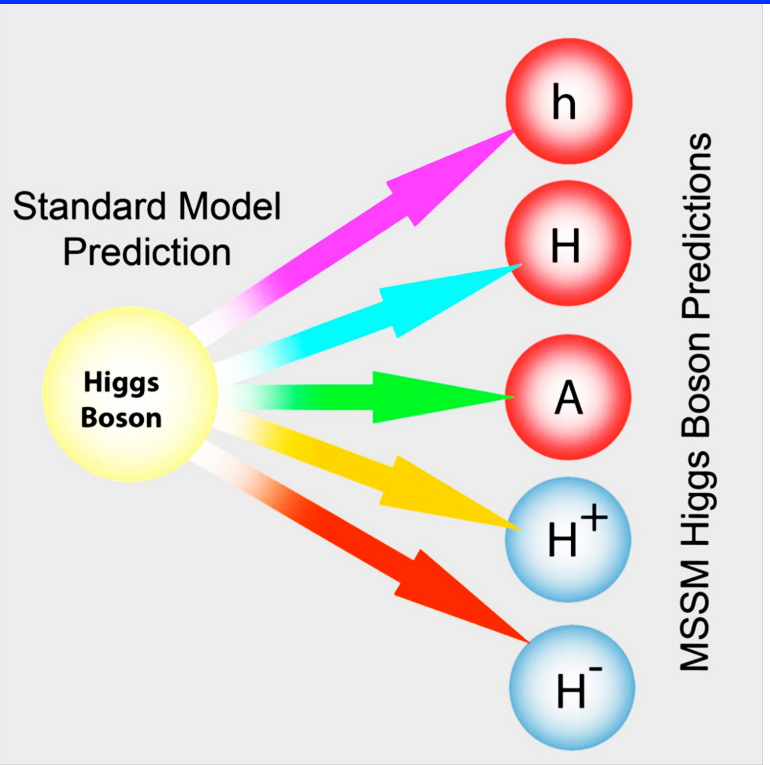
Exotic Higgs searches at ATLAS



Lei Zhang

Nanjing University

Introduction

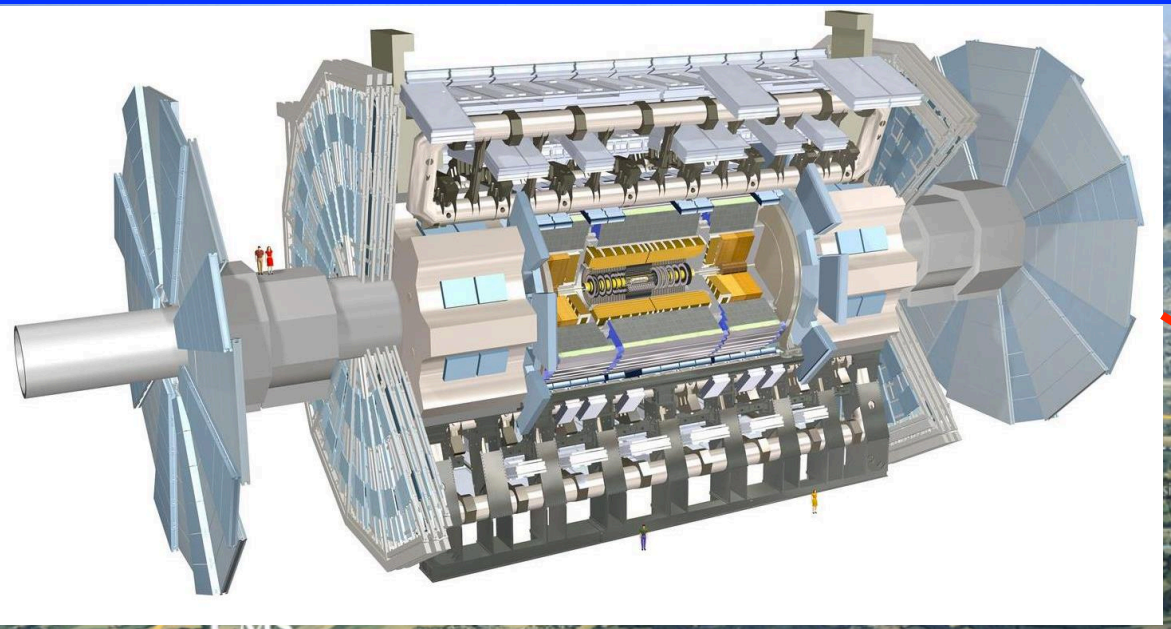
- Discovery of the 125 GeV Higgs boson, whose property are consistent with SM prediction, has confirmed the EW Spontaneous Symmetry Breaking mechanism

- But, SM can not explain
  - How and why EW SSB happened?
  - New phenomena, e.g. matter and anti-matter asymmetry, dark matter, dark energy, etc.

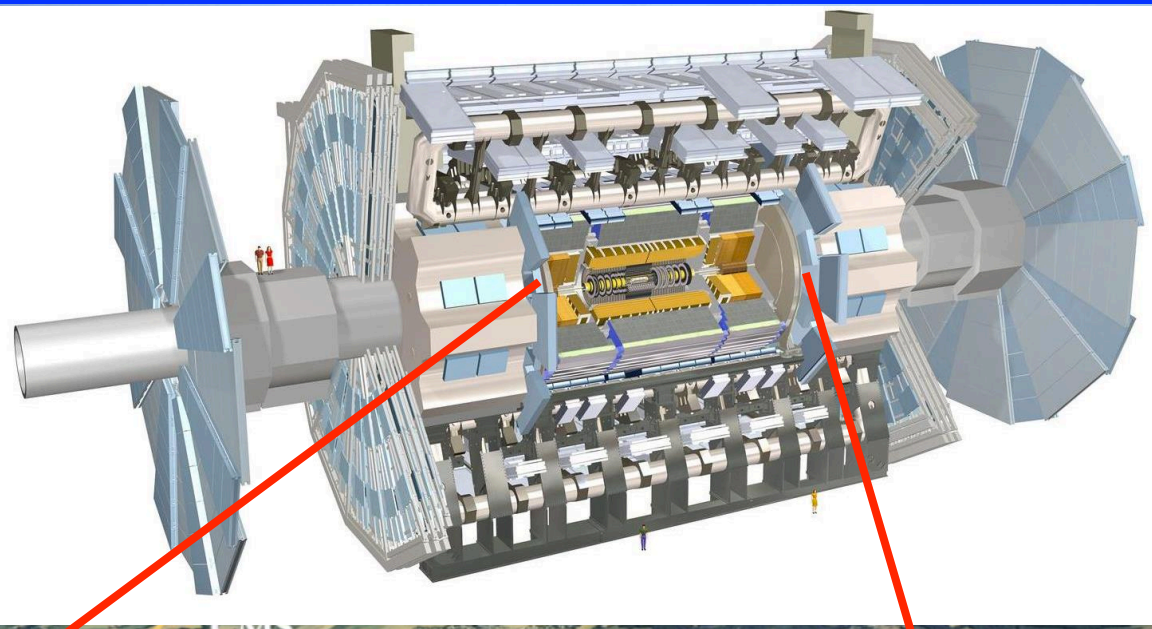
- Many open questions demand physics Beyond SM, many of which related to mass (fermion), scalar field, phase transition, etc.

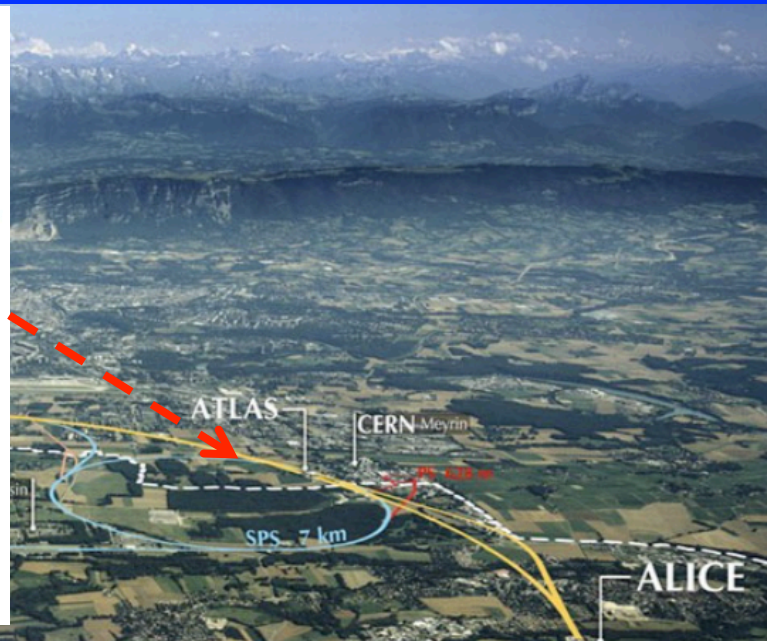
LHC collider

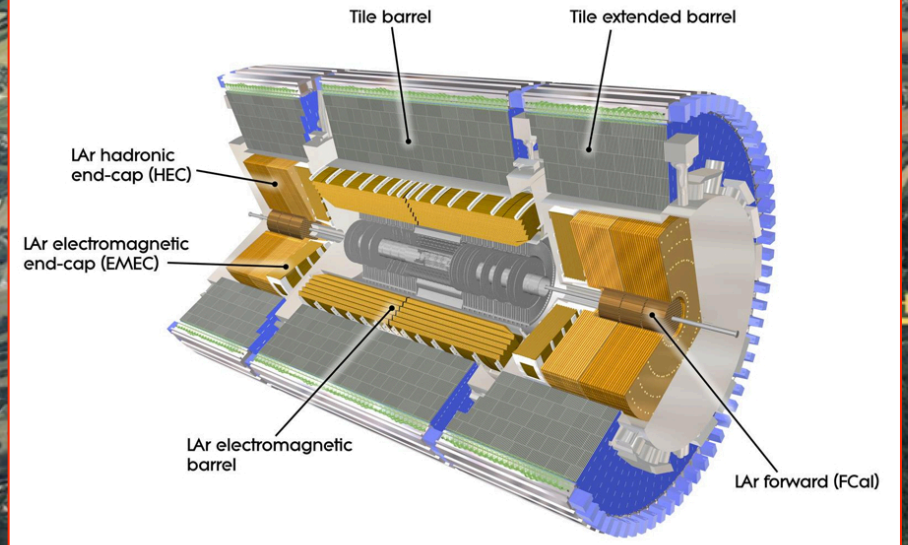
ATLAS experiment

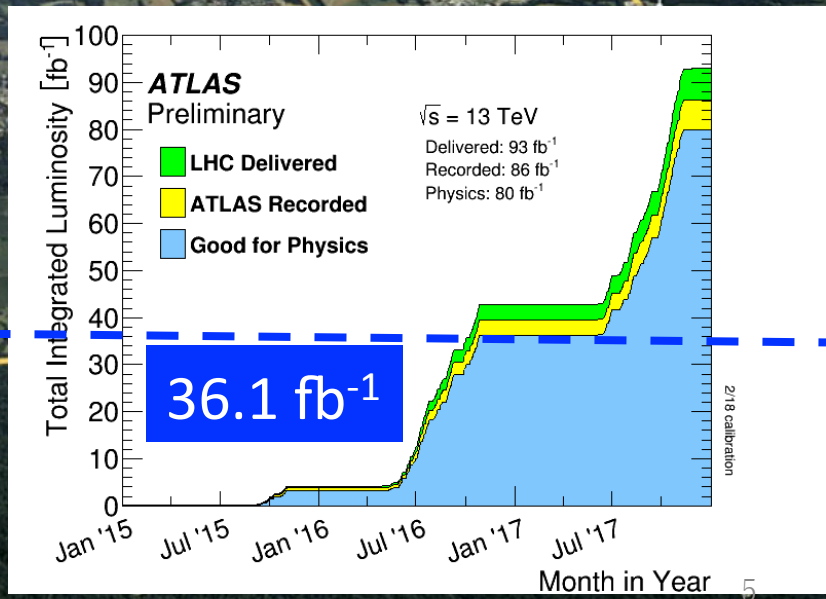


ATLAS experiment









Exotic Higgs world at ATLAS

Heavy neutral Higgs

- $A/H \to \tau\tau$
- $A/H \to ttbar$
- $H \to ZZ$
- $A \to ZH$ / Zh
- $H \to WW$
- ■ ■ ■

Charged Higgs

- $H^{\pm} \to \tau\nu$
- $H^{\pm} \to tb$
- $H^{\pm\pm} \to l^{\pm}l^{\pm}$
- $H^{\pm} \to WZ$
- ■ ■ ■

LFV, FCNC

- $h \to e\tau$, $\mu\tau$
- $t \to uh$, ch

Rare decay

- $h \to \gamma\rho$, $\gamma\phi$
- $Z(ll)$+h(inv)

h to light bosons

- $h \to Z_{dark}Z_{dark}$
- $h \to aa \to 4b$

Double Higgs

- $hh \to 4b$
- $hh \to \gamma\gamma bb$
- ■ ■ ■

ATLAS public Higgs physics results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Exotic Higgs world at ATLAS

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LFV, FCNC

- $h \to e\tau$, $\mu\tau$
- $t \to uh$, ch

h→invisible will be presented by Rui

Rare decay

- $h \to \gamma\rho$, $\gamma\phi$
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Exotic Higgs world at ATLAS

Heavy neutral Higgs

- A/H→ττ
- A/H→ttbar
- H→ZZ
- A→ZH / Zh
- H→WW

Charged Higgs

- $H^{\pm}\rightarrow\tau\nu$
- $H^{\pm}\rightarrow tb$
- $H^{\pm\pm}\rightarrow l^{\pm}l^{\pm}$
- $H^{\pm}\rightarrow WZ$

LFV, FCNC

- h→eτ, μτ
- t→uh, ch

Only focus on representative recent 13 TeV results

Rare decay

- h→γρ, γϕ
- Z(*ll*)+h(inv)

h to light bosons

- $h\rightarrow Z_{dark}Z_{dark}$
- h→aa→4b

Double Higgs

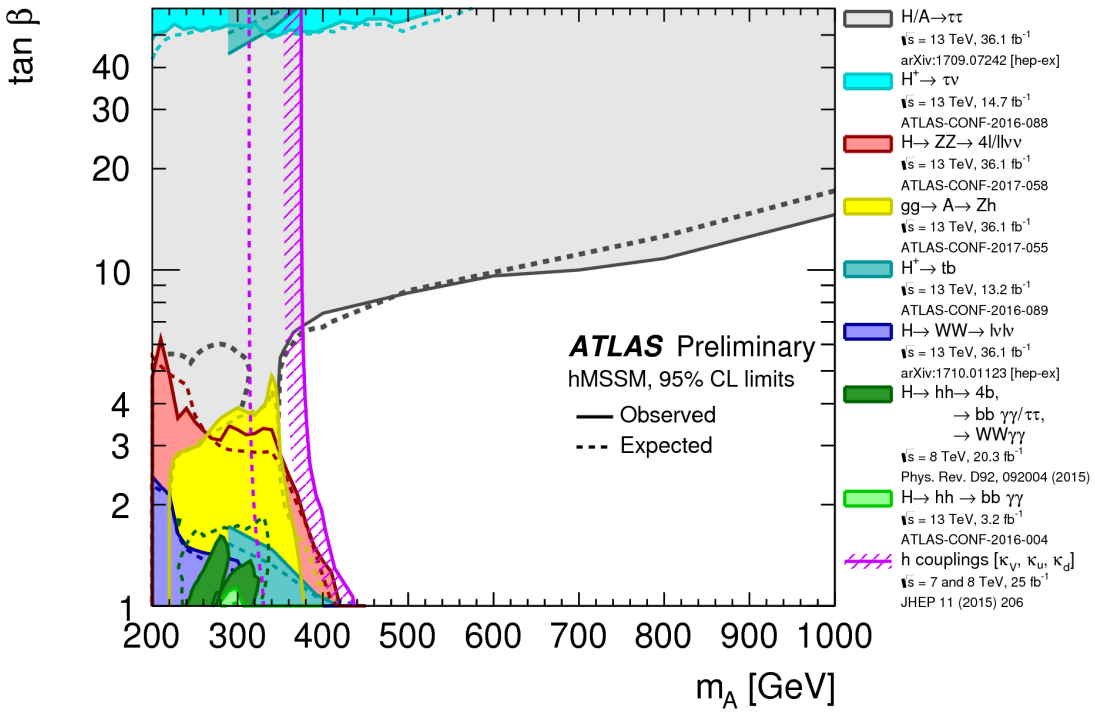
- hh→4b
- hh→γγbb

ATLAS public Higgs physics results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Extra Higgs bosons

- 2HDM is the minimum extension of Higgs sector and predicts 5 Higgs bosons: $H^{+/-}$, A, H, h
- Benchmark models, e.g. MSSM, have two free parameters at tree level: m_A, $\tan\beta = v_u/v_d$ (ratio of VEV of two Higgs doublets)



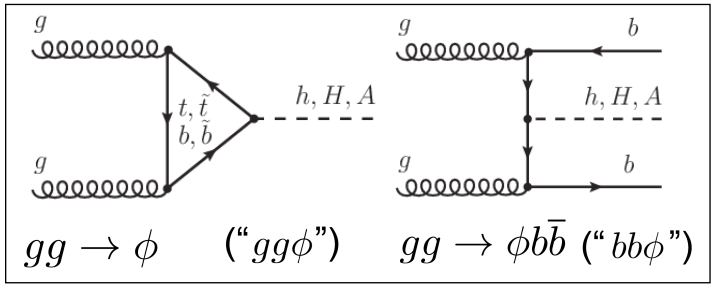
A/H→ττ

Two ττ decay modes

- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$

Categorization:

- b-veto and b-tag

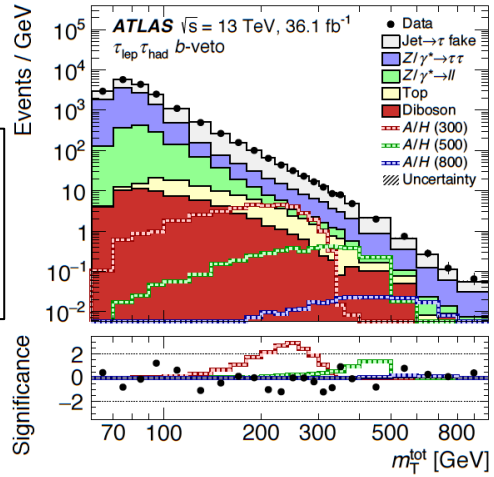


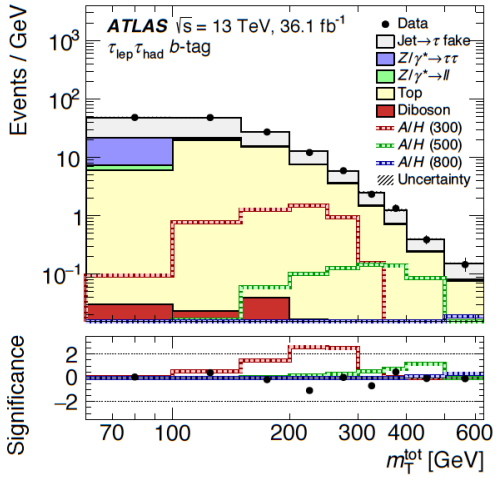
Backgrounds

- Jet→τ fake determined by data-driven method

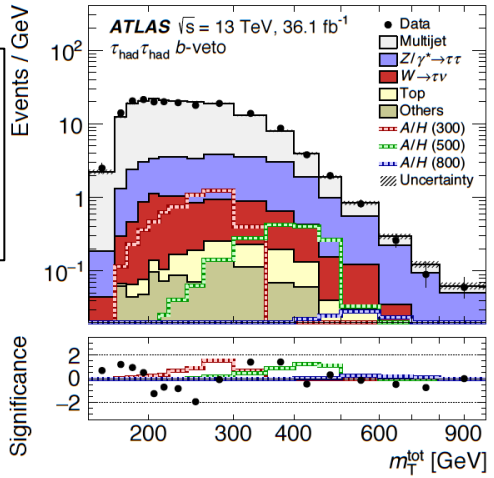
bveto **btag**

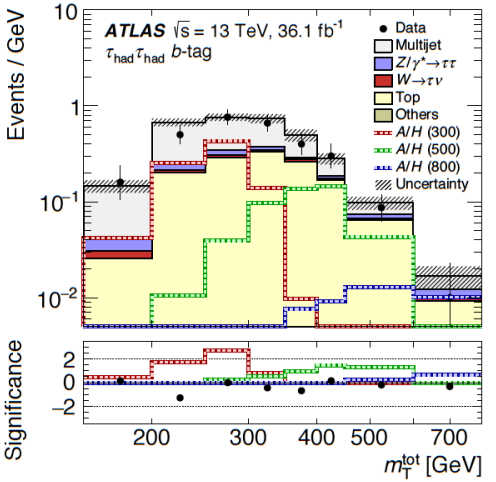
$\tau_{e/\mu}\tau_{had}$





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





Final discriminant

$$m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau_1} + \mathbf{p}_{\mathrm{T}}^{\tau_2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

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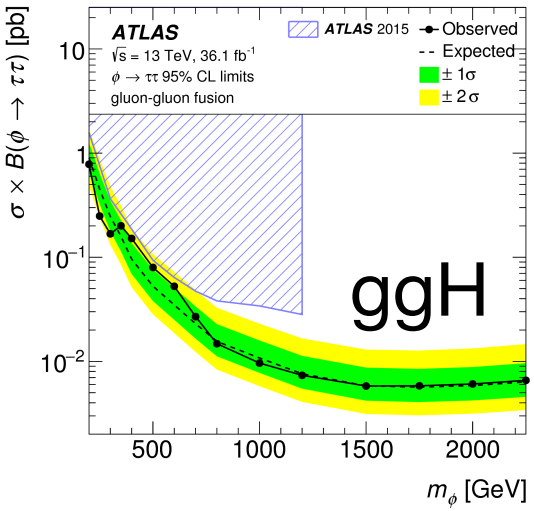
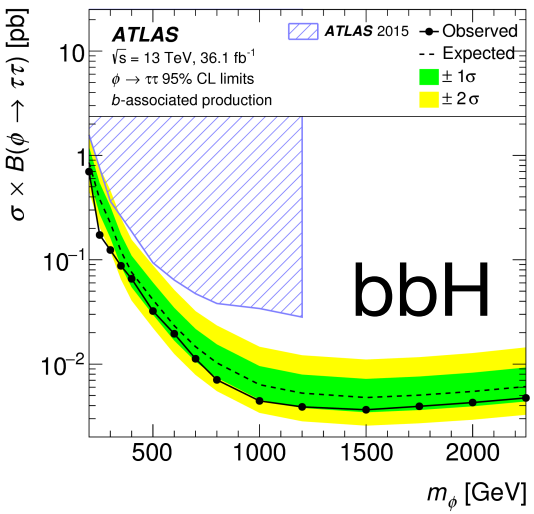
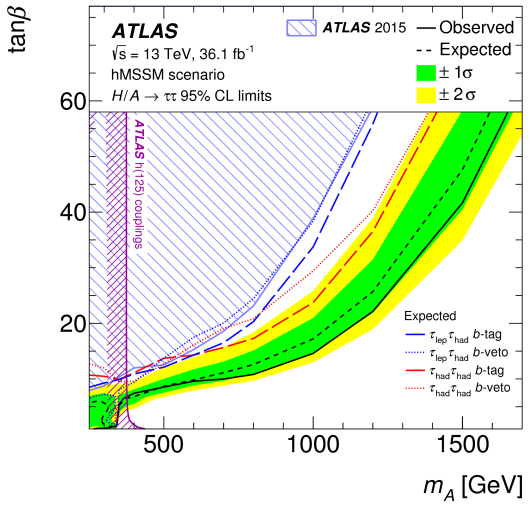
A/H→ττ: exclusion limit

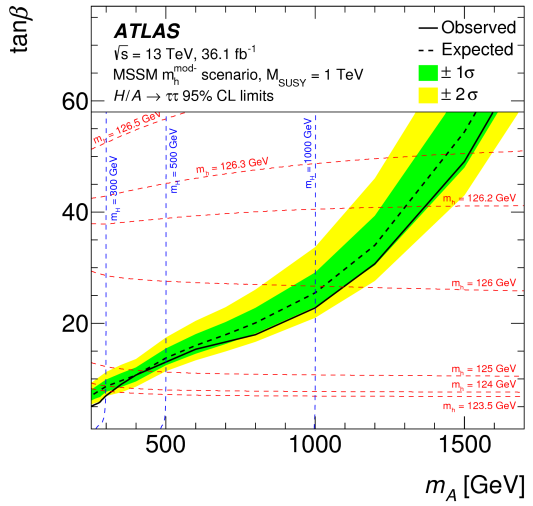


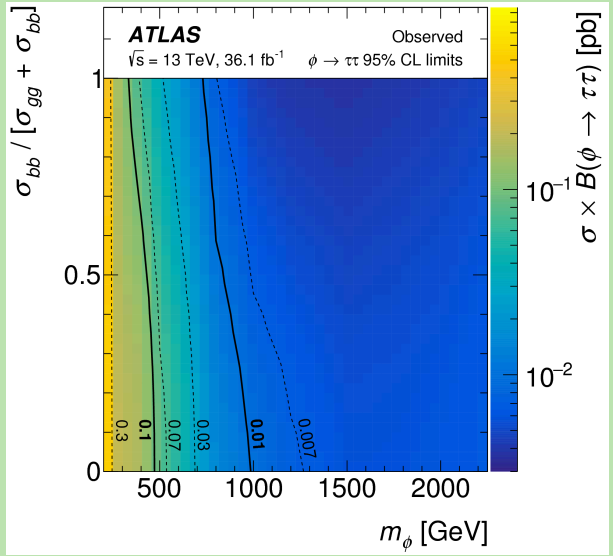


hMSSM



MSSM m_h^{mod+}





- Xsec as a function of bbH fraction and scalar boson mass

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H→ZZ→ llll or llνν

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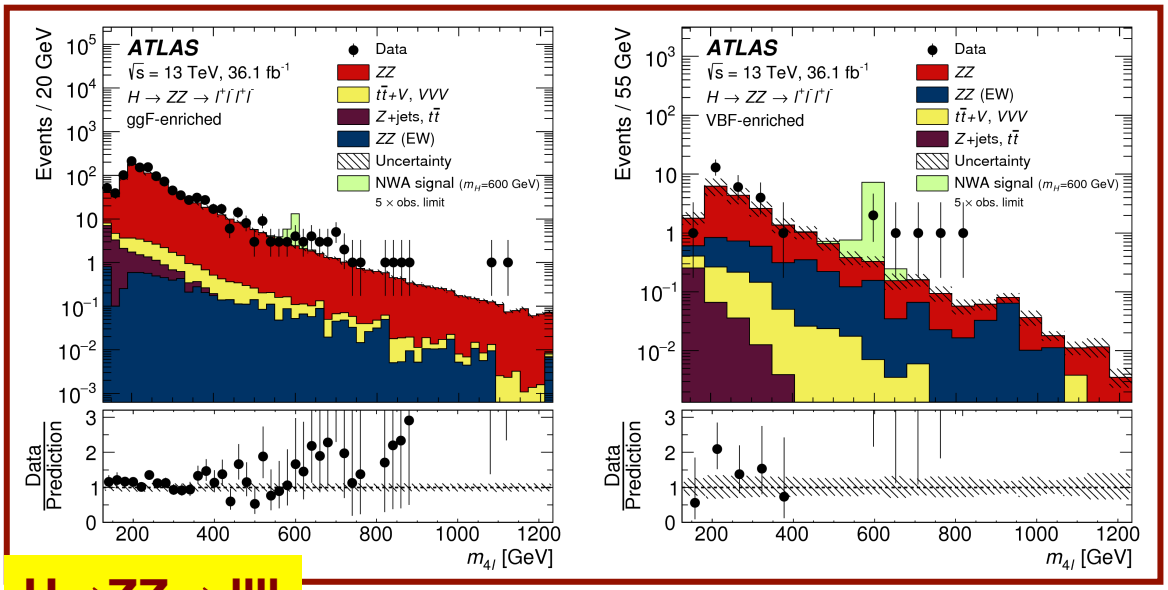
- Search for a high mass resonance in
  - ZZ→4l or 2l2ν
- Dedicated ggF and VBF categories

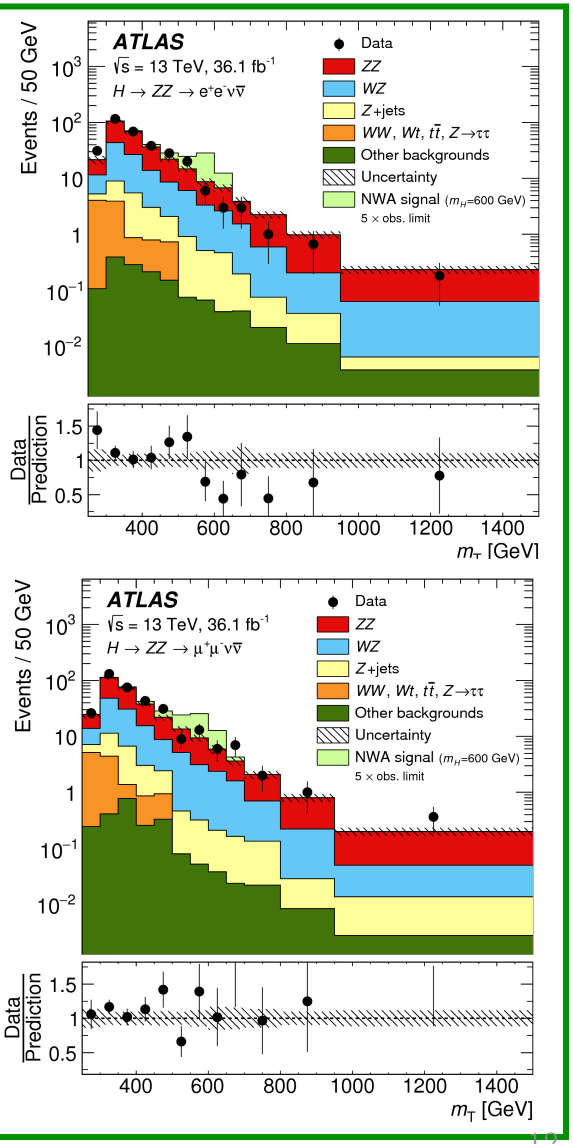
ZZ→2l2ν final discriminant:

$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

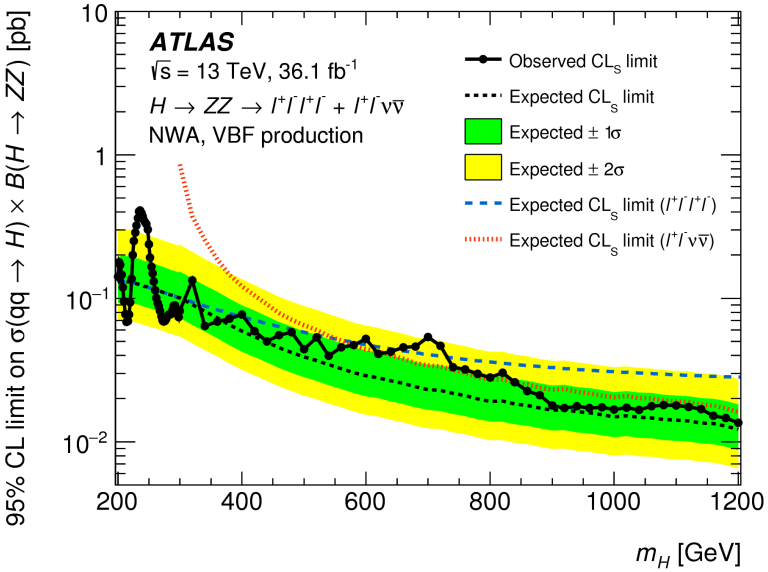


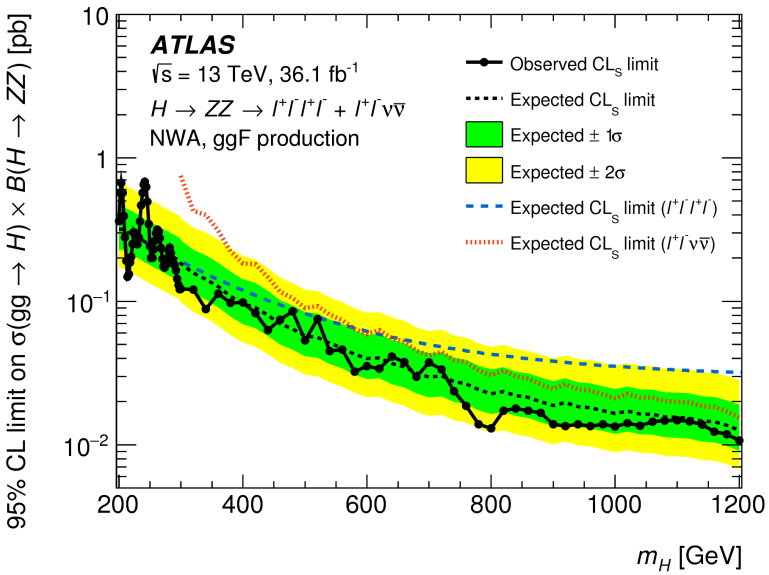
H→ZZ→ llll

H→ZZ→ llνν

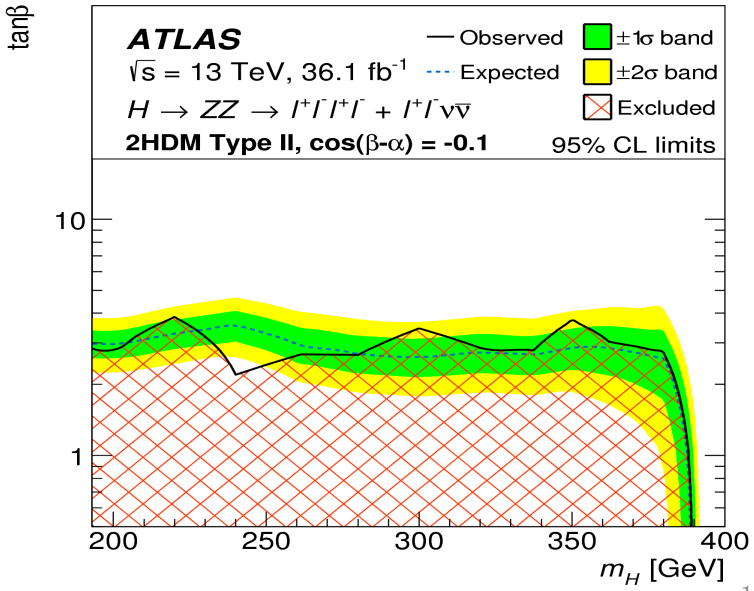


H→ZZ→ llll or llνν





- Excess (~2σ) around 250 GeV
- Different Higgs width (1, 5, 10 %) considered
- Results interpreted for various models



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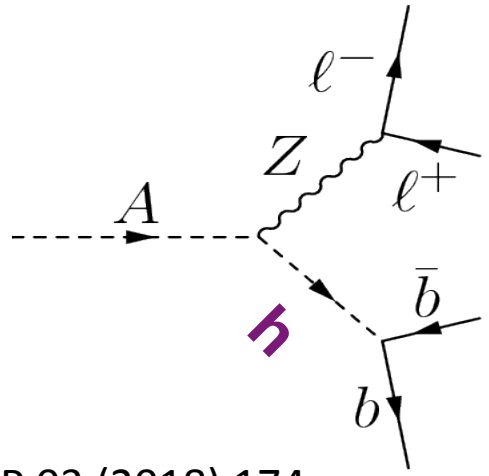
A→Zh→ll/νν bb

- CP odd Higgs boson A→Zh→ll/νν bb
  - h: 125 GeV SM-like Higgs
- Production modes: ggA and bbA



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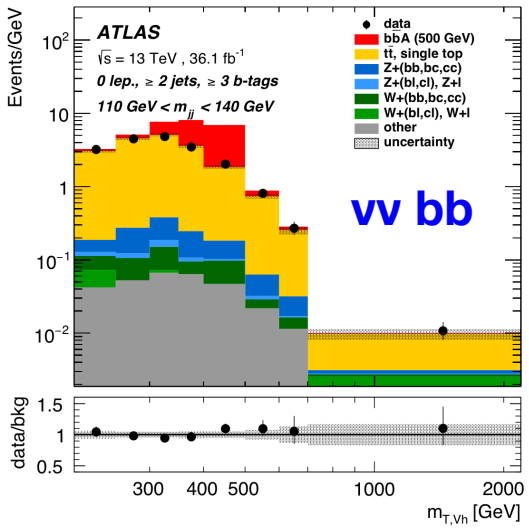
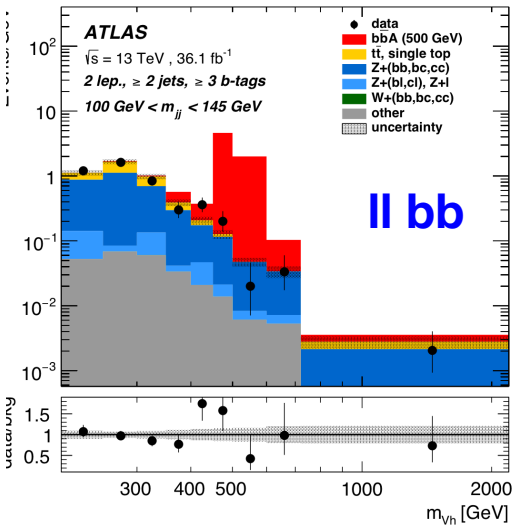
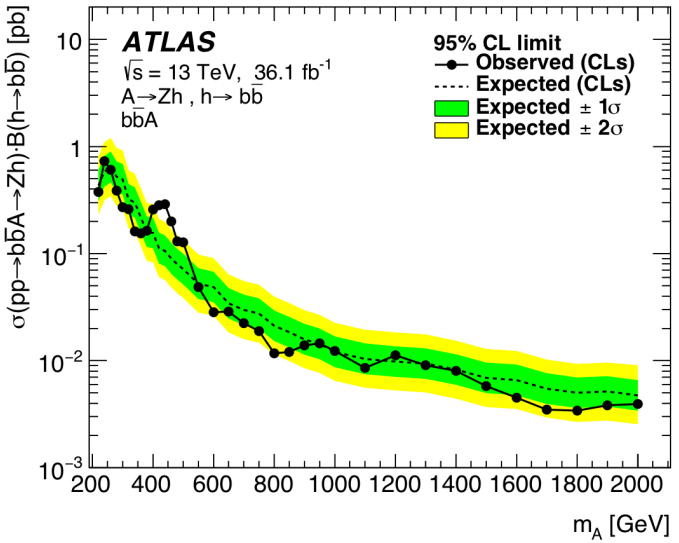


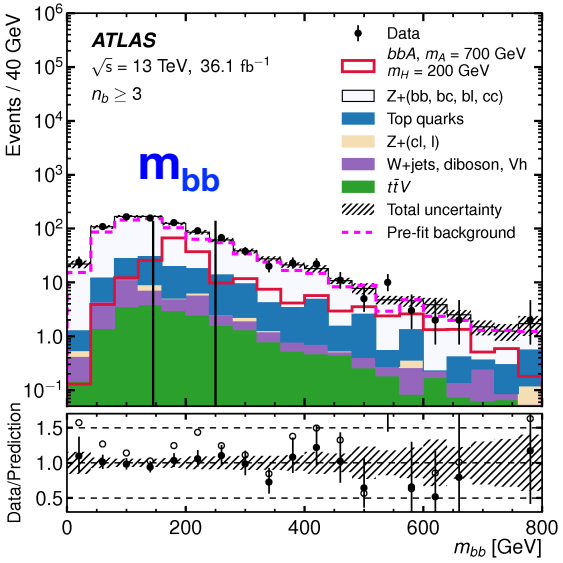


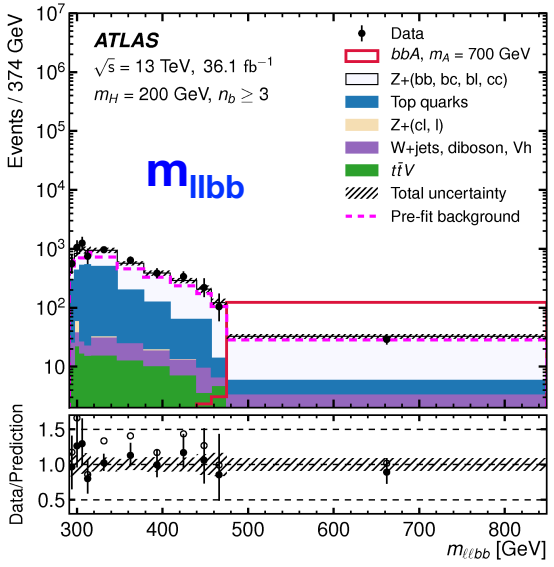


A→Zh: minor excess observed around 400 GeV

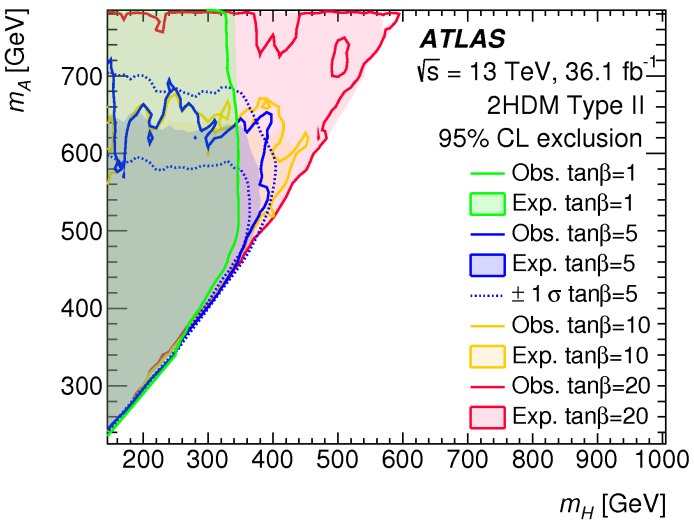
A→ZH→llbb

- Relax the mass degeneracy, by assuming $m_A > m_H$
  - H is the heavy CP-even Higgs
- Searches performed by scanning both m_A and m_H





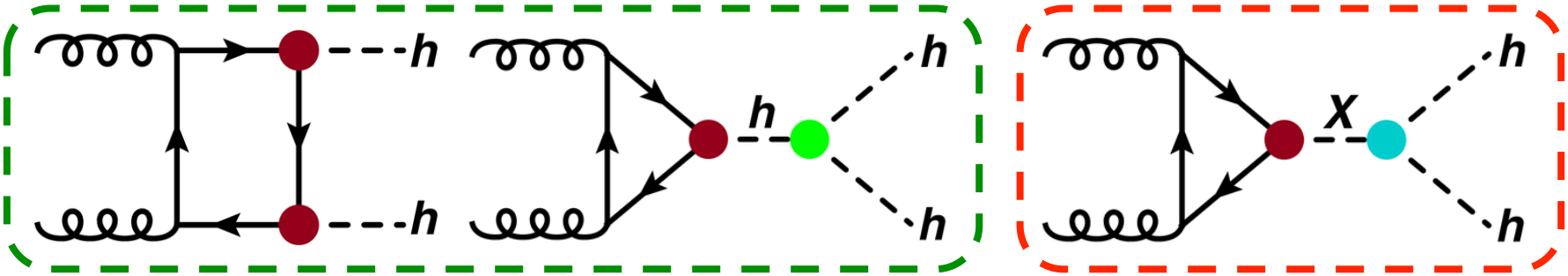
m_H=200 GeV, as example



arXiv: 1804.01126

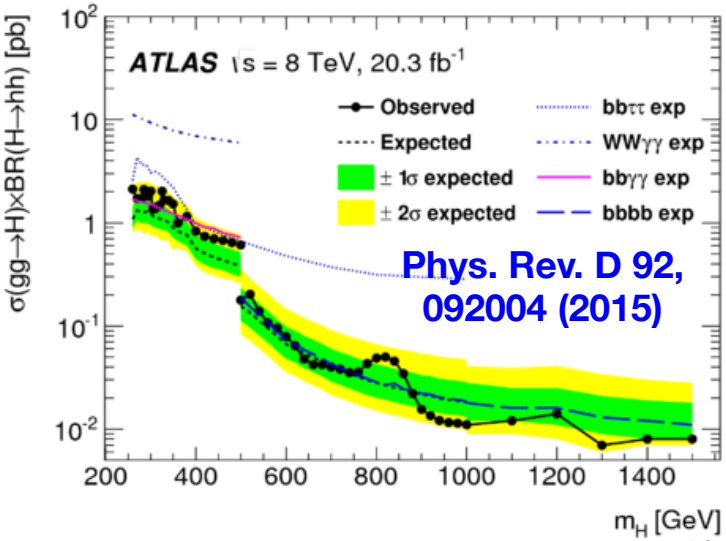
Double Higgs production

- Extremely small SM expectation (31 fb @ 13 TeV)
  - Important for measuring the Higgs self-coupling



Significantly enhanced in BSM

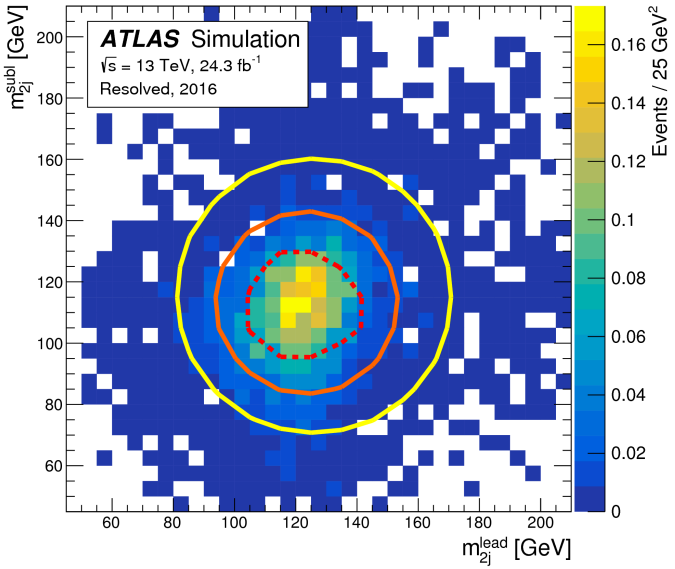
- **Resonant enhancements**
  - KK-graviton, Heavy Higgs in 2HDM
- **Non-resonant enhancements**
  - Change λ_{hhh}, etc.

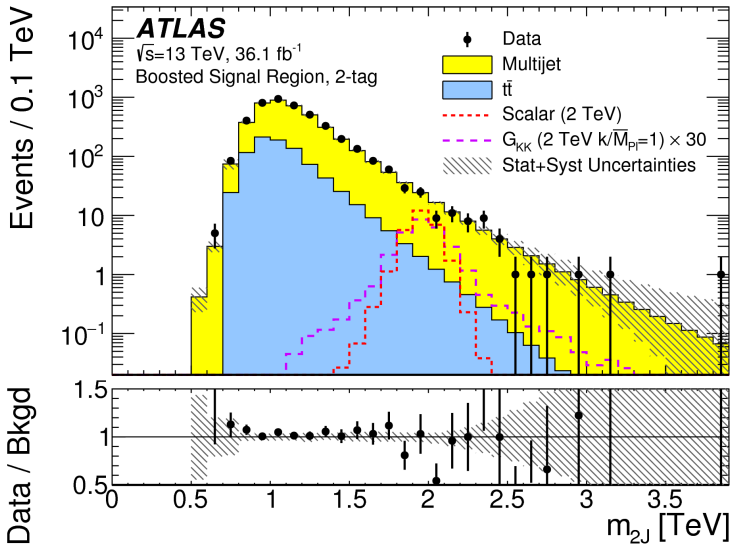


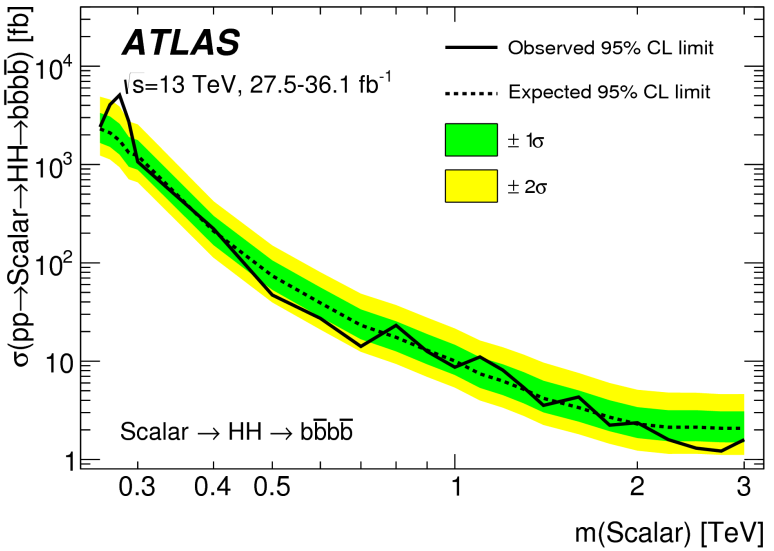
Di-Higgs search: bbbb

arXiv:1804.06174

- Resolved and boosted categories
  - According to H→bb topology
- Selection: 2D of di-jet (fat-Jet) mass
  - Multi-jet determined from the sideband region







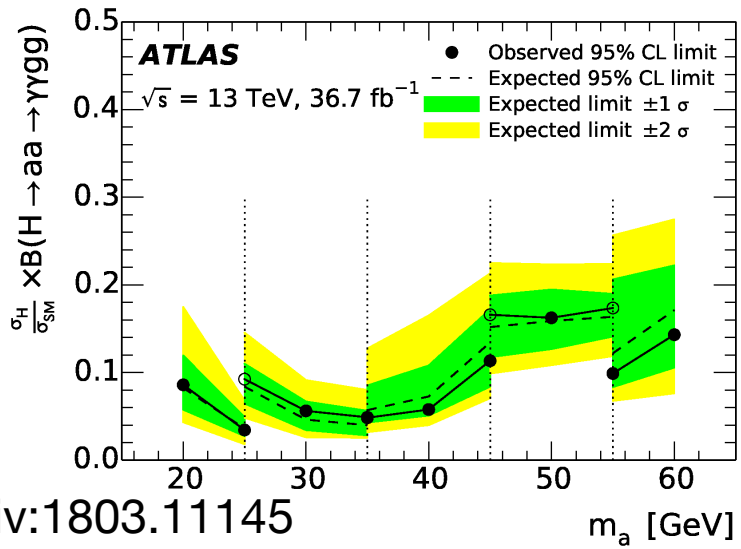
✧ **Non-Res: observed limit is 13×SM**

Higgs rare or exotic decay

Existing measurements constrain the non-SM Higgs boson decay Br<~30%

h→aa→γγjj

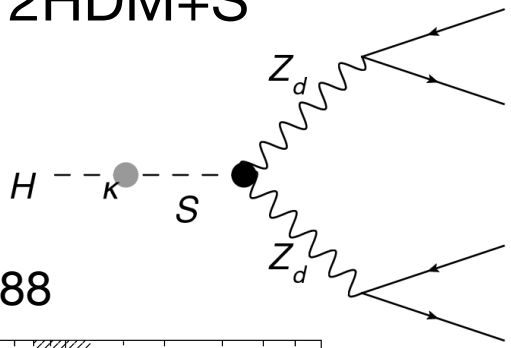
- Light scalar motivated by 2HDM+S: a→γγ or gg
- VBF to suppress γγ+multi-jet background
- Optimized in different mass ranges



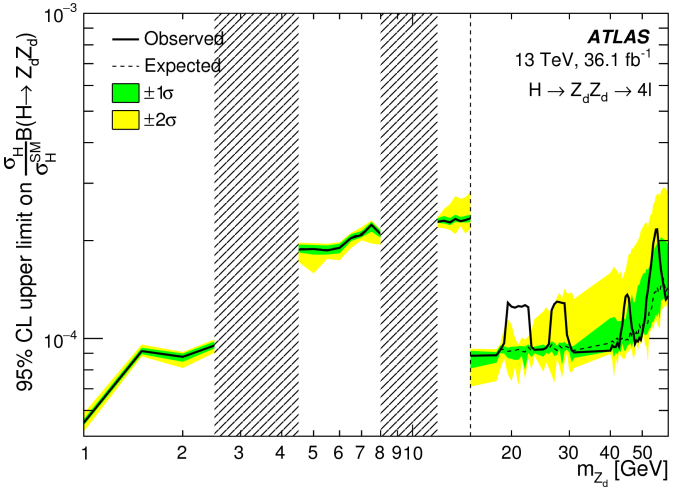
arXiv:1803.11145

h→Z_dZ_d→4l

- Light gauge bosons in dark-sector U(1) group or pseu-doscalar in 2HDM+S

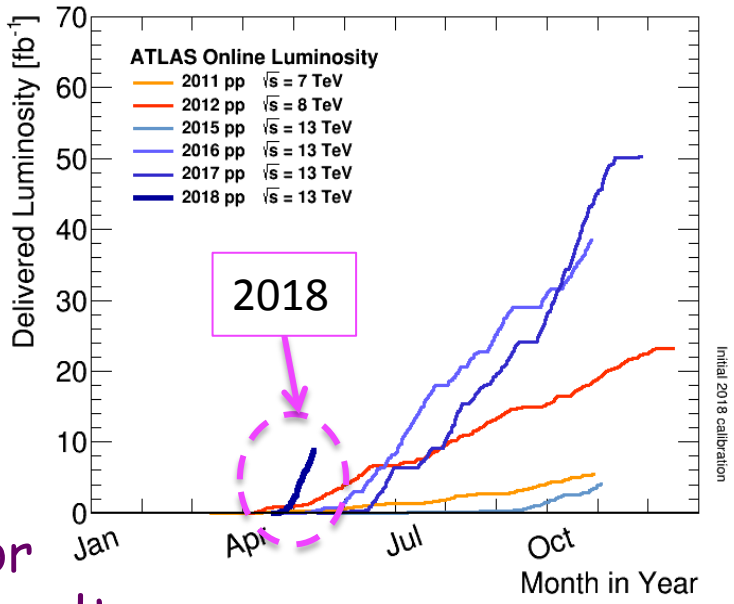


arXiv:1802.03388

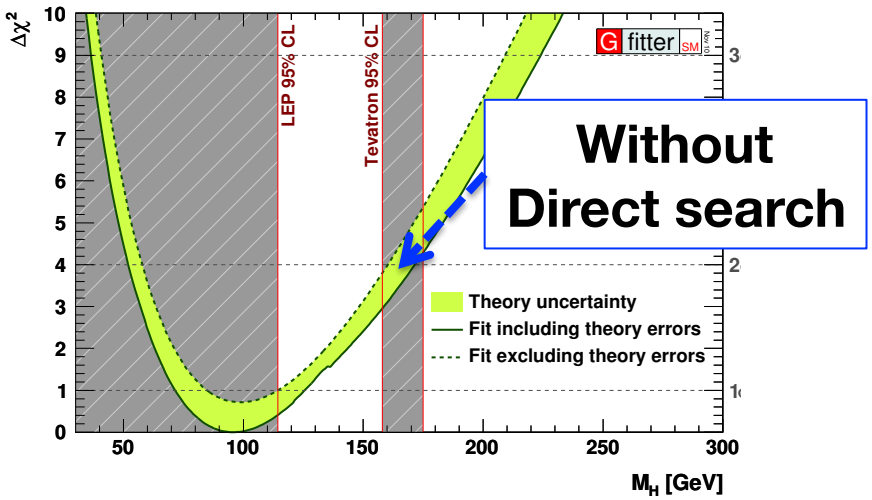


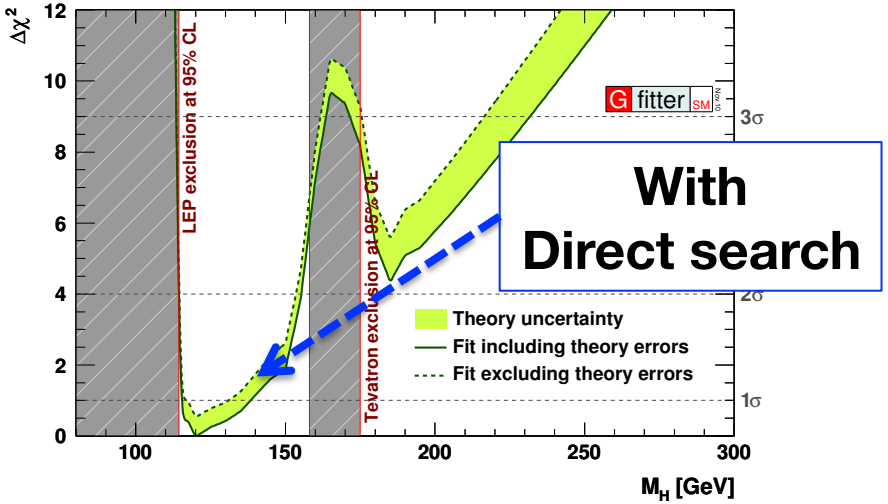
Summary

- Exotic Higgs searched extensively at ATLAS, large BSM parameter space suppressed
- ~3 times more data will be collected by the end of 2018, more exciting results ahead.



Ask not what the negative results can do for you, ask what you can do for the negative results



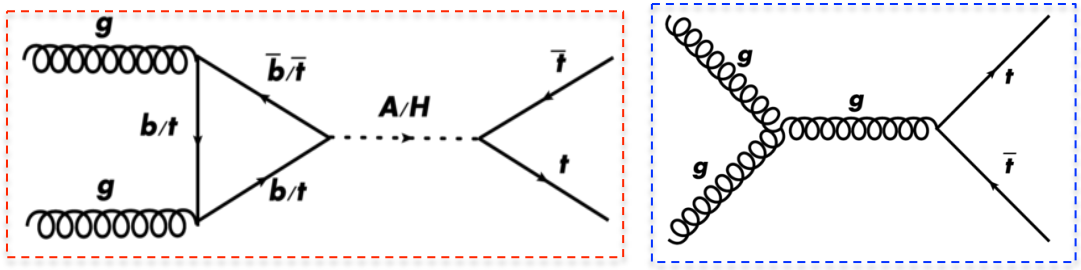


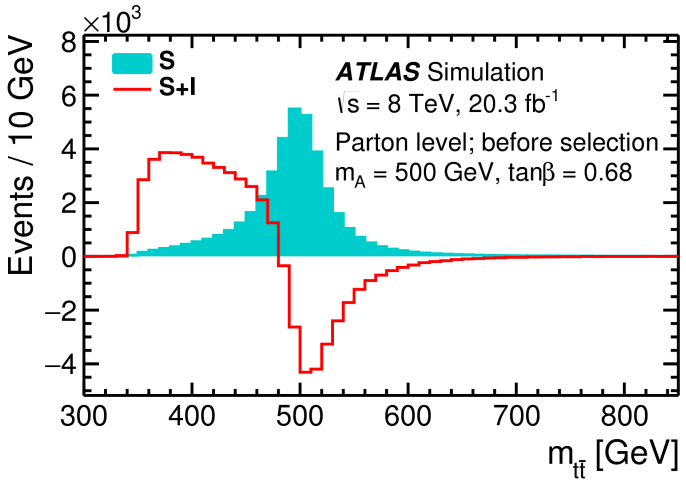
Andreas Hoecker's talk, at **2010**, Challenges for Precision Physics at the LHC

Thank you!

A/H→ttbar

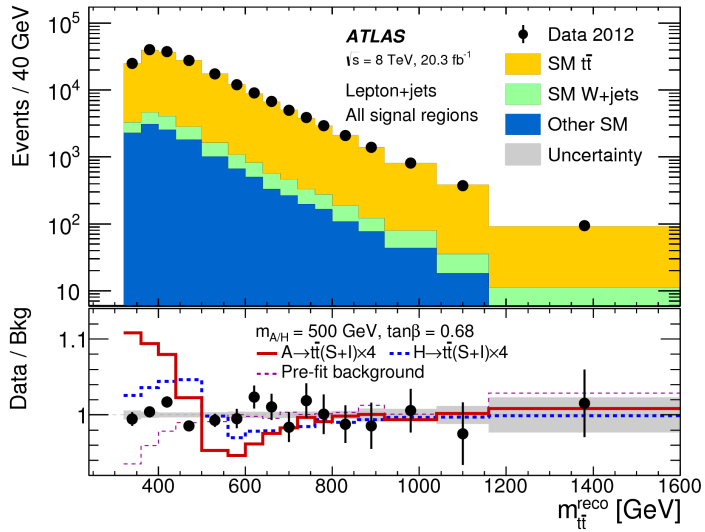
- Re-interpretation of 8 TeV semi-leptonic ttbar analysis
- Peak-dip signature: Interferes with SM ttbar production





- Limits on tan β set for various mass in the 2HDM-II alignment limit points

Mass [GeV]	tan β:	m_A obs.	m_A exp.	m_H obs.	m_H exp.	$m_A = m_H$ obs.	$m_A = m_H$ exp.
500		< 1.00	< 1.16	< 1.00	< 0.77	< 1.55	< 1.50
550		< 0.69	< 0.79	< 0.72	< 0.52	< 1.10	< 0.92
600		–	< 0.59	< 0.73	–	< 1.09	< 0.93
650		–	–	–	–	–	< 0.62

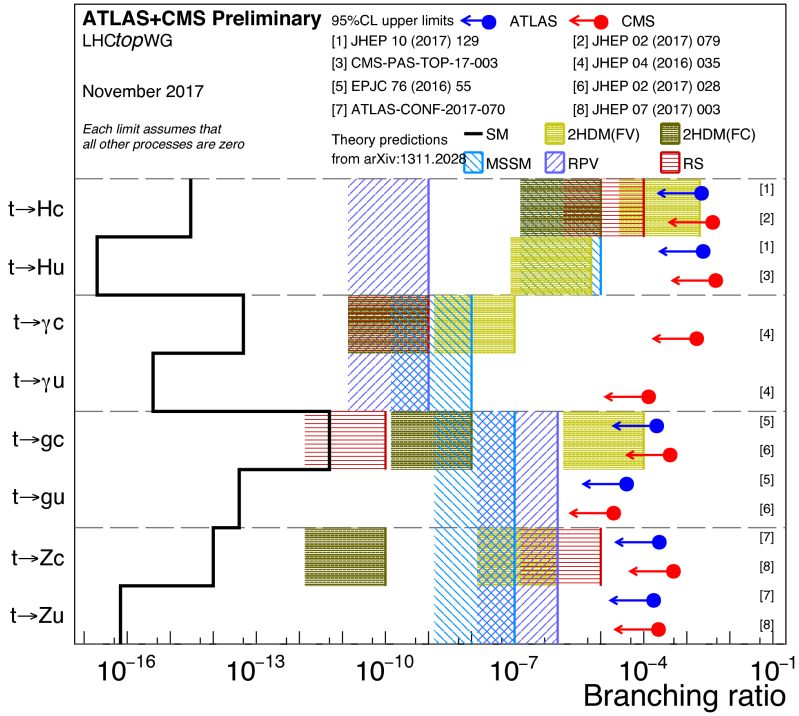


Note: "-" means no exclusion for tanβ>0.4

Flavour Changing Neutral Current

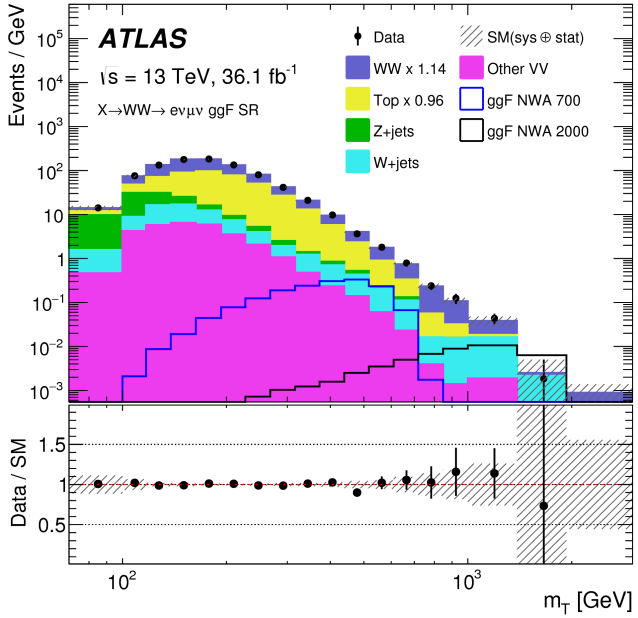
- FCNC highly suppressed in SM, but get enhanced in many BSM models, 2HDM, SUSY, Extra Dim, etc
- Search for flavor changing neutral current in top decays using 36.1 fb^{-1} with $t \to qh$ q=c,u, $h \to \gamma\gamma$

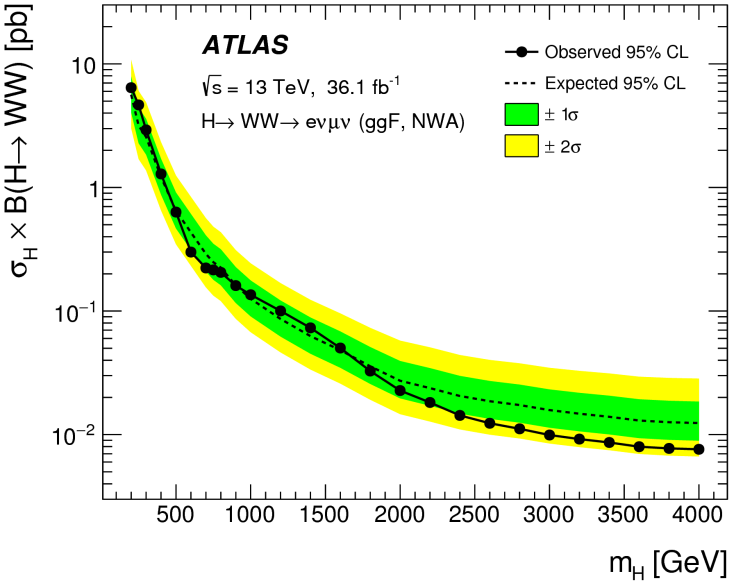
- $t \to ch$ branching ratio of 2.2×10^{-3} at 95% C. L.
  - Corresponding limit on tcH coupling is 0.09
- Limit on $Br(t \to uh)$ 2.4×10^{-3}

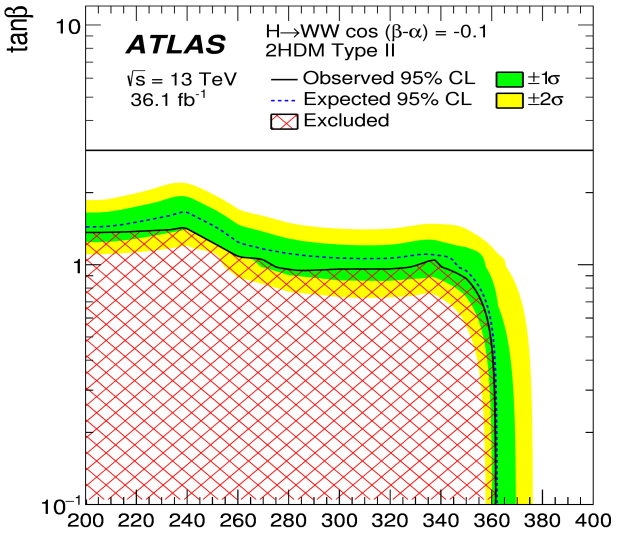


H→WW→evμv

- High mass resonance in WW→evμv
  - 3 categories: ggF, VBF1J, VBF2J
- WW and Top backgrounds
  - Determined from control regions
- Interpreted in 11 different scenarios







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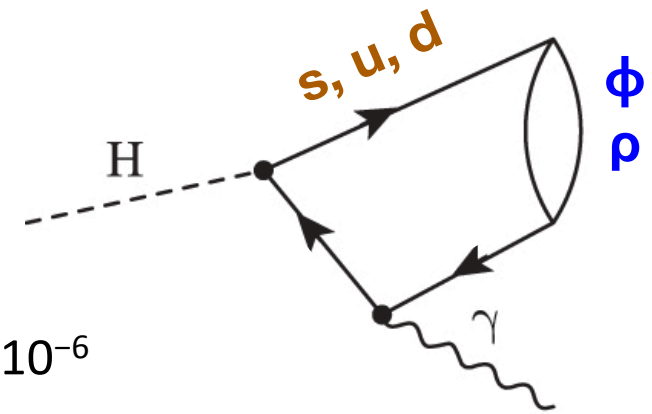
h→γρ and γϕ

h→γρ and γϕ

- SM h→γγ (γ*→ρ/ϕ) dominant
- Probe modified Yukawa coupling of 1st or 2nd generation quarks



B(H→γρ/ϕ)

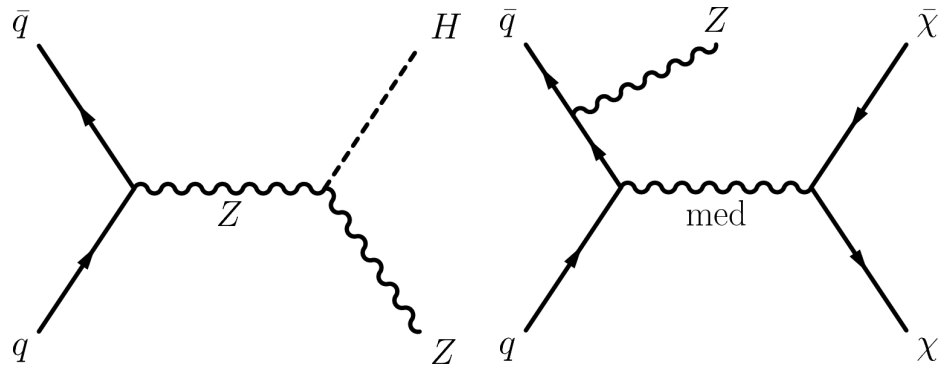
- Obs: (8.8/4.8) ×10^{-4}, SM: (2.3/17) ×10^{-6}

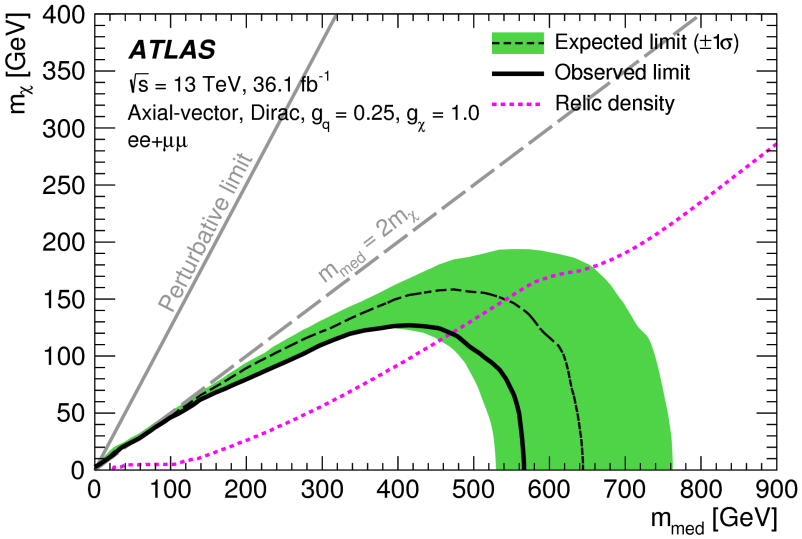
arXiv: 1712.02758

Higgs decay to invisible

PLB 776 (2017) 318

- Method: tag Z→2l





Obs (Exp) upper limit of Br(H→inv) < 67% (39%)

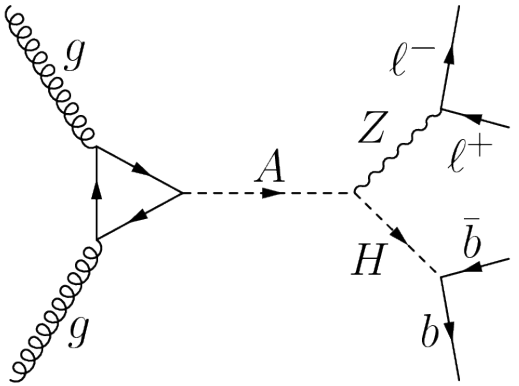
- Summary of all available results

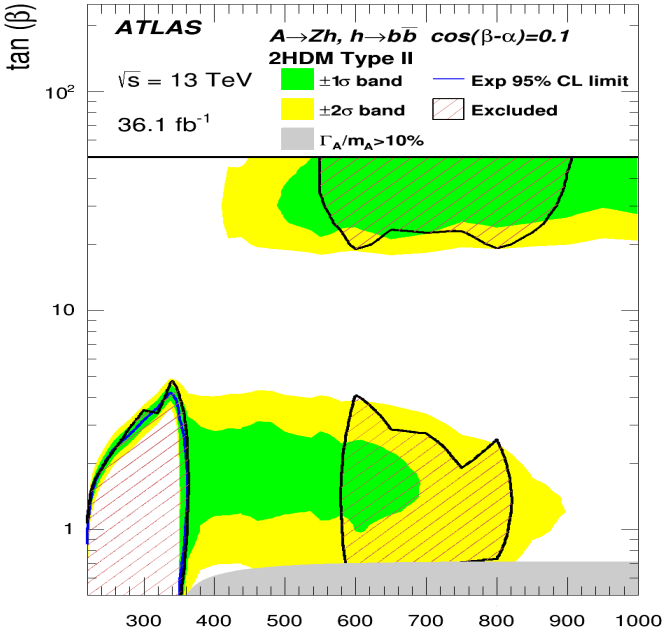
95% CL upper limits on $\mathcal{BR}(H \to \text{inv})$ from Run I and Run II data

Channel	ATLAS		CMS	
$Z(\ell\ell)H$	0.67	36.1 fb^{-1}	0.40	35.9 fb^{-1}
$V(\text{had}) + E_{\text{T}}^{\text{miss}}$	0.78	20.3 fb^{-1}	0.49	35.9 fb^{-1}
Mono-jet	1.59	20.3 fb^{-1}	0.74	35.9 fb^{-1}
VBF	0.28	20.3 fb^{-1}	0.28	35.9 fb^{-1}
Combined	**0.25**	4.7+20.3 fb^{-1}	**0.24**	35.9 fb^{-1}

A→ZH or Zh→llbb

- CP odd Higgs boson search in llbb final state
- Two analyses: A→ZH and Zh
  - h: SM-like Higgs
  - H: heavy CP-even Higgs
- Production modes:
  - Gluon fusion and b associated





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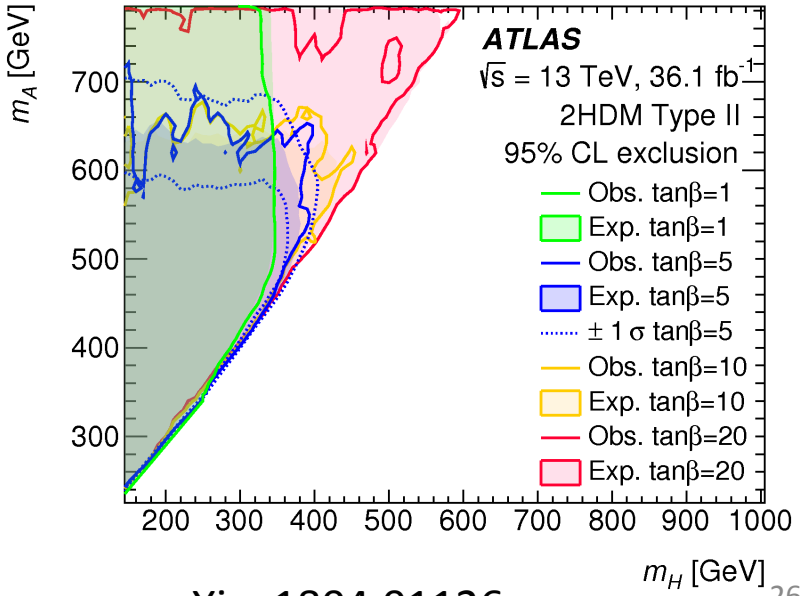
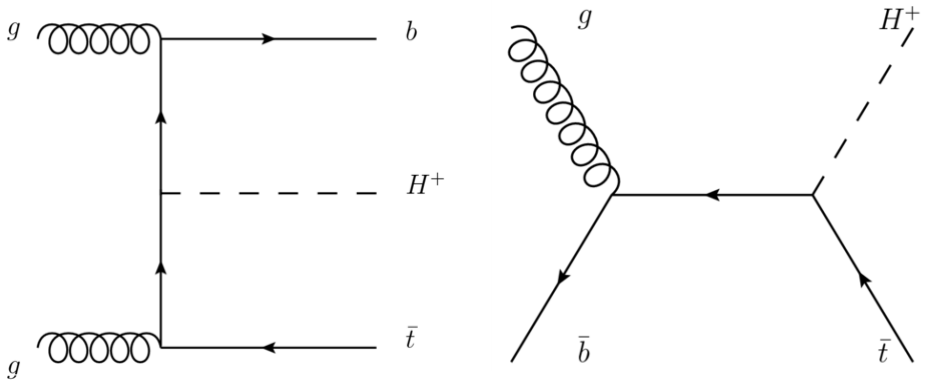


arXiv: 1804.01126

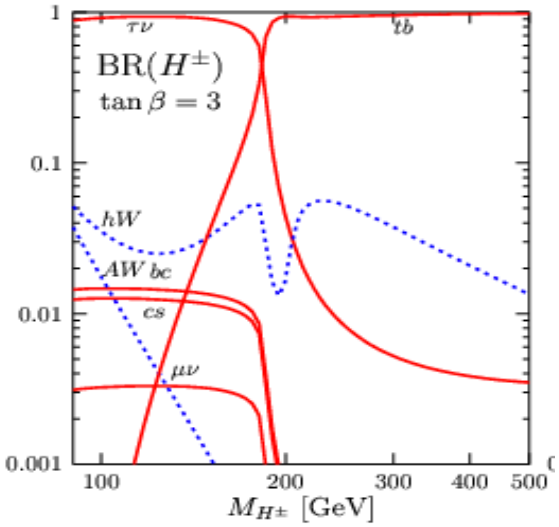
Charged Higgs

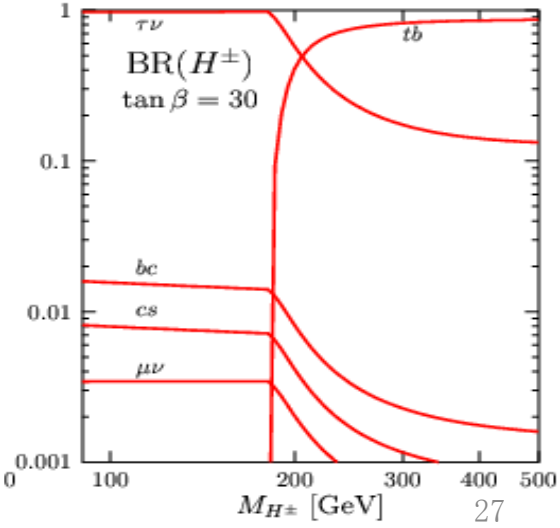
- Dominant production is in association with top quarks in most benchmark models



Decay mode in type-II 2HDM

- $H^{\pm} \rightarrow tb$ at high mass
- $H^{\pm} \rightarrow \tau\nu$ at high tan β





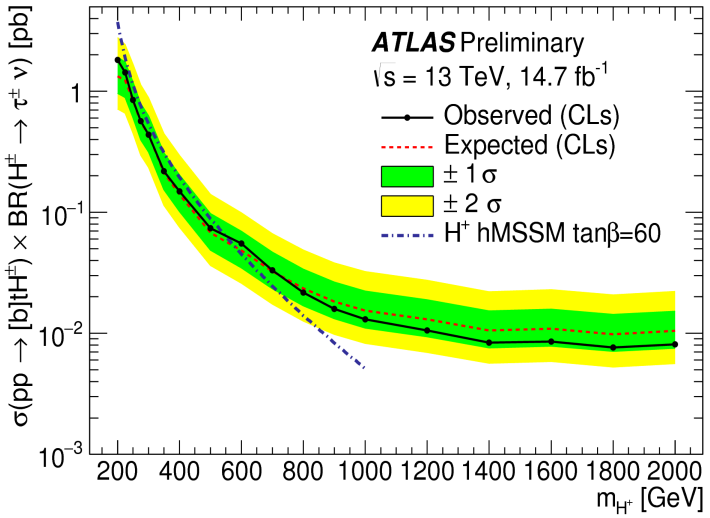
$H^{+} \rightarrow tb$ with 13 fb^{-1} in ATLAS-CONF-2016-089

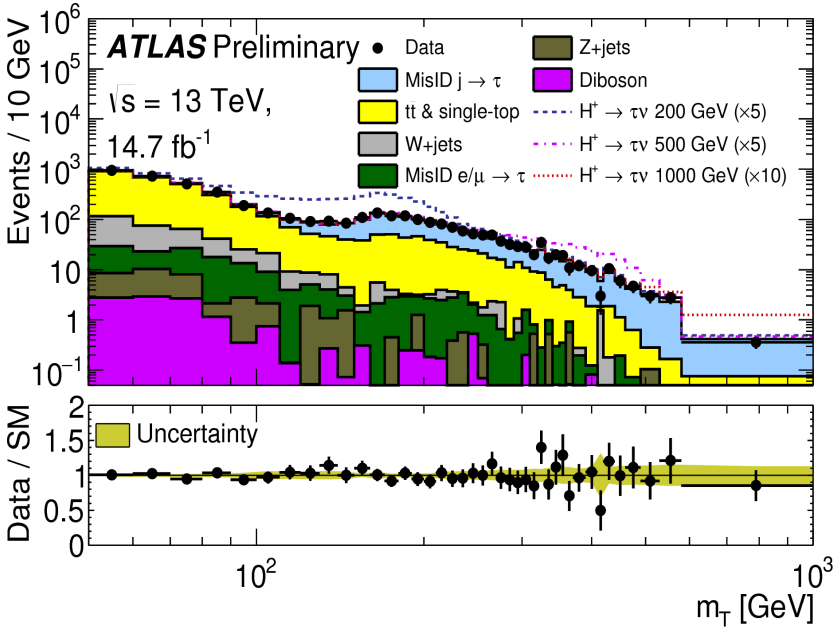
$H^+ \to \tau\nu$ search

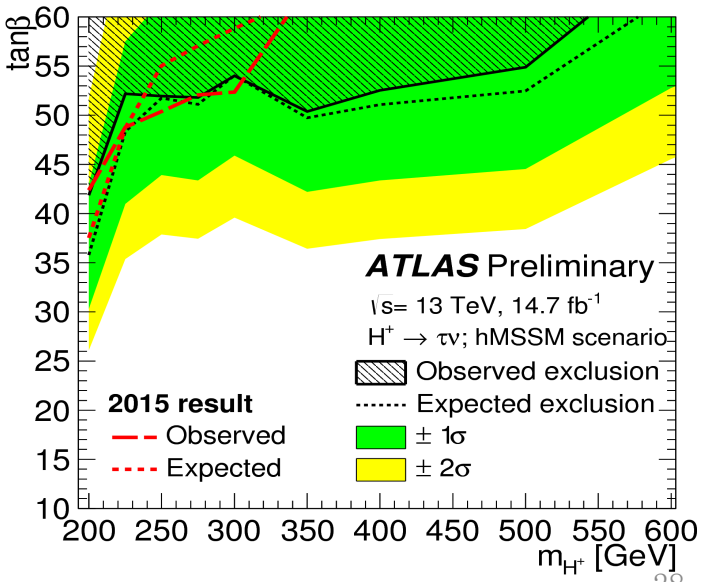
ATLAS-CONF-2016-088

Event selection

- High p_T τ_{had} and large E_T^{miss}
- Hadronic top quark (3 jets, ≥1 b-jet)

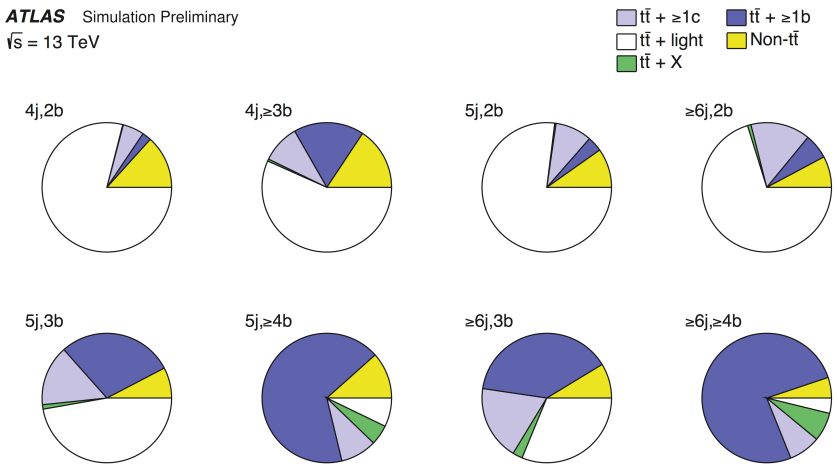


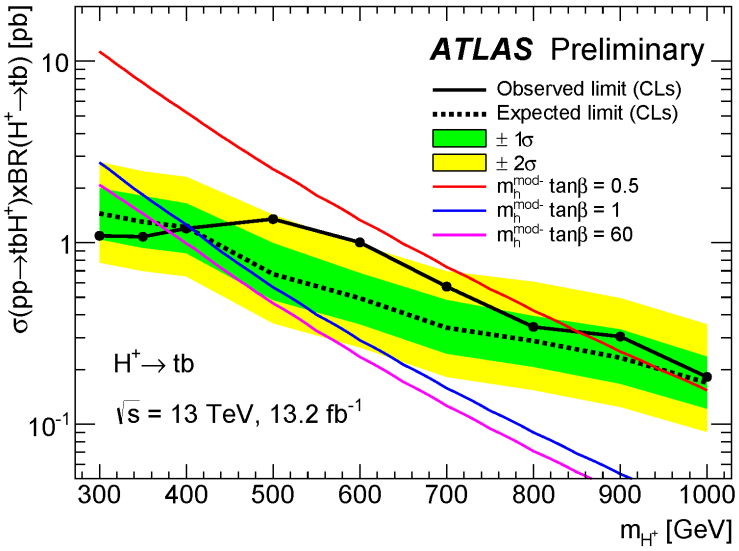


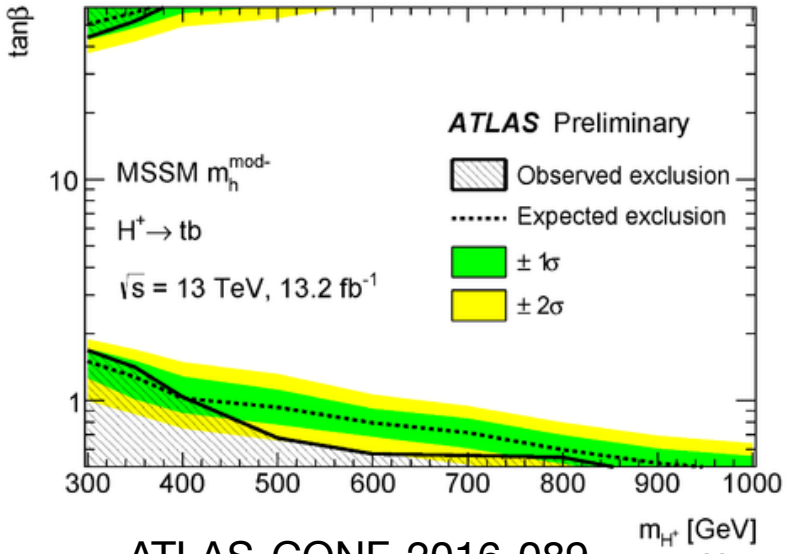


$H^+ \rightarrow tb$

- Signature: ttbar+1/2 b
- Multivariate analysis method (BDT) used
- Event categorization w.r.t. number of b-jet

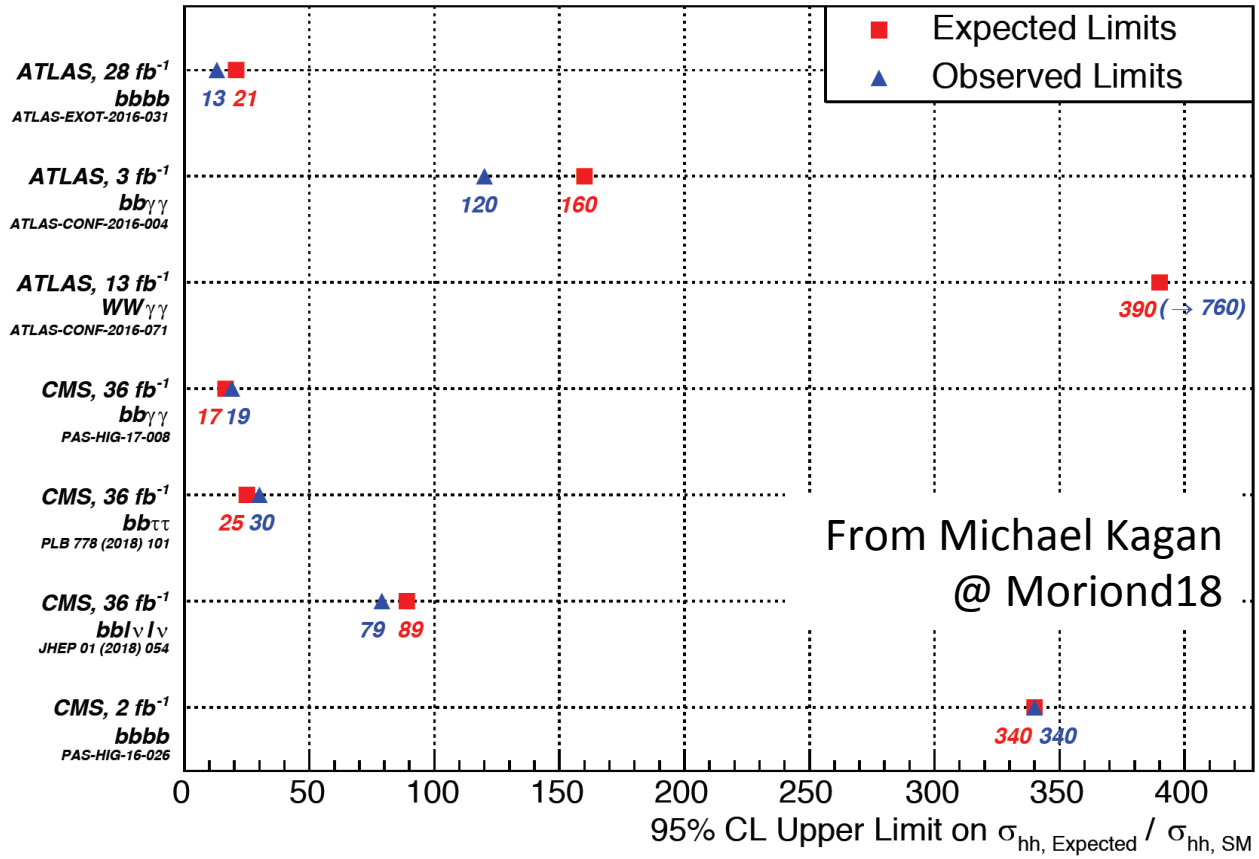






ATLAS-CONF-2016-089

Di-Higgs: non-resonance summary



- Best channel limits on anomalous trilinear coupling: [-8, 15]

For 2HDM electroweak baryogenesis to occur [8, 23], the requirement mA > mH is necessary for a strong first-order phase transition to take place in the early universe. The A boson mass is also bounded from above to be less than approximately 800 GeV, whereas the lighter CP-even Higgs boson, h, is required to have properties similar to those of a Standard Model (SM) Higgs boson and is assumed to be the Higgs boson with mass of 125 GeV that was discovered at the LHC.