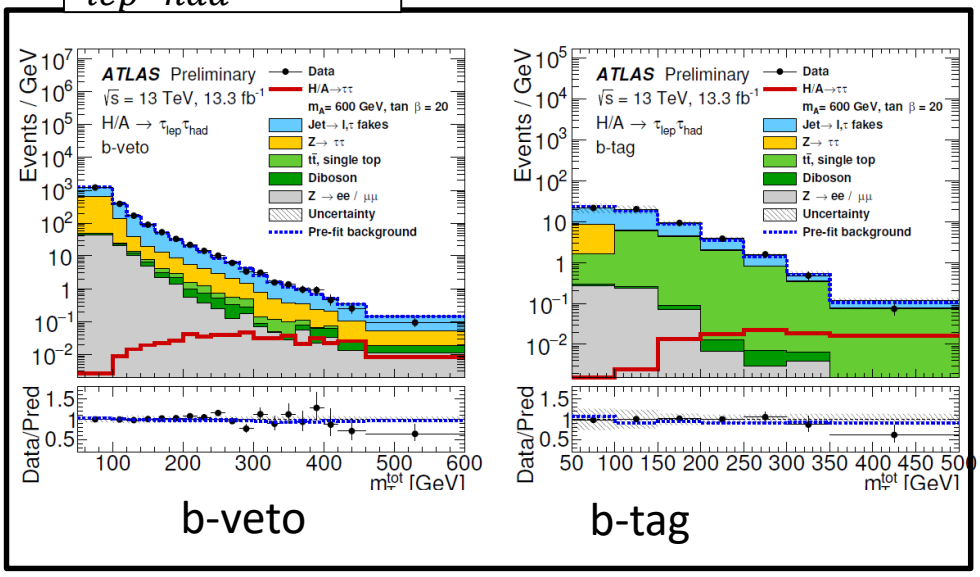
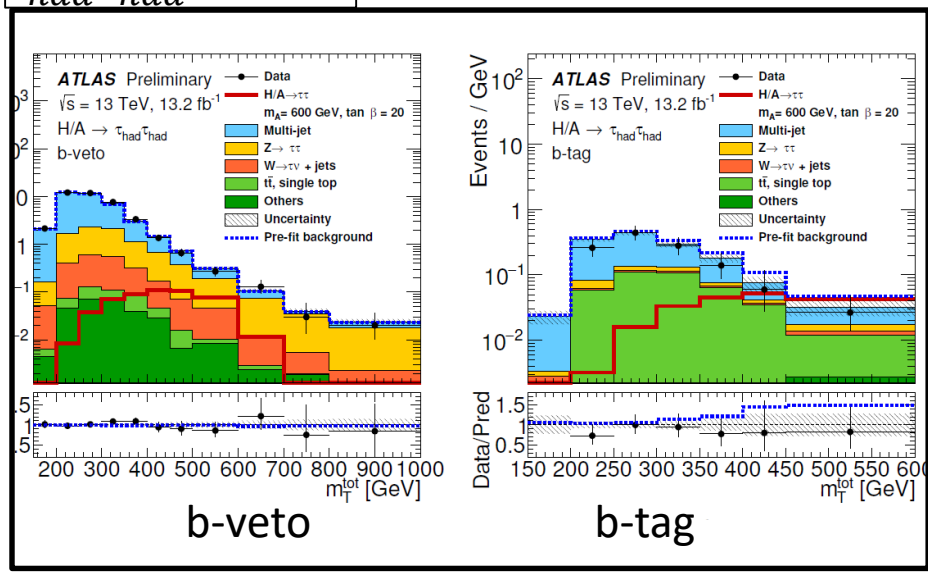
$\tau_{lep}\tau_{had}$ channel

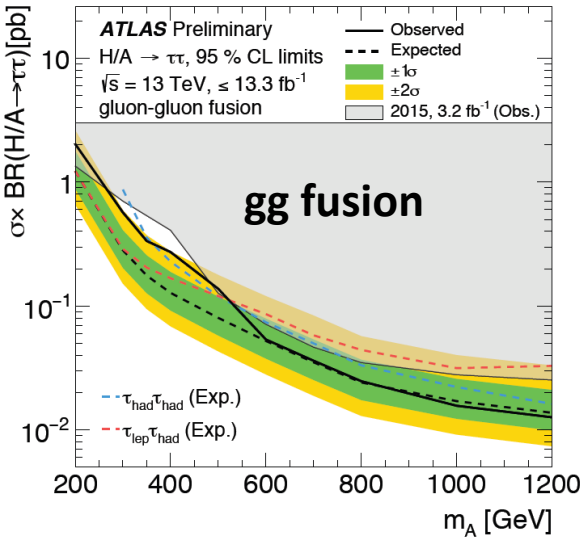


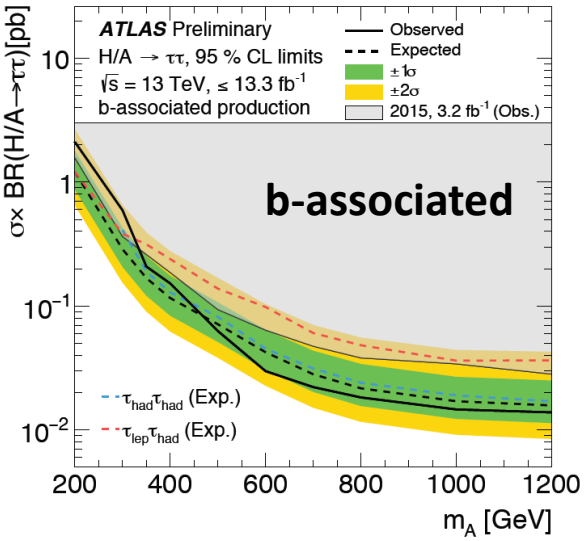
$\tau_{had}\tau_{had}$ channel



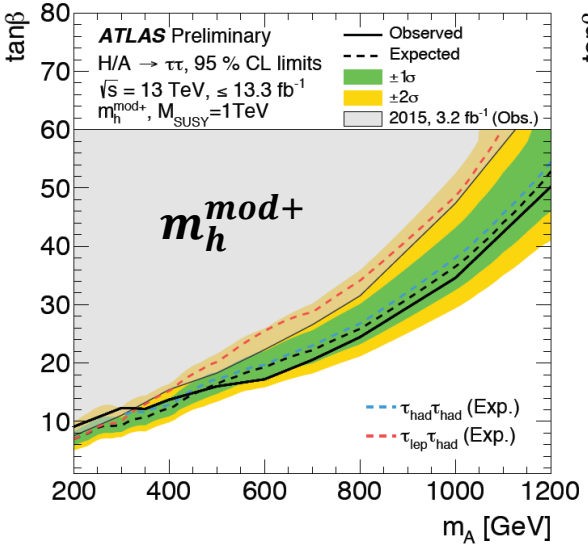
$H/A \rightarrow \tau\tau$ Limits

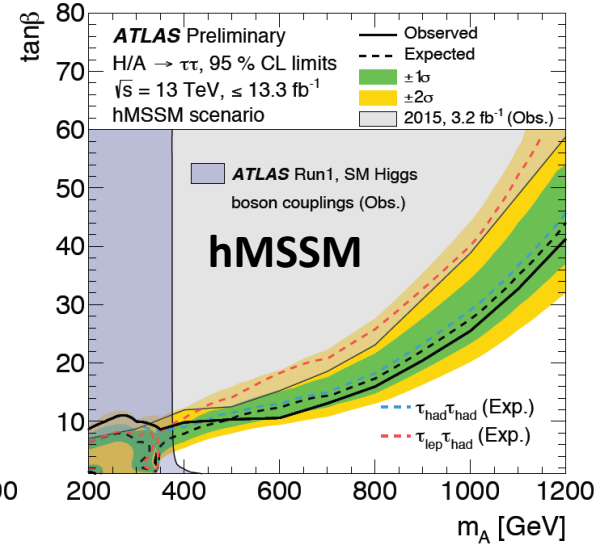
Upper limits for production cross section times branching ratio



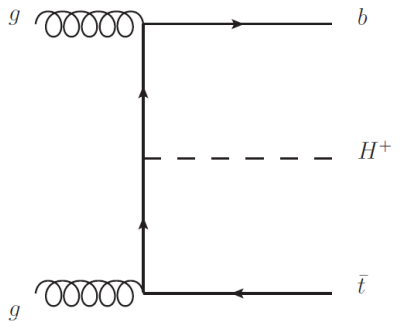


Excluded regions in MSSM scenarios

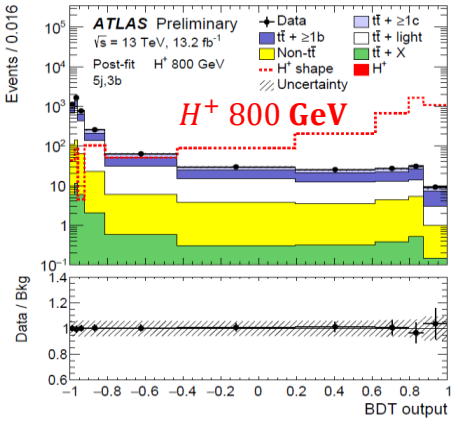




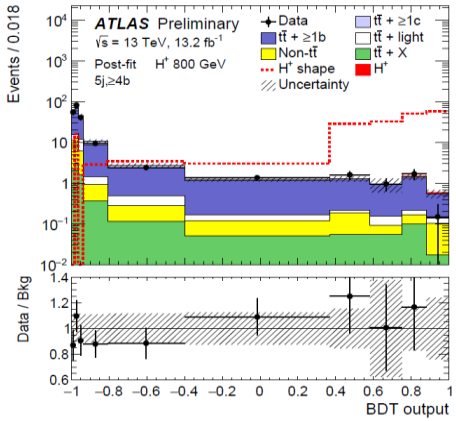
$H^+ \rightarrow tb$



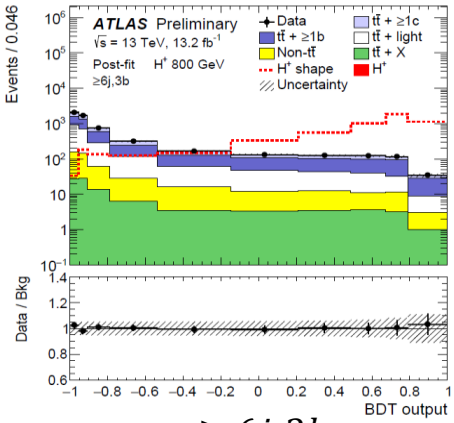
- Search in $l + jets$ channel.
  - $tbH^+ \rightarrow tb(tb) \rightarrow l + E_T^{miss} + 2q + 4b$
- Four signal regions with different the jet/b-tag multiplicities.
- S/B separation by BDT with event kinematics.



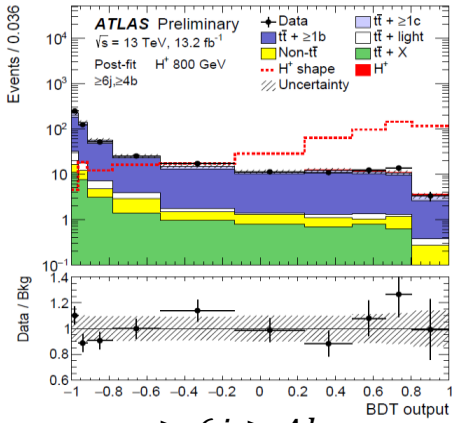
$5j, 3b$



$5j, \geq 4b$

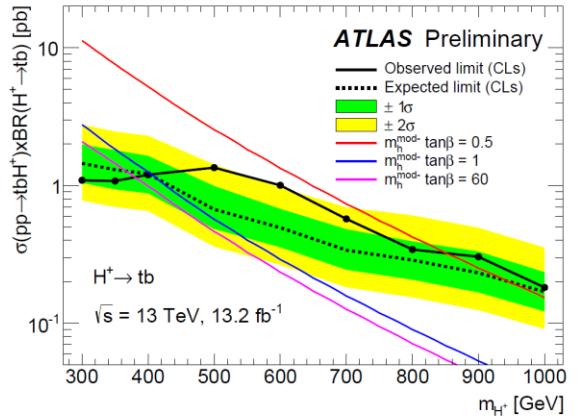


$\geq 6j, 3b$

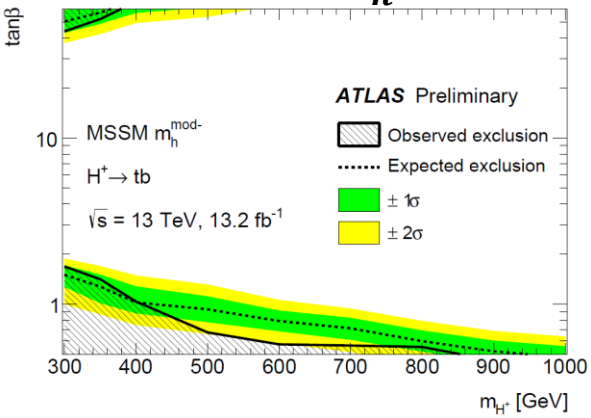


$\geq 6j, \geq 4b$

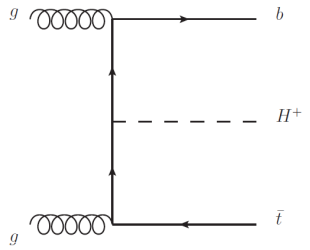
Limit on $\sigma \times Br$



Exclusion on m_h^{mod-}

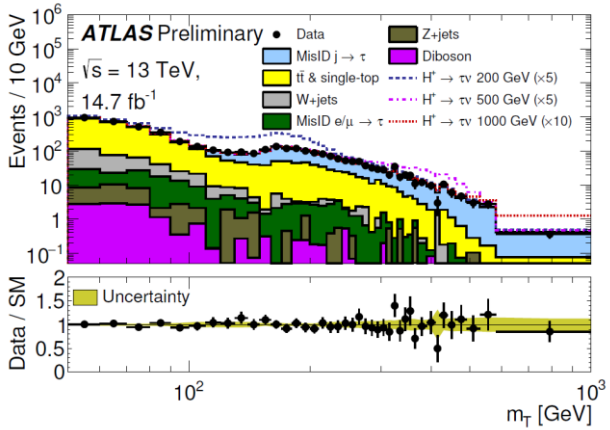


$H^+ \to \tau\nu$

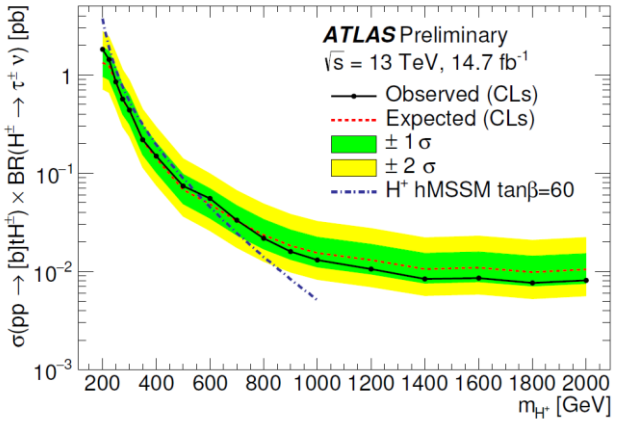


- Analysis with $\tau_{had} + E_T^{miss} + \geq 3jets, \geq$ 1b-tag events
  - $tbH^+ \to (qqb)b(\tau\nu) \to \tau_{had} + E_T^{miss} + 2q + 2b$
- Require $E_T^{miss} > 70(90)$ GeV for 2015(2016) data, τ_{had} w/ $P_T^{vis} > 40$ GeV, ≥3jets w/ $P_T > 25$ GeV, ≥1b-tag
- Dominant background: jets mis-IDed as τ, modelled by data driven methods.
- Final discriminant: $m_T(\tau_{had}, MET)$.

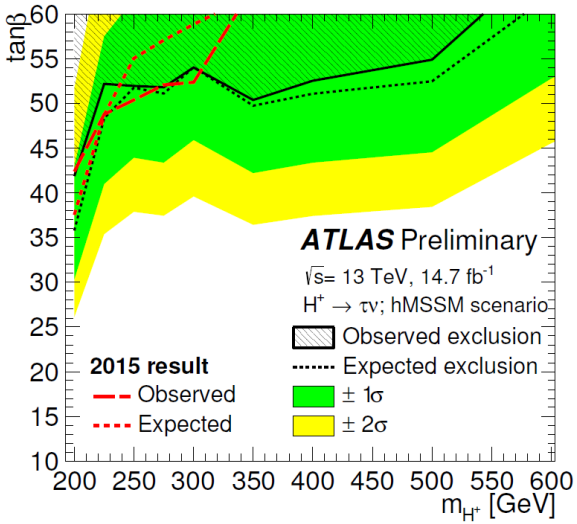
$m_T(\tau_{had}, MET)$ distribution



Limit on $\sigma \times Br$

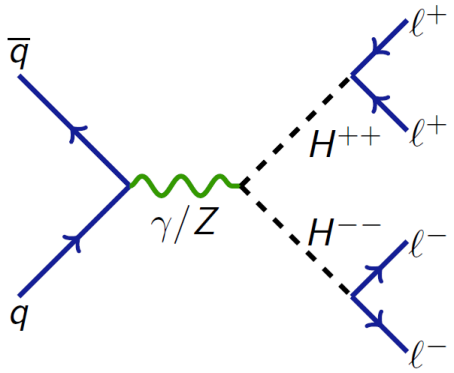


Constraint on hMSSM

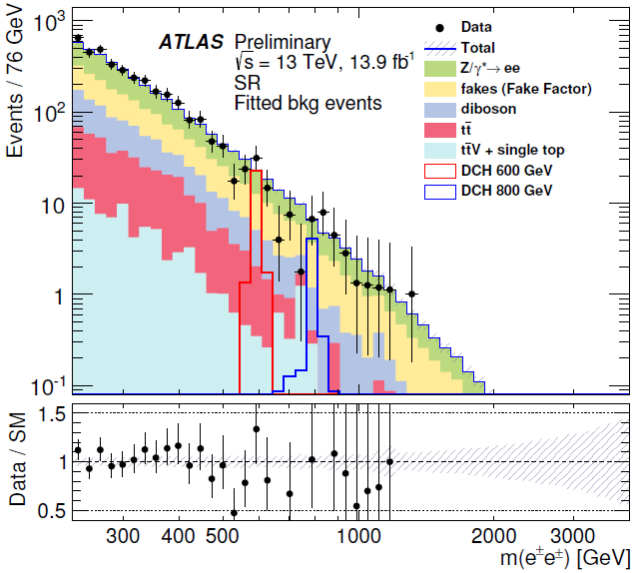


$H^{++} \rightarrow e^+e^+$

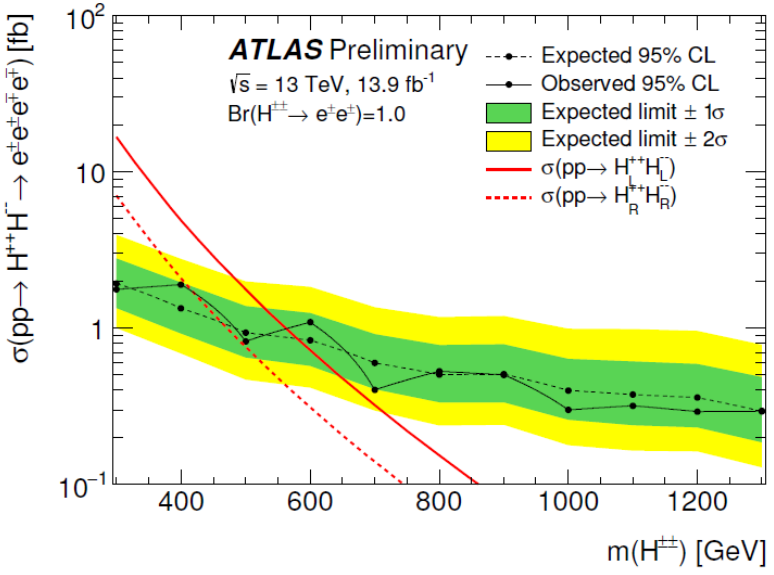
- Doubly Charged Higgs can arise in left-right symmetry models (LRSM), Higgs Triplet Models, etc.
- Predominantly pair produced via Drell-Yan.
- SS dielectron events w/ $M(e,e) \geq 300$ GeV.
- Main background charge mis-measurement in $Z/\gamma \rightarrow ee$, diboson and $t\bar{t}$, and jet faking leptons. Both modelled in data-driven methods.



SS dielectron mass distribution



Cross section Limit on H^{++} production



3.2 fb^{-1}

$A \to Zh \to \ell\ell bb/\nu\nu bb$

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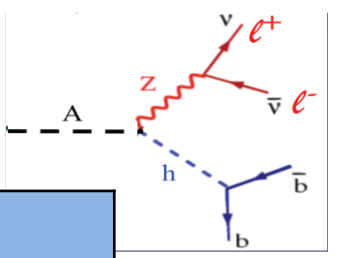


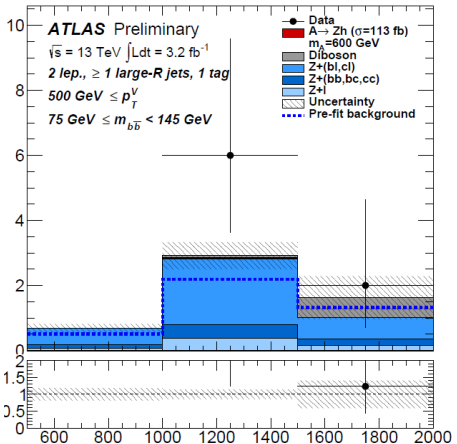
- CP-odd *A* boson decaying to h(125).

0 lepton	**2 lepton** $e^+e^-, \mu^+\mu^-$
MET trigger	single lepton trigger
$E_T^{miss} > 150$ GeV	$m(\ell^+, \ell^-)$ compatible w/ m_Z
$P_T^Z = E_T^{miss}$	$P_T^Z = P_T^{\ell^+} + P_T^{\ell^-}$

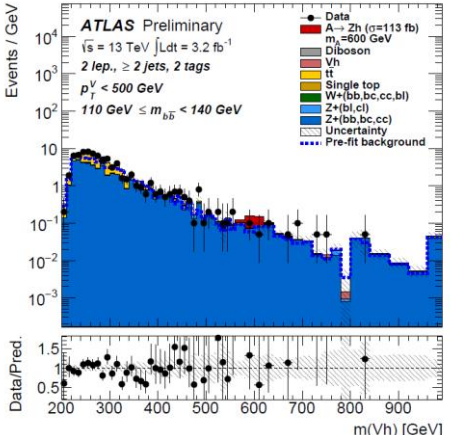
- 0/2 lepton channel is subdivided into four subchannels:

High P_T^Z (P_T^Z>500 GeV)		**Low P_T^Z (P_T^Z <500 GeV)**	
≥1 large-R Jet ($\Delta R = 1.0$)		≥2 small R jets ($\Delta R = 0.4$)	
m_J compatible w/ m_h		m_{jj} compatible w/ m_h	
b-tagging on track jets ($\Delta R = 0.2$) inside large-R Jet		b-tagging on the small R jets	
1 b-tag	**2 b-tag**	**1 b-tag**	**2 b-tag**

$m_T(MET, J)$ for 0 lepton high-P_T^Z 2 b-tag channel:



$m(lljj)$ for 2 lepton high-P_T^Z 2 b-tag channel:

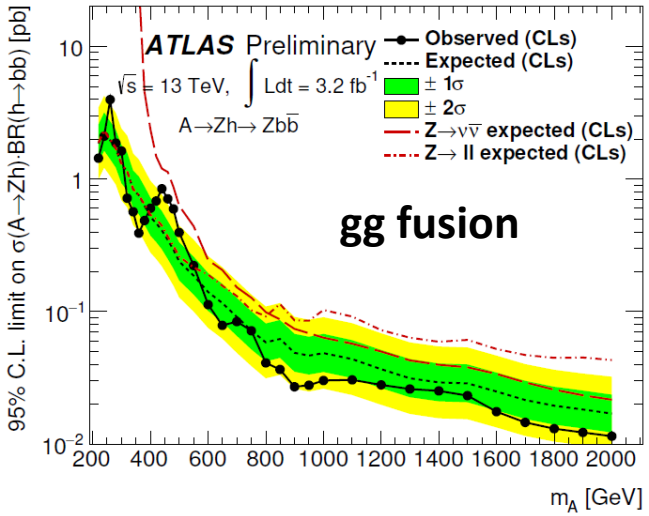


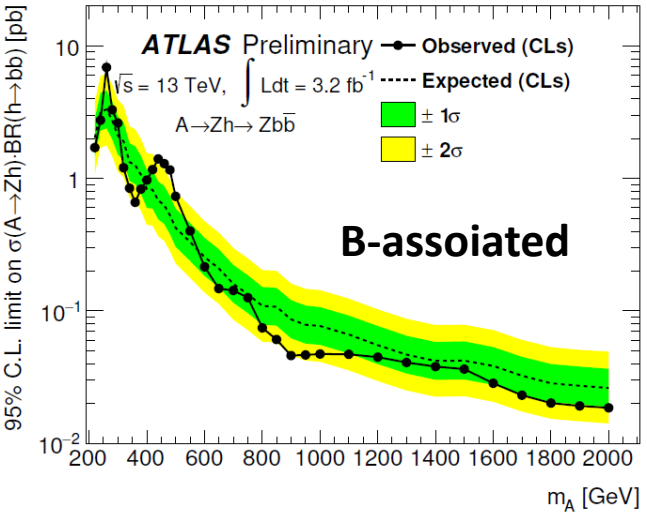
$A \to Zh \to \ell\ell bb/\nu\nu bb$ Limits

subsamples by #b-tags:

Separation between gg-fusion and b-association production.

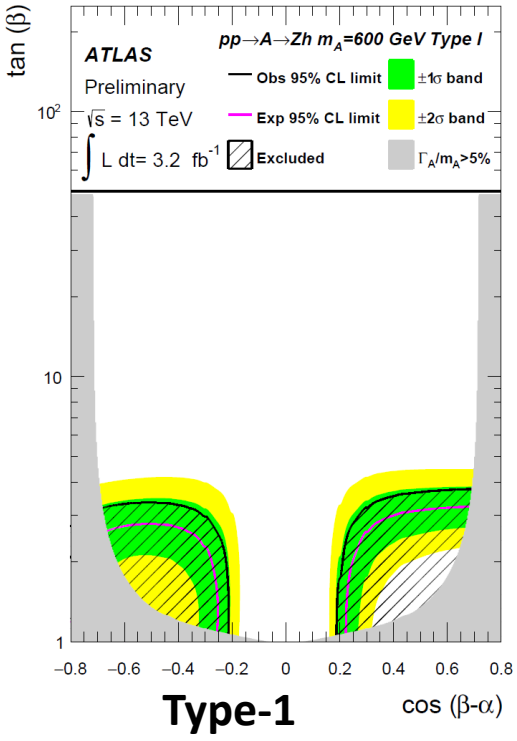
95% CL limit on $\sigma \times Br$

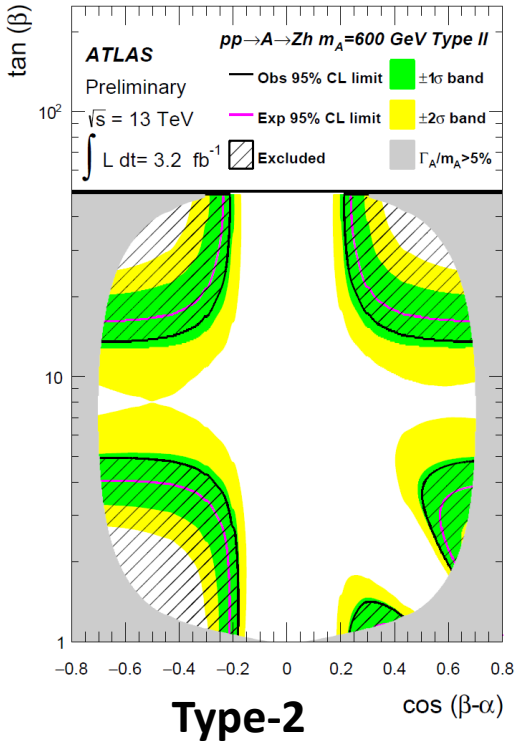




95% CL Exclusion on 2HDM parameters

$m_A = 600\ \mathrm{GeV}/c^2$





2HDM limits calculated assuming that A, H, and $H^{\pm}$ are degenerate in mass.

Summary

- A wide range of heavy BSM Higgs signals have been searched for at ATLAS with the $\sqrt{s}$ =13 TeV data.
- Presented today were Summer 2016 results with 13.2-15.4 fb^{-1} data.
- No sign of additional Higgs boson so far.

- Many analyses will be updated in Summer 2017 with full 2015+2016 data.
- Stay tuned!!

13 TeV data recorded by ATLAS

	$\mathbf{fb^{-1}}$
2015	3.9
2016	35.6

BACKUP

Search for $X \to \gamma\gamma$ in 2015 data

JHEP 09 (2016) 1

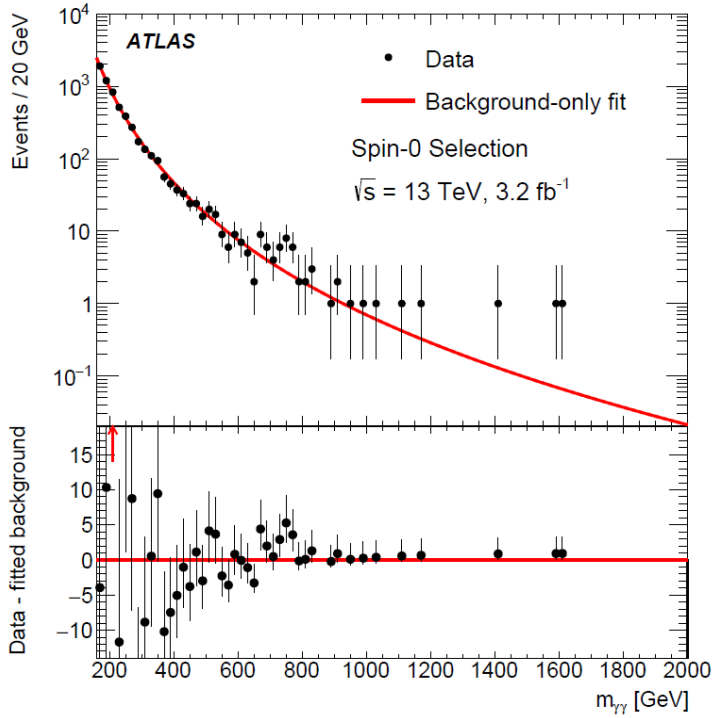
ATLAS
2015 Data
3.2 fb^{-1}

One of main measurement channels for h(125)

- Mass, spin, ….
- Can be used to search for BSM particles.

Event Selection:

- $2\gamma, P_T^1 > 40, P_T^2 > 30$ GeV.
- $P_T^1 > 0.4m_{\gamma\gamma}, P_T^1 > 0.3m_{\gamma\gamma}$.
- 2878 ev w/ $m_{\gamma\gamma} > 200$ GeV$/c^2$.



CMS PAS EXO-15-004

CMS 2015 data (2.9 fb^{-1}) showed an excess around 750 GeV$/c^2$.

Local Significance $\sim 3\sigma$

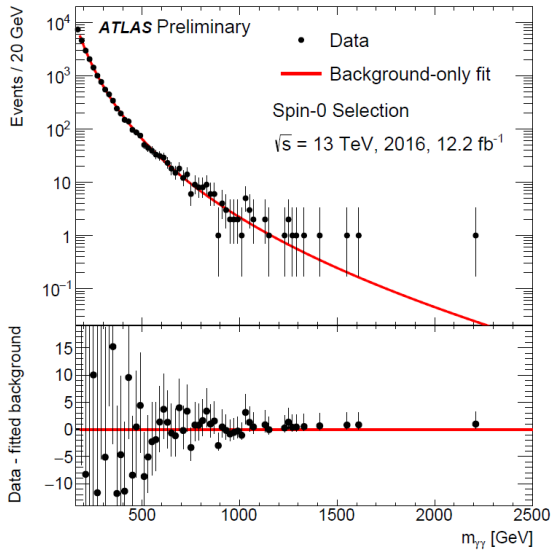
Global Significance $\lesssim 1.7\sigma$

	Spin 0
Mass (GeV$/c^2$)	~750
Local Significance	3.8σ
Global Significance	2.1σ

Search for $X \rightarrow \gamma\gamma$ in 2016 data

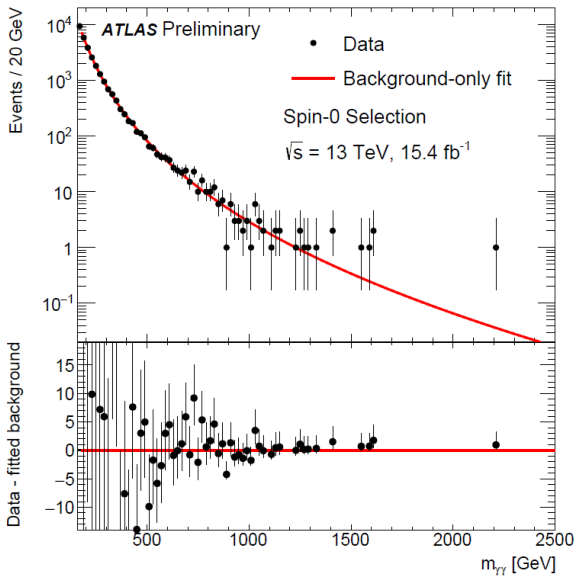
- One of main measurement channels for h(125).
- 2015 data ($\sqrt{s}$=13 TeV, 3.2 fb $^{-1}$) had an excess at $m_{\gamma\gamma}$~750 GeV/c^2.
  - Local/Global significance ~ 3.8σ / 2.1σ
  - CMS had similar excess with local ~ 3σ

ATLAS 2016 data: 12.2 fb^{-1}



2016 data in agreement with expected background within 1σ.

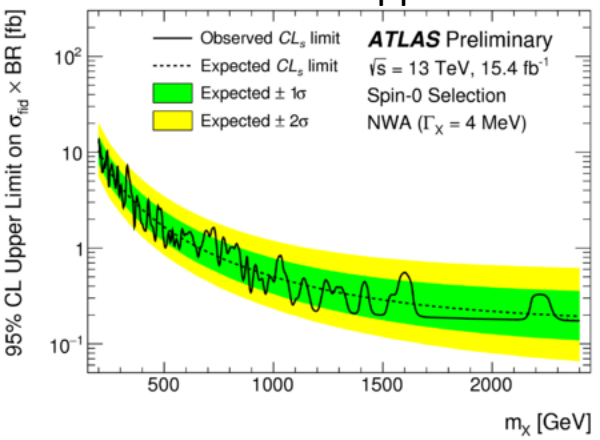
ATLAS 2015+2016 data: 15.4 fb^{-1}



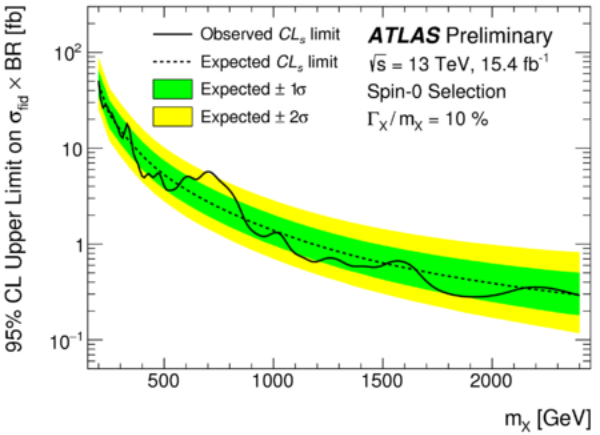
With 2015+2016 combined data, largest local significance in 700-800 GeV was 2.3σ for 710 GeV.

Limits on $\sigma_{fid} \times Br$

Narrow Width Approx.



$\Gamma_X/m_X = 10\%$



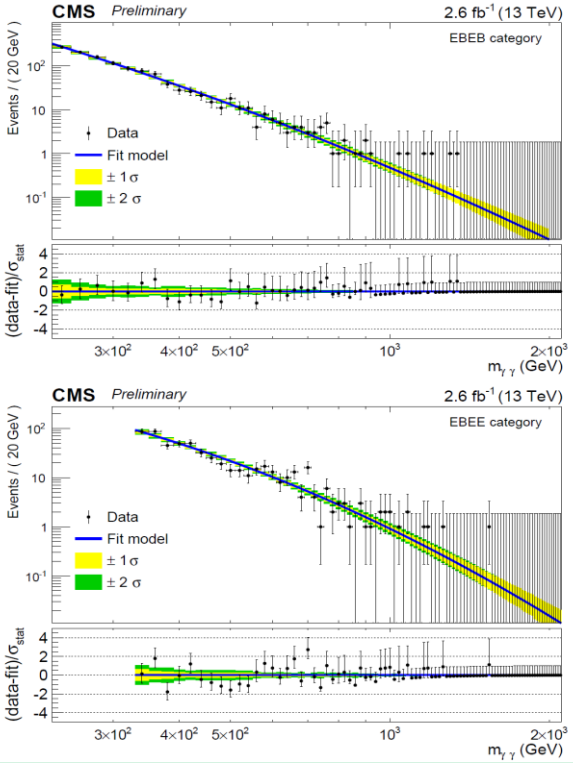
Search for $X \to \gamma\gamma$ at CMS

CMS PAS EXO-15-004

CMS 2015 data (2.9 fb^{-1}) showed an excess around 750 GeV/c^2.

Local Significance $\sim 3\sigma$

Global Significance $\lesssim 1.7\sigma$



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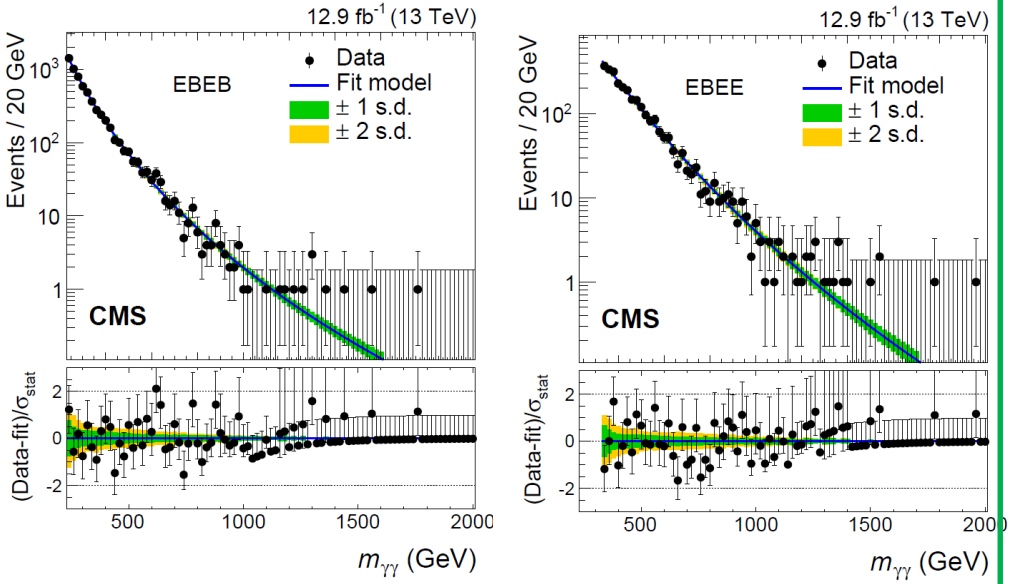
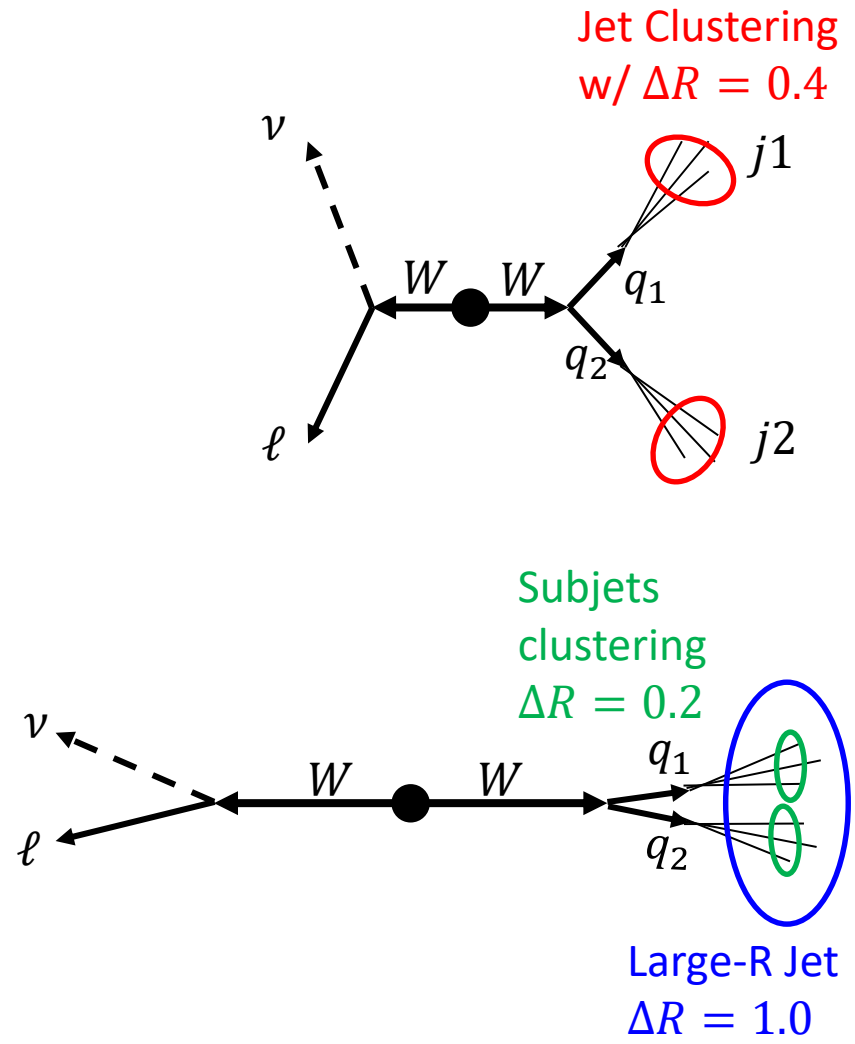
No significant excess in 2016 data (12.9 fb^{-1}).



$H \to WW \to \ell\nu qq$
Boosted Boson Tagging

- Hadronically decaying W
- Traditional analysis:
  - Find two jets clustered $\Delta R = 0.4$.
  - Calculate the dijet mass.

- For large P_T^W :
  - The two jets often merge.
  - Cluster the whole hadronic energies into a large-R jet, with $\Delta R = 1.0$.
  - Analyze the substructure of the large-R jet to redefine the jet mass.
    - Run jet clustering with $\Delta R_{subjet} = 0.2$, and find subjets inside the large-R jet.
    - Discard subjets with $P_T^{subjet} > 5\% \times P_T^{large-R\ jet}$
    - Mass of large-R jet calculated using calo-clusters inside surviving subjets.
  - Large-R jet considered to originate from *W* boson, if its mass is consistent with m_W.



Jet substructure $D_2^{\beta=1}$ definition

arXiv:1409.6298v1

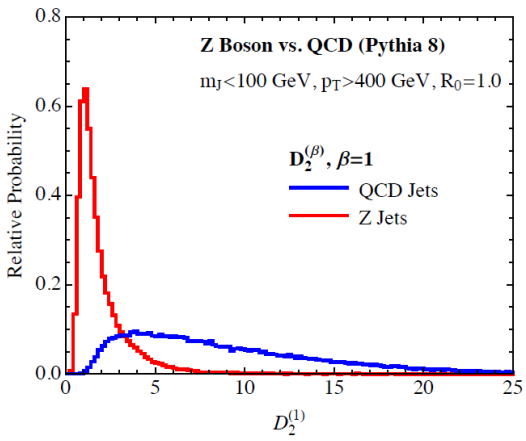
- **Boosted Z Bosons vs. QCD** The two- and three-point energy correlation functions, $e_2^{(\beta)}$ and $e_3^{(\beta)}$, have been shown to be among the most powerful observables for identifying the hadronic decays of boosted Z bosons [53]. We discuss the phase space defined by $e_2^{(\beta)}$ and $e_3^{(\beta)}$, and determine which regions are populated by signal and background jets. Using this understanding of the phase space, we propose a powerful discriminating variable to identify boosted two prong jets, given by

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} .$$

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} ,$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} ,$$

(2.2)

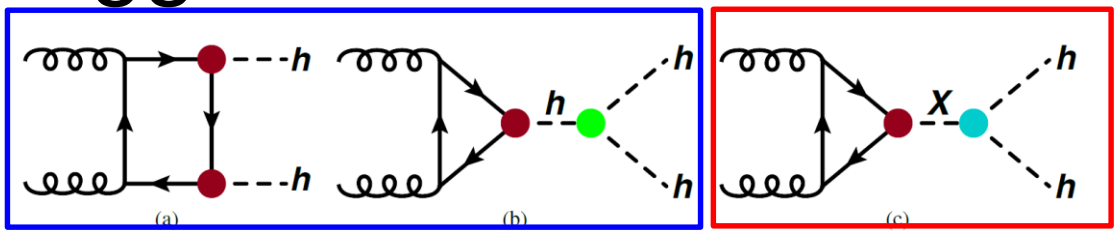


In all following discussions, the term constituents means particles in the case of truth jets and LCW topoclusters in the case of calorimeter jets.

arXiv:1510.05821v2

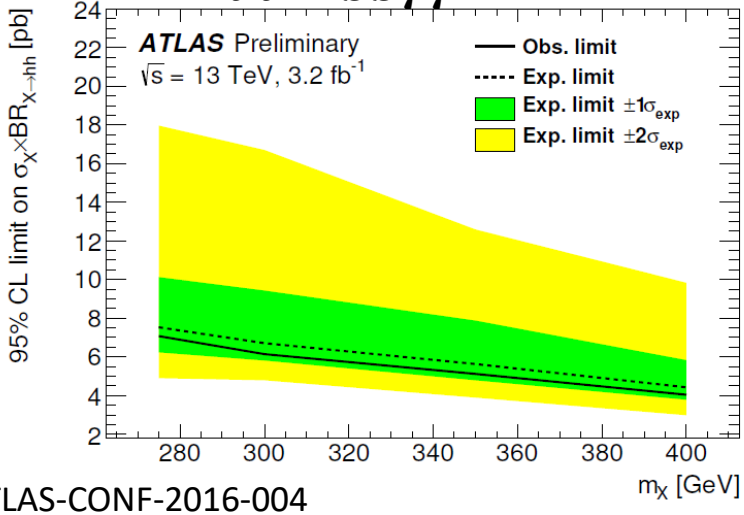
Dihiggs searches in ATLAS Run2

SM processes



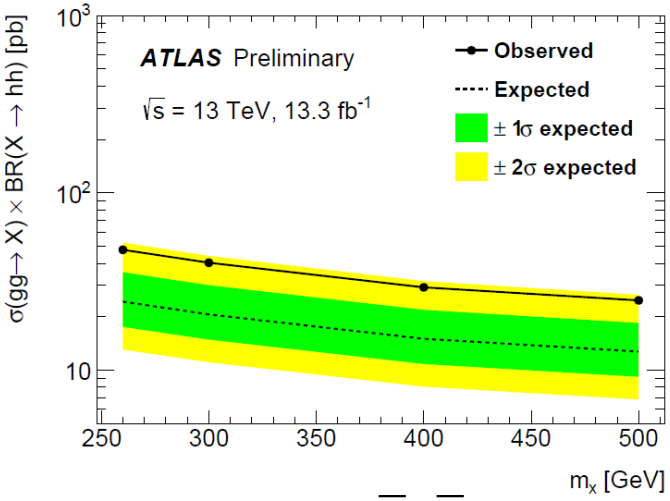
X can be heavy Higgs boson *H/A*.

$X \to hh \to b\bar{b}\gamma\gamma$



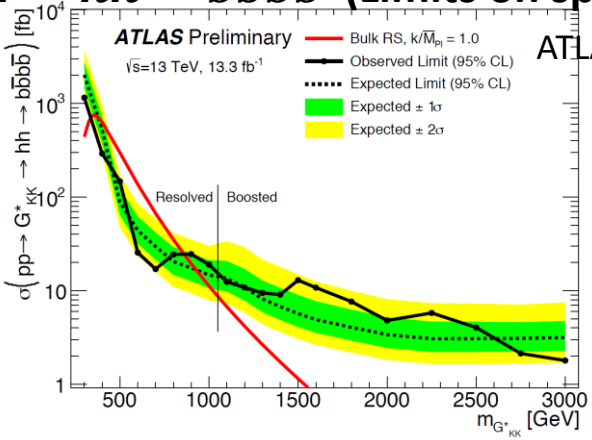
ATLAS-CONF-2016-004

$X \to hh \to \gamma\gamma WW \to \gamma\gamma\ell\nu jj$



ATLAS-CONF-2016-071

$X \to hh \to b\bar{b}b\bar{b}$ (Limits on spin-2 particle)



ATLAS-CONF-2016-049

For dihiggs and Higgs rare decays at ATLAS, see **Jason Veatch**'s talk in BSM Higgs I session.