Searches for Exotic Higgs Boson Production at CMS and ATLAS

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ATLAS EXPERIMENT

CMS

On behalf of the ATLAS and CMS Collaborations

Searches for Exotic Higgs

Talk outline:

- The Higgs Boson (h) was discovered 7 years ago. Measurements so far in line with Standard Model (SM) predictions.
- We know that the SM gives an **incomplete description** "hierarchy problem" ($m_h << m_{Planck}$), matter-antimatter asymmetry and dark matter
- Higgs mechanism provides a window to **Beyond the Standard Model (BSM) physics**
- Many BSM theories available including **extra Higgs doublets, composite Higgs, extra dimensions, Higgs portals to dark matter etc..**
- At the LHC we search for these **additional Higgs bosons** over a wide **mass range** (from low $m_H < 125$ GeV to as high as possible)**,** testing different **mass hierarchies/couplings etc.**

Results:

- Based on **results of data analyses from ATLAS and CMS** with LHC **pp collisions at 13 TeV** (+8, 7 TeV), typically **~36 fb^{-1}**
- In some cases full Run 2 statistics: **13 TeV, 139 fb^{-1}** selection based on results issued in the ~last year
- *Due to time constraints can only show a selection of results with a focus on the most recent ones*

Talks at HC2019:

- Search for additional low-mass (m<125 GeV) Higgs bosons at CMS, *M.A. Shahzad*
- Searches for BSM Higgs at ATLAS, *S. Farrington*
- *Plus: Searches for exotic visible Higgs boson decays at CMS and ATLAS , M. Kolosova*

2 Higgs Doublet Models

- A simple, viable and theoretically well motivated model is the **Two Higgs Doublet Model, ϕ_1, ϕ_2**
- **4 types** arise that satisfy observation of no Flavour Changing Neutral Currents
- Yukawa couplings depend on parameters **tanβ = v2/v1** ratio of vacuum expectation values, **α mixing angle** of CP even scalar bosons plus 4 masses of Higgs bosons:
- *Higgs Bosons: scalar **h**, scalar **H**, pseudo-scalar **A** and charged **H***
- ***125 GeV boson = h*** and for this SM like ***h* => cos(α-β) = 0 *alignment limit***

Example: Yukawa couplings for H normalized to those of h(SM)

Type	λ_{ii}^U	λ_{ii}^D	λ_{ii}^L	
I	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$	(fermiophobic)
II	$1/\tan\beta$	$-\tan\beta$	$-\tan\beta$	(MSSM)
III/Y	$1/\tan\beta$	$-\tan\beta$	$1/\tan\beta$	(flipped)
IV/X	$1/\tan\beta$	$1/\tan\beta$	$-\tan\beta$	(Lepton specific)

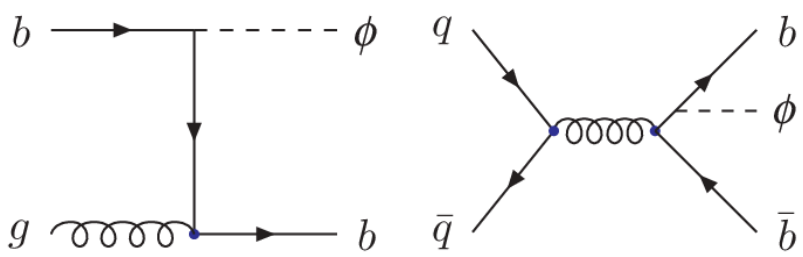
- High **tanβ**
- *ττ* -> type II and X, ATLAS: JHEP01(2018)055, CMS: JHEP09(2018)007 on 36 fb^{-1} of Run 2 data, stringent limits on MSSM and Z' phase space
- *bb* -> type II and Y. Also enhanced b-associated production wrt SM
- Low **tanβ**
- *tt* -> all types

Search for Heavy H in b(b)H→bb

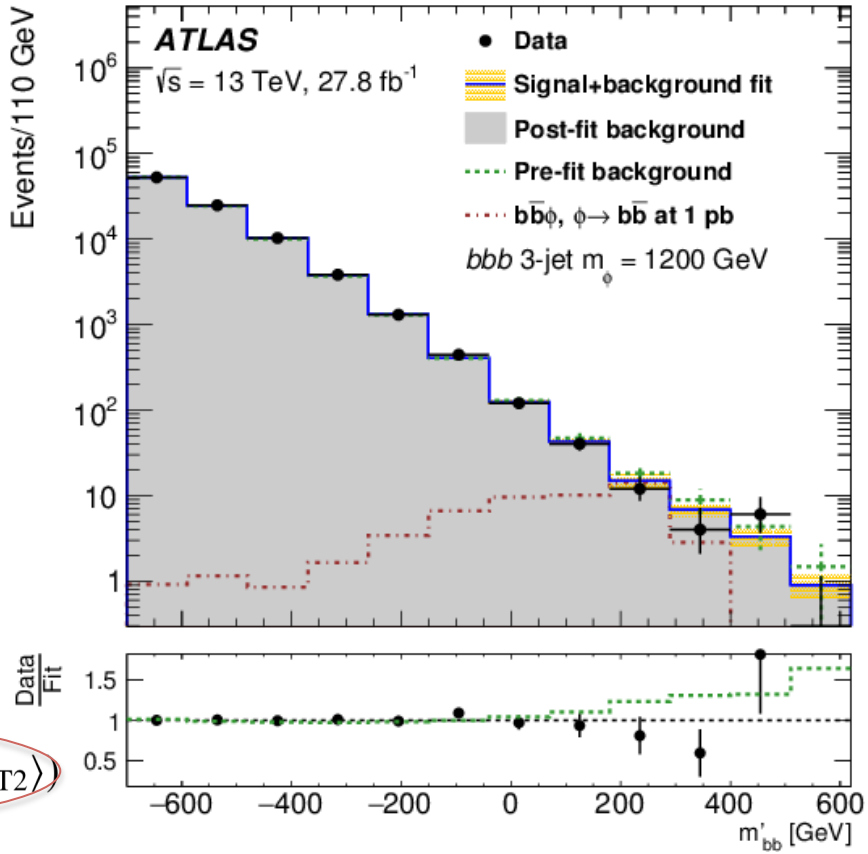
CMS: JHEP08(2018)113

ATLAS: arxiv:1907.02749

sensitive to type II and flipped, for high tanβ



- ATLAS search for a scalar φ [A/H] produced in association b-quark(s) with ***28 fb^{-1} at 13 TeV***
- a selection for ≥3 b-jets **optimizes S/B**, events with only **2 b-tagged jets** used for **QCD Control Regions** and shape in signal region
- 3, 4 and ≥5 **jet signal regions**
- trigger based on high E_T *b*-tagged (1 or 2) jets
- ***p_{T1}, p_{T2}*** and ***m_{bb}*** are studied with a ***Principal Component Analysis*** for each mass point, ***m'_{bb}*** *used as discriminating variable in a binned maximum likelihood fit*

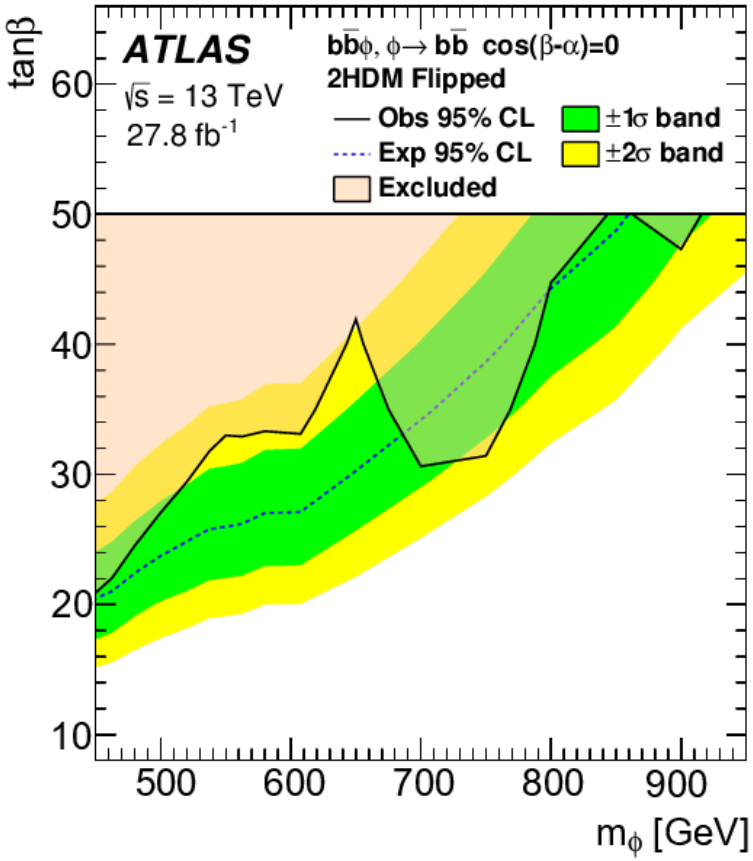


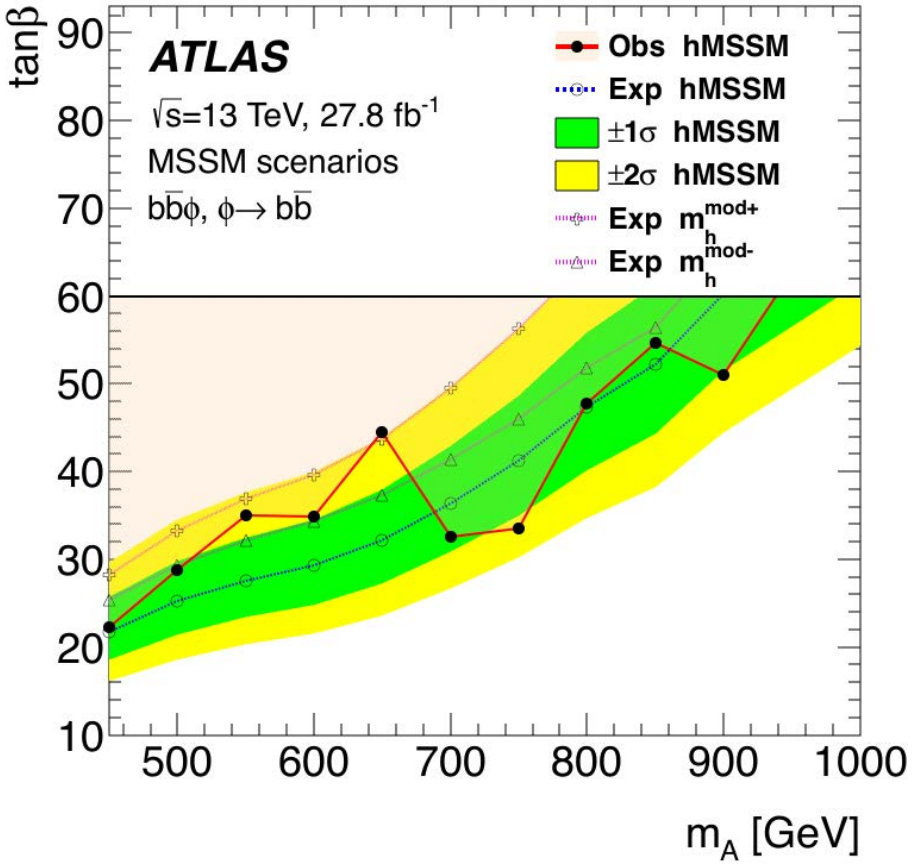
$$m'_{bb} = c_{m_{bb}}(m_{bb} - \langle m_{bb}\rangle) + c_{p_{T1}}(p_{T1} - \langle p_{T1}\rangle) + c_{p_{T2}}(p_{T2} - \langle p_{T2}\rangle)$$

Search for Heavy H in b(b)H→bb

- ***Exclude*** $\sigma(pp \to b\bar{b}\phi) \times \mathcal{B}(\phi \to b\bar{b})$ ***< 4 - 0.6 pb in mass range 450-1300 GeV***

=> interpretation in **2HDM flipped** model and several **MSSM benchmark** scenarios



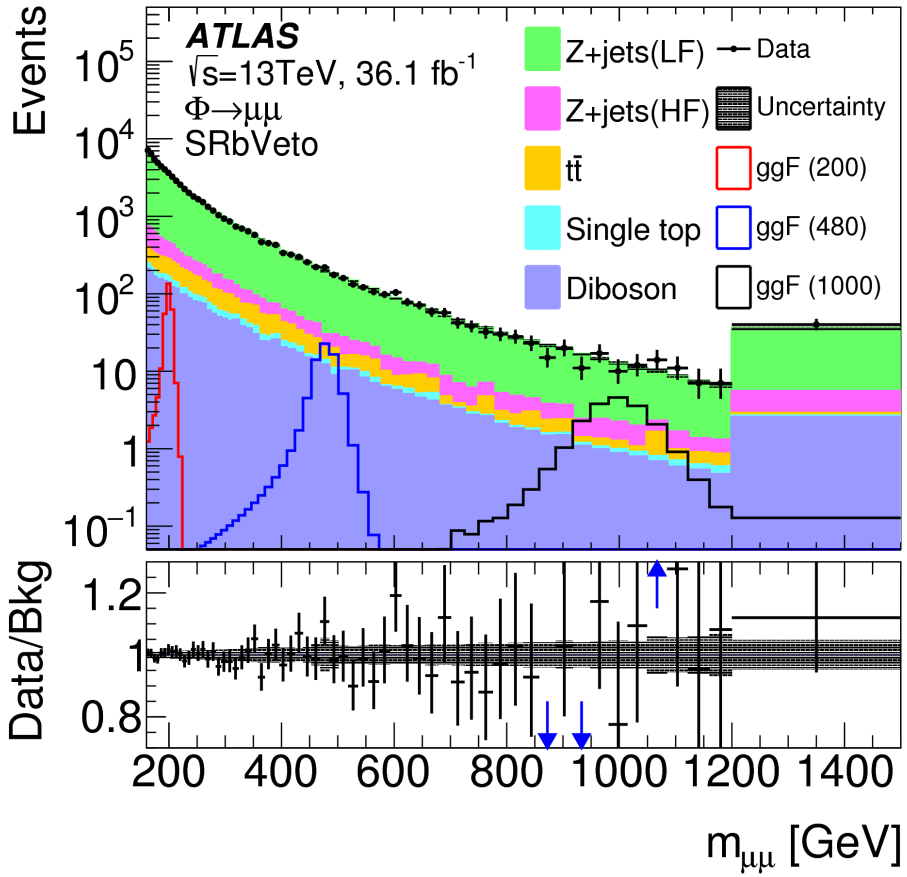


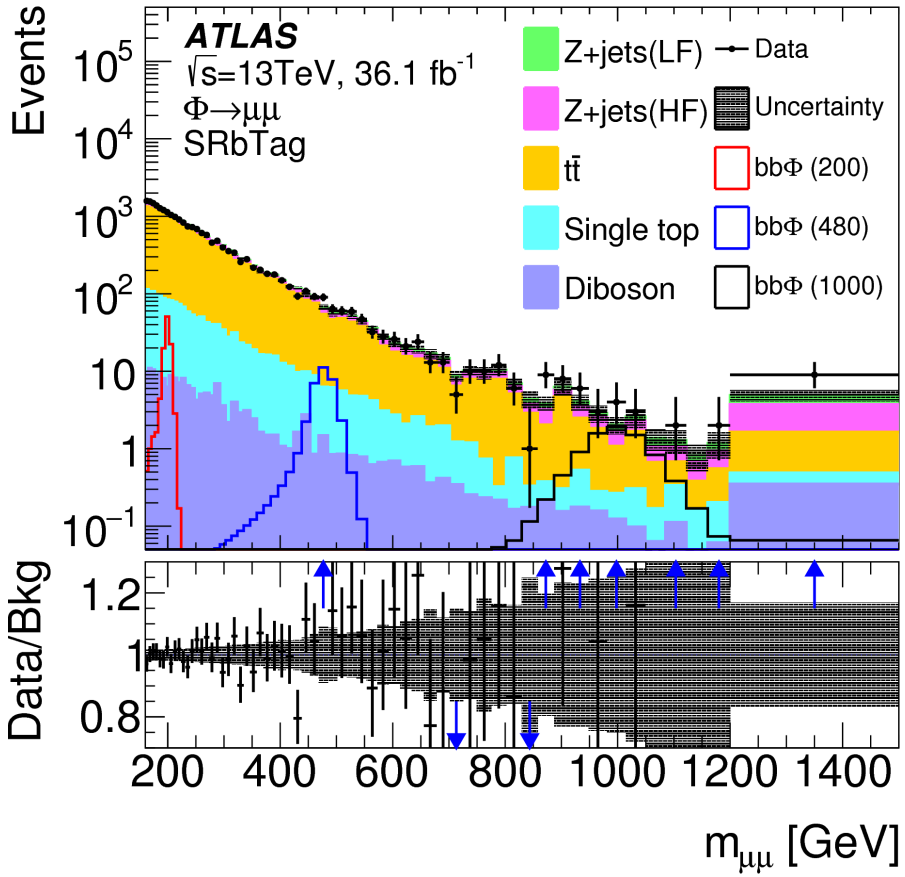
- **tanβ >50,60** not considered, since Higgs coupling becomes non-perturbative
- **hMSSM limits** comparable to $H^+ \to \tau\nu$ but less stringent than $\phi \to \tau\tau$ (see backup)
- **2HDM flipped** exclusion limits complement A->Zh and A->ZH searches

Search for Heavy H→μμ

ATLAS: JHEP07(2019)117

- H/A➛μμ is 300 times smaller than ττ but clear signature, similar kinematics. *A model independent analysis. Facilitate comparisons with MSSM, Z', Flavourful Higgs predictions*
- **b-associated** and **ggF** production modes **b-tag** and **b-veto** categories
- background from simulations + control regions(low $m_{\mu\mu}$) + low/high p_T^{miss}(bTag) for Z/ttbar
- Narrow width approximation for masses 0.2-1 TeV



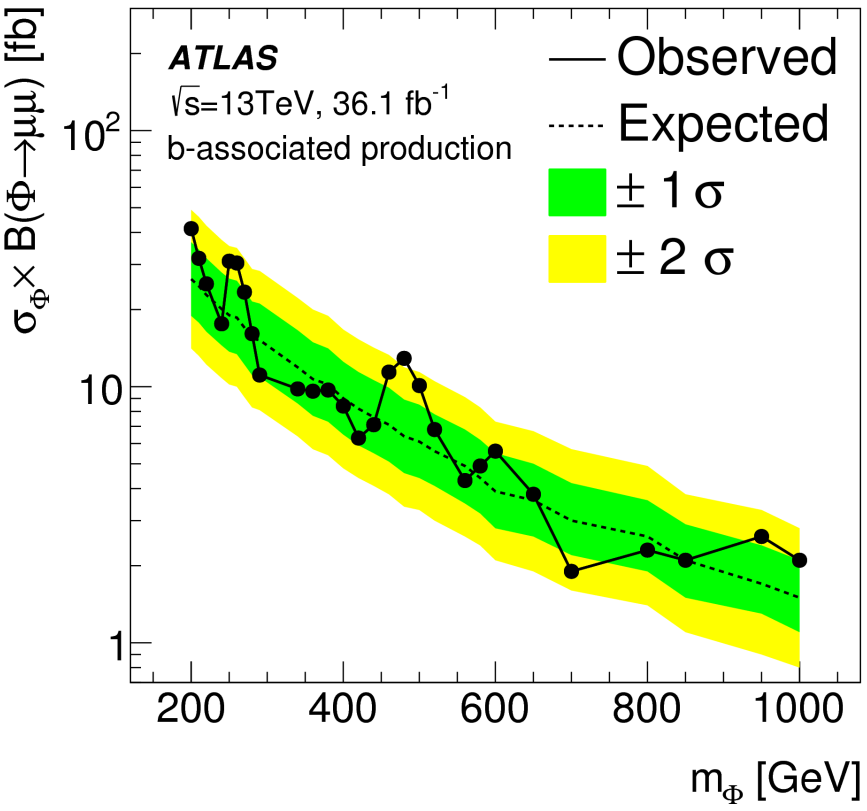


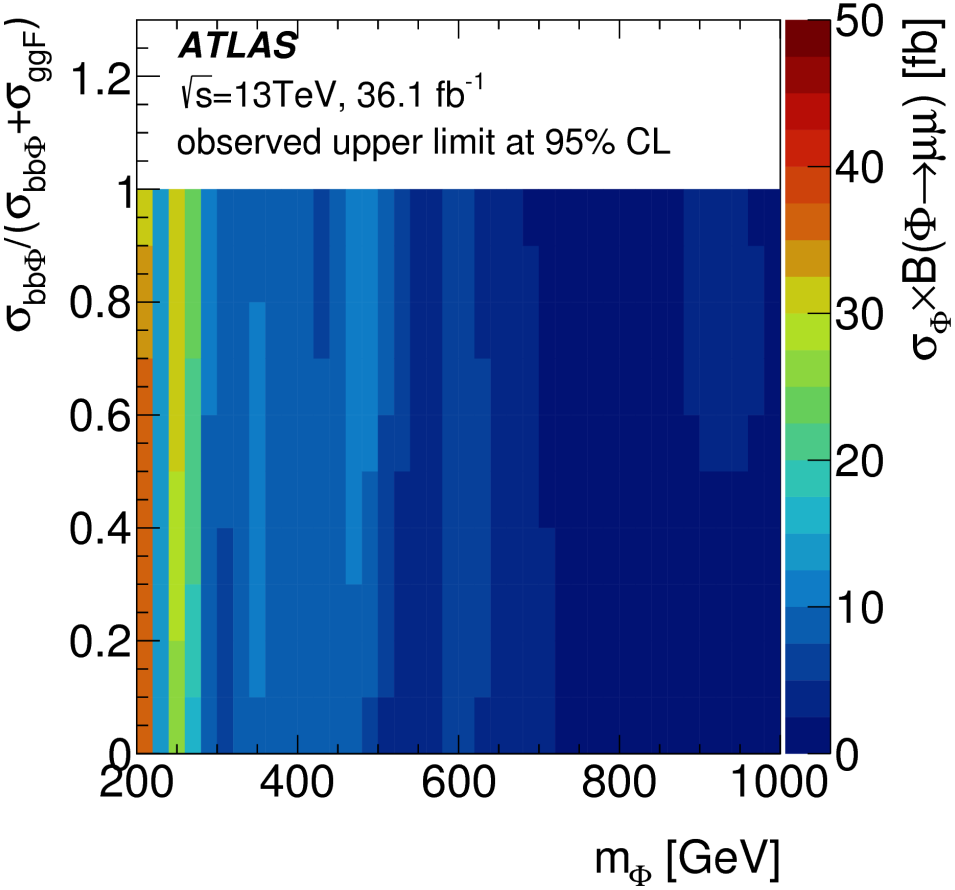
Search for Heavy H→μμ

ATLAS: JHEP07(2019)117

- Plot shows limit on cross section x BR versus mass for **b-associated** production. Similar limits also for **ggF** production mode
- Can also place limits on fractional contribution of b-associated production mode

Observed limits consistent with expected, **2.3σ** for **m_ϕ=480 GeV**, **0.6σ** after look-elsewhere effect

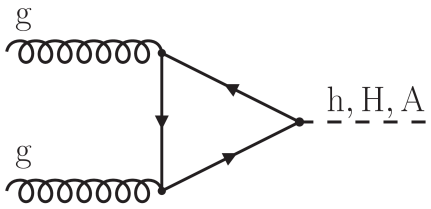




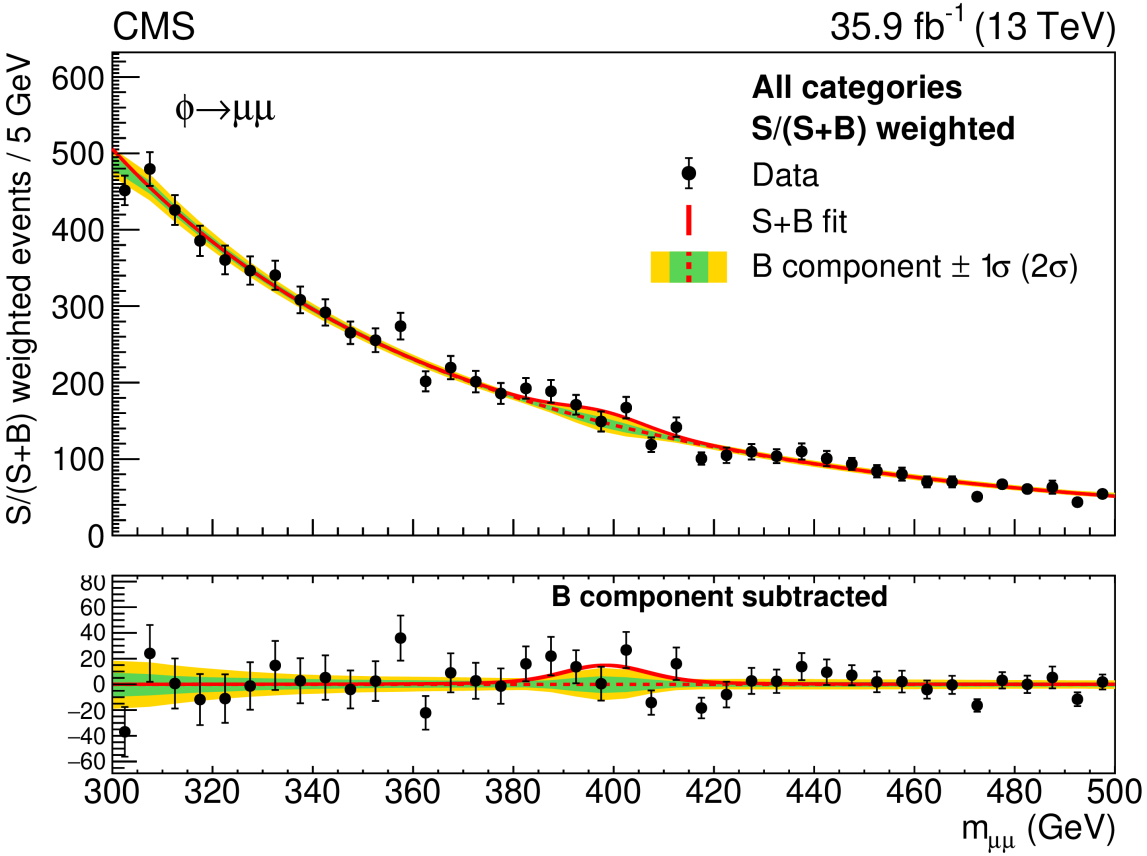
Search for MSSM H→μμ

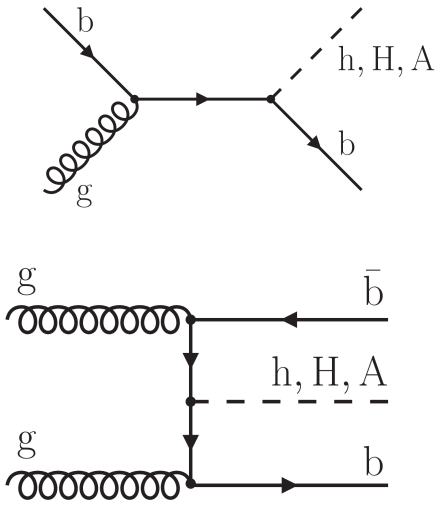
CMS: arxiv:1907.03152

- *An MSSM devised analysis (plus model independent)*
- Two categories:
  1) strictly one b-jet (to avoid large top bkg) 2) no b-tagged jet
- Fit to signal (**including all three neutral bosons** with mass, width and BR dictated by MSSM) + smooth analytical shape for the background from data



dominant for tan β < 30



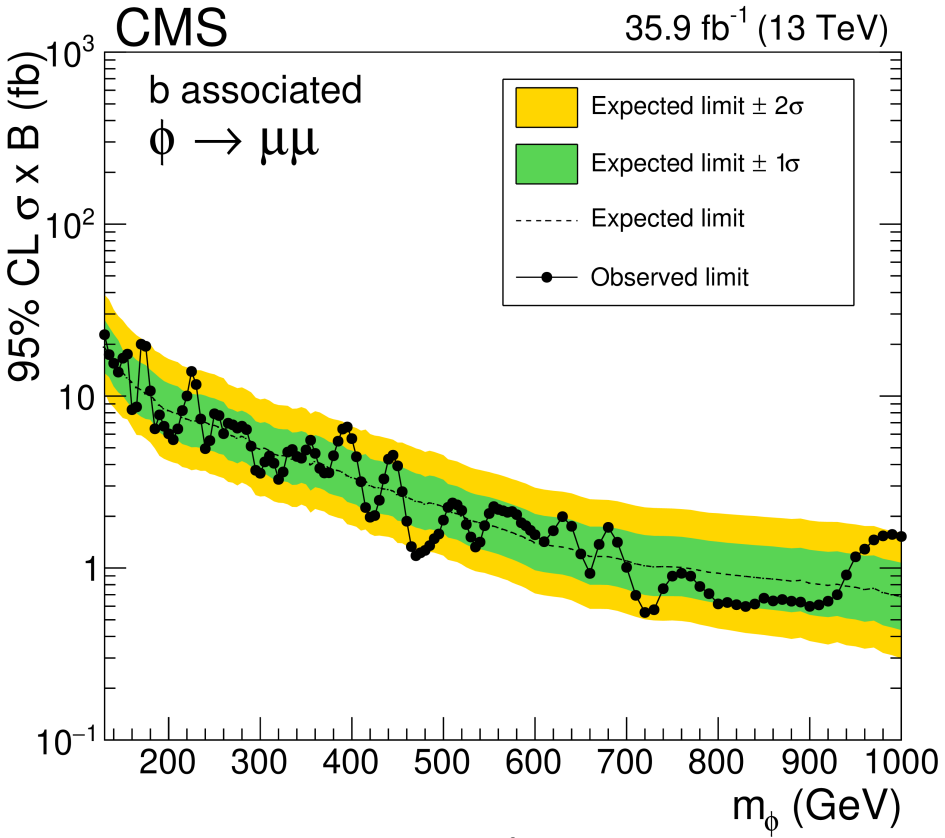


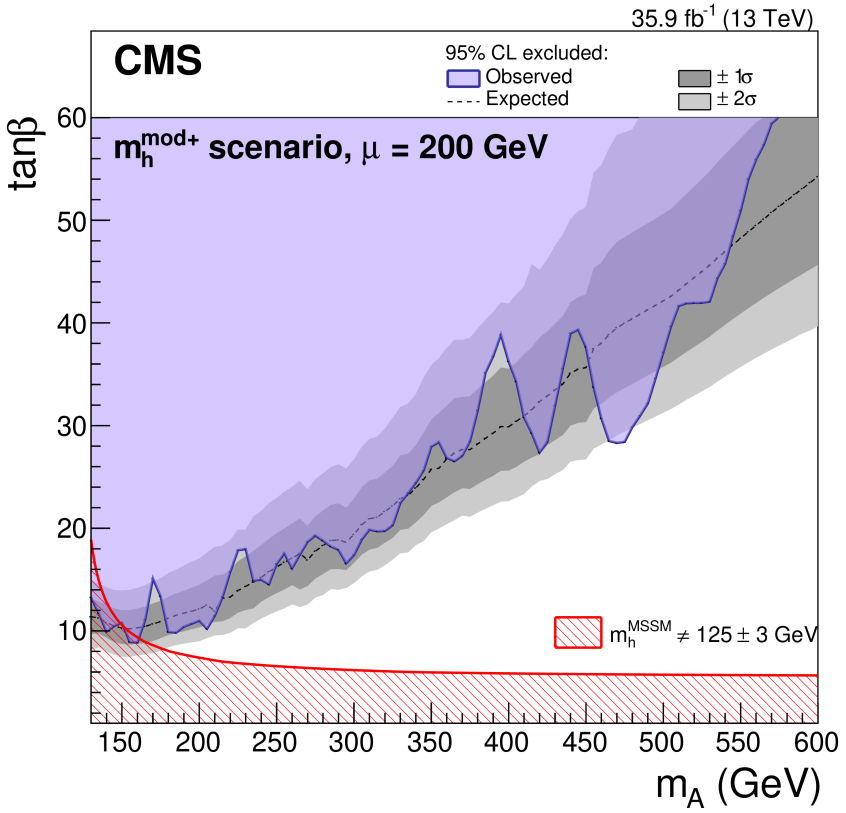
enhanced coupling to down-fermions at high tan β

Search for MSSM H→μμ

CMS: arxiv:1907.03152

- Example exclusion plot vs m_ϕ for b-associated production in narrow width approximation
- Around twice sensitivity as ATLAS
- Limits also for signal width 10% x m_ϕ (less stringent than narrow width approximation)



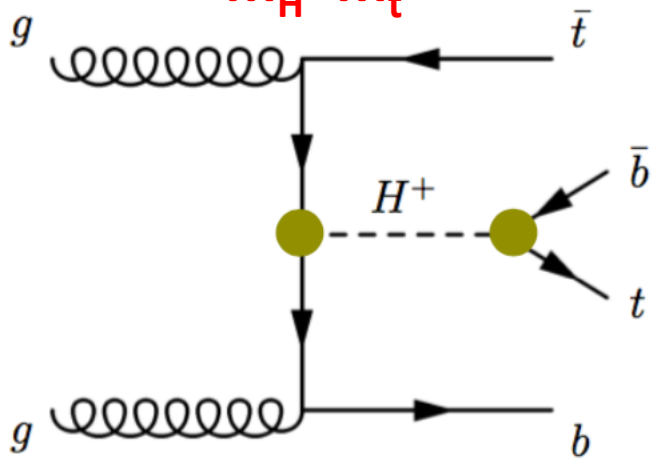


- Interpretation for $\mathbf{m_h^{mod+}}$, exclusion from **tanβ > 10-60**, extended beyond Run 1 analysis
- Similar conclusion for hMSSM (due to similar H and A cross sections)
- ϕ->ττ analysis excludes wider region although ϕ->μμ better than ϕ->bb for m_A<400 GeV

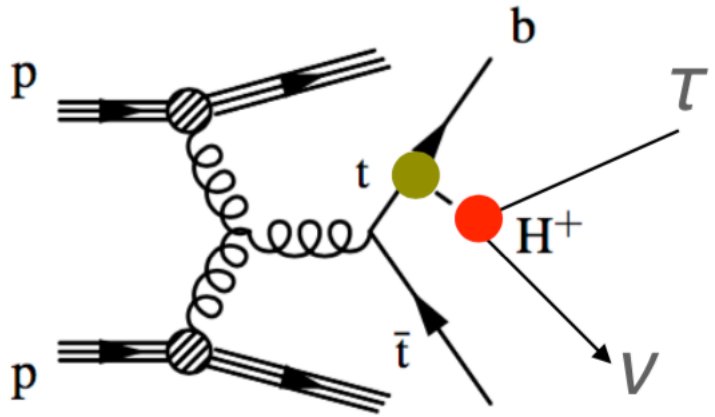
Charged Higgs Searches

- Charged Higgs bosons predicted in e.g. 2HDM, Higgs triplet models
- Produced with top quark
- Together **tb** and **τν** are collectively the largest BR

$m_H > m_t$



$m_H < m_t$

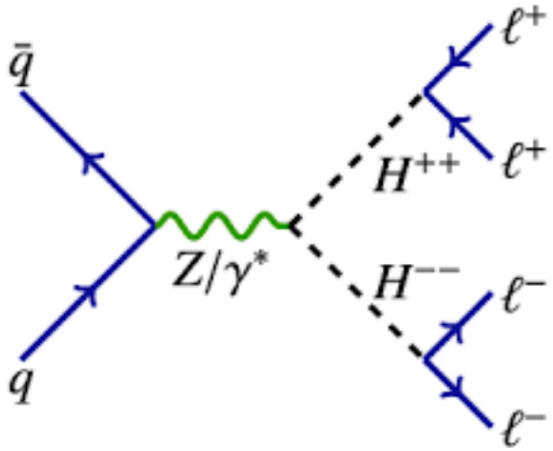


- Doubly charged Higgs produced in e.g. Left Right Symmetric Model and Higgs Triplet Model
- Production is dominated by pair production
- Decays dominated by 2 same sign charged leptons or 2 same sign W bosons

Published results from ATLAS on 36 fb^{-1}

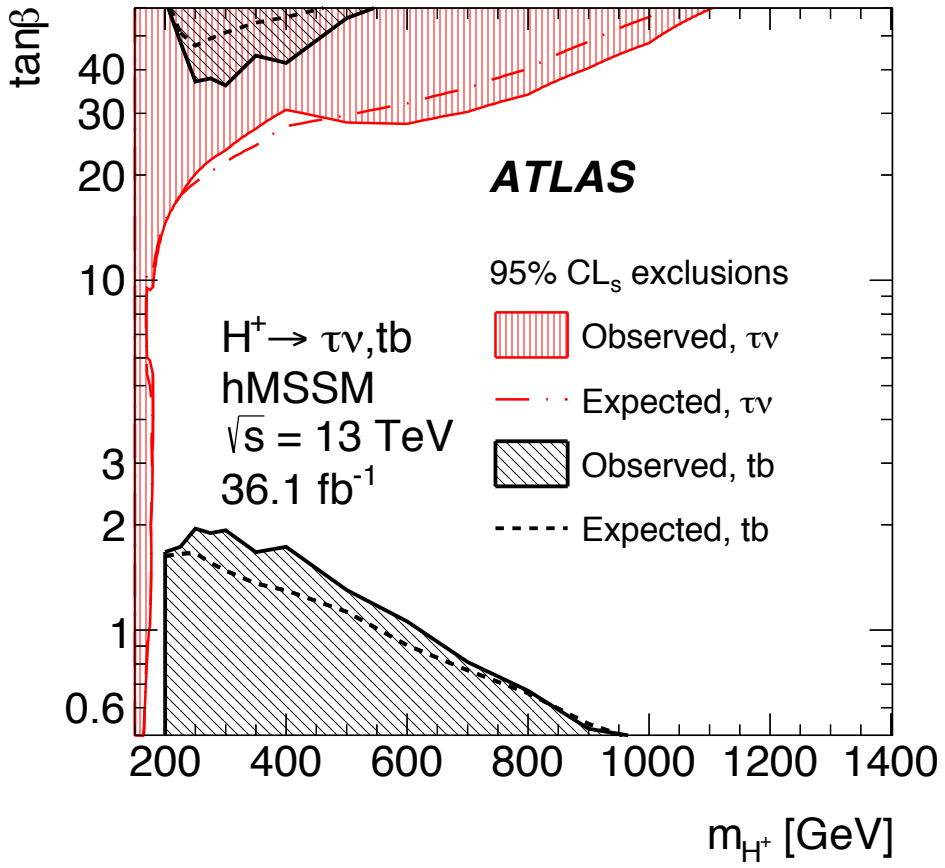
Eur. Phys. J. C 78 (2018) 199 (charged leptons),

Eur. Phys. J. C 79 (2019) 58 (Ws)



Charged Higgs Searches

- **H->tb (36 fb^{-1}):** CMS preliminary results (July 2019) in fully hadronic CMS-PAS-HIG-18-018 and final results (August 2019) in *leptonic final state*: arxiv:1908.09206. ATLAS final results JHEP11(2018)085 using *leptonic final states*
- **H->τν (36 fb^{-1}):** with *hadronic τ decays*, ATLAS JHEP09(2018)139 and CMS JHEP07(2019)142
- Typical exclusion on σ x B of 6 pb at m_H=80 GeV and 3 fb for m_H=3 TeV



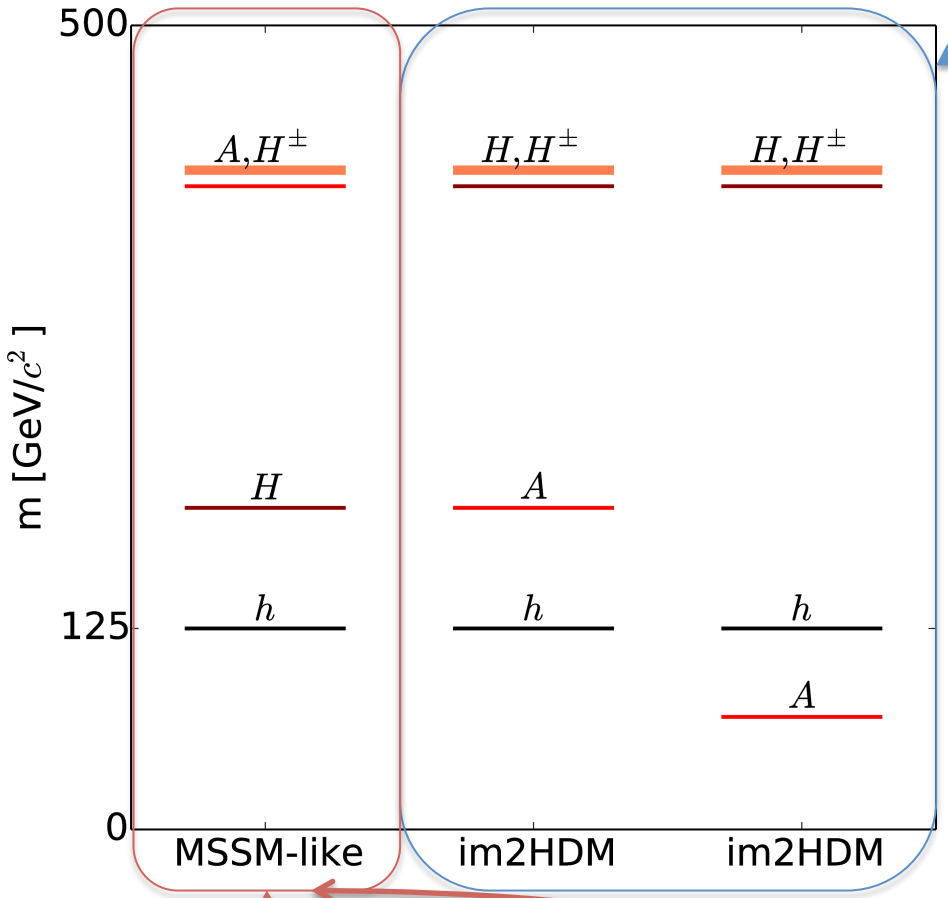
ATLAS interpretation in a MSSM benchmark (type II) combines searches for decays to ***τν*** and decays to ***tb***

Can see the different roles in the plane tanβ-m_H+

- Also search for light H^+ (100-160 GeV) decaying to W^+A(15-75 GeV) with eμμ and μμμ final states, CMS: Phys. Rev. Lett. 123 (2019) 131802

Probing Mass hierarchy and couplings

Probe hierarchy to reveal underlying physics



"classical scenario": **degenerate A/H$^{\pm}$**

in addition, H and A are typically assumed to be close in mass

Unconventional mass hierarchies

- Light A in (b)A ➛ττ , CMS: JHEP05(2019)210
- H ➛ ZA ➛ll bb , May 2019, CMS: CMS- PAS-HIG-18-012
- ~light H ➛γγ, CMS: PLB 793 (2019) 320–347

Probe couplings

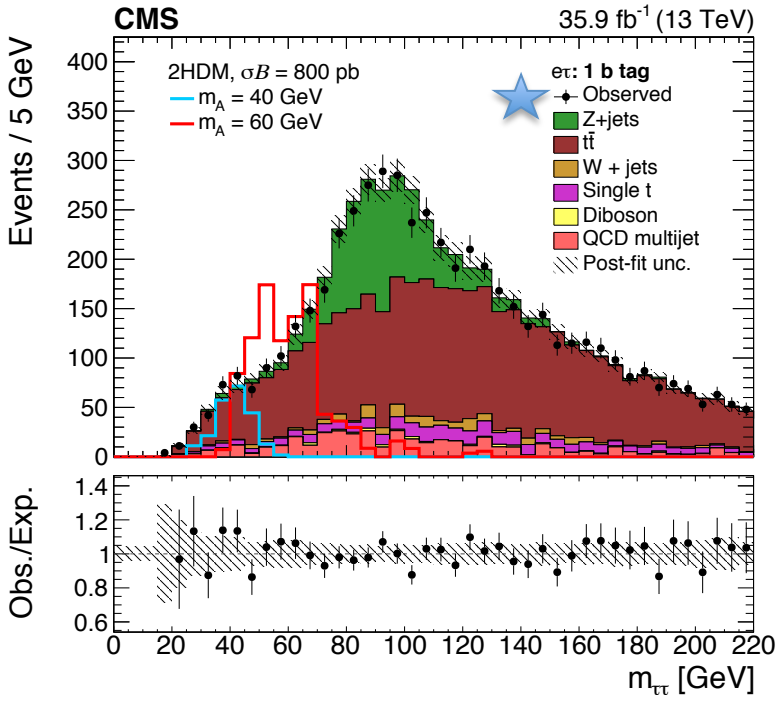
- A ➛ *Zh* ➛ *llττ*, CMS: PAS-HIG-018-023, March 2019
- H ➛WW, CMS: CMS-PAS-HIG-17-033, March 2019
- A ➛ *Zh* ➛ *ll bb, CMS:* CMS-PAS-HIG-18-005
- A ➛ *Zh* ➛ *(ll /νν) bb* ATLAS: JHEP 03 (2018) 174

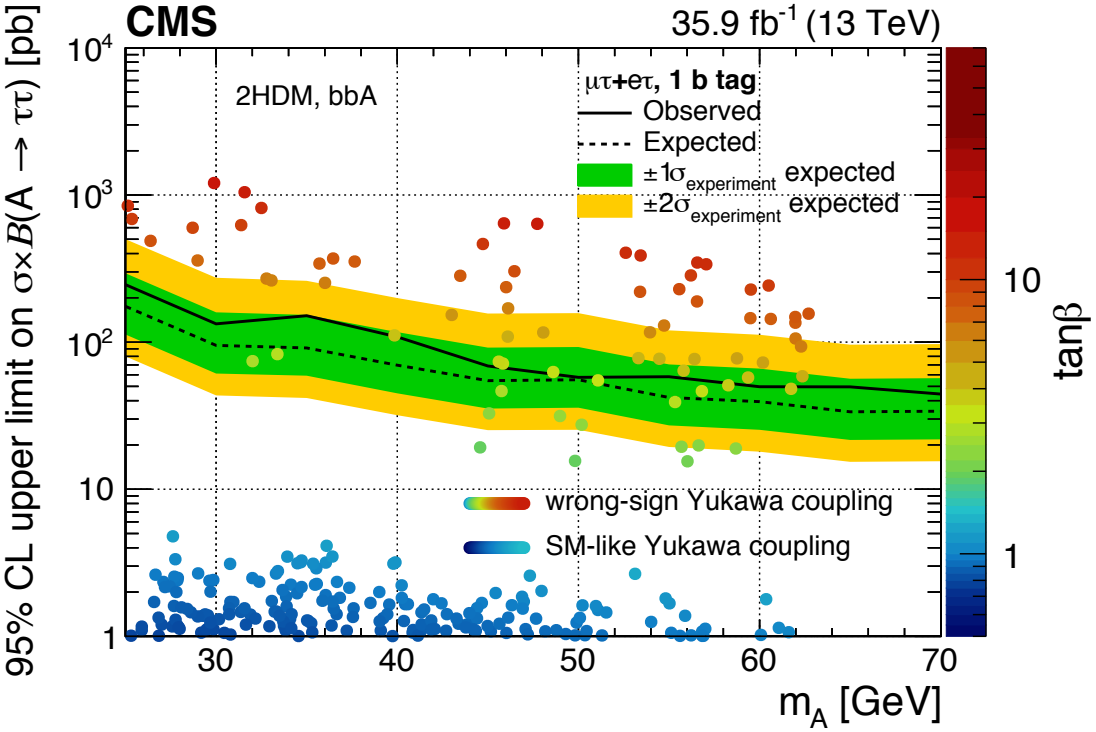
Light Neutral A in $b(b)A \rightarrow \tau\tau$

sensitive to type II and X, for high tanβ

CMS: JHEP05(2019)210

- CMS studied also a less conventional scenario using 36 fb^{-1} at 13 TeV
- a ***light Higgs*** **(20-70 GeV)** decaying to ττ and produced in association with b-quarks
- selection requires one τ_{lep} and one τ_{had} ,maximum likelihood fit of tau-pair invariant mass $m_{\tau\tau}$ to extract the signal strength





Yukawa coupling of *opposite sign* w.r.t. SM, many σ excluded at high tanβ

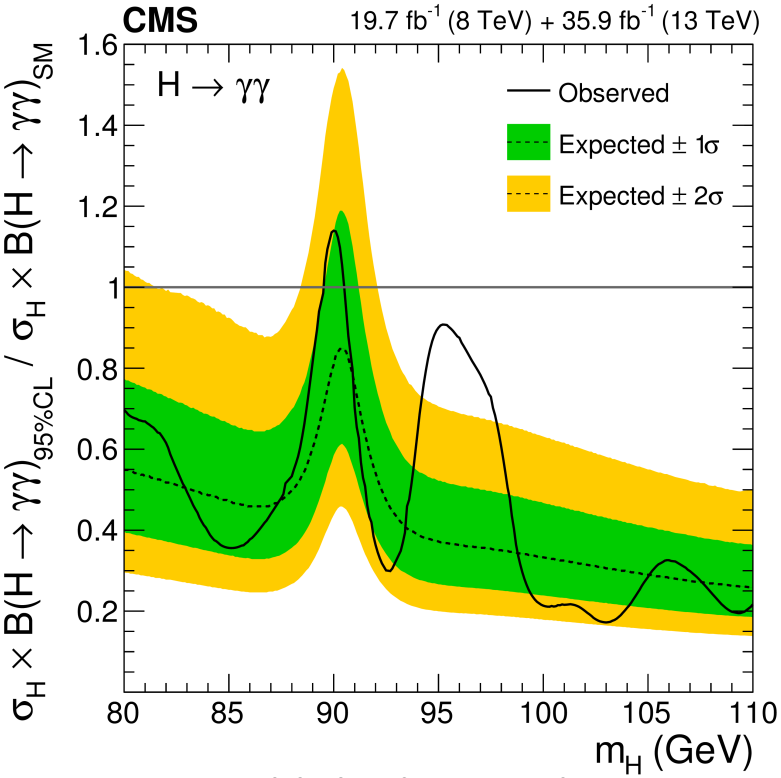
tanβ 0.6-2.0 and with SM-like sign give σ x B < observed limit

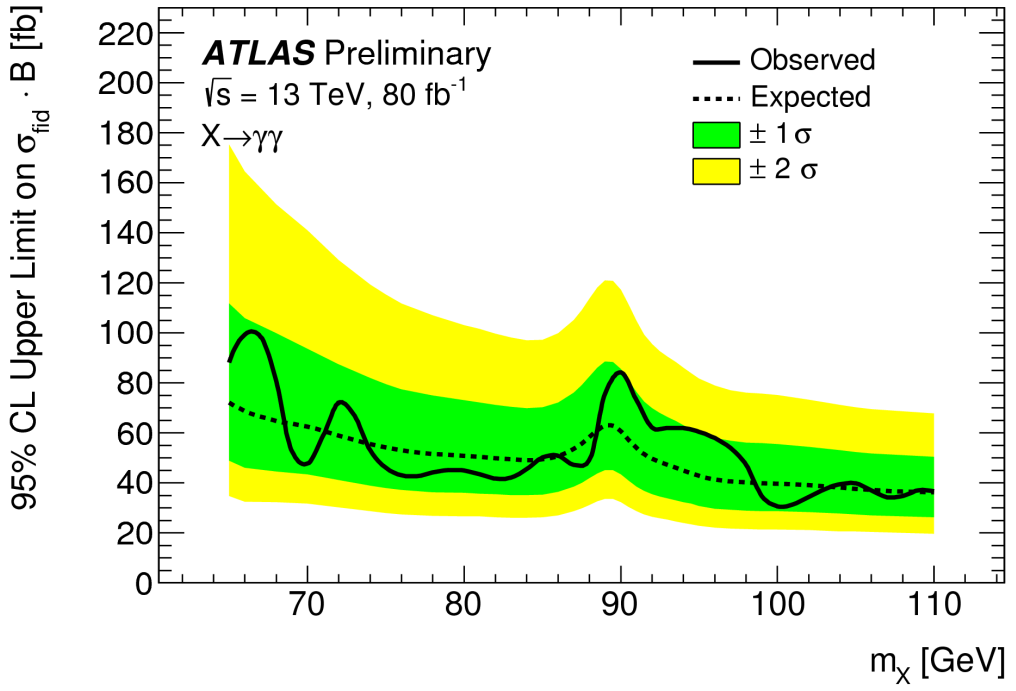
SM-Like H→γγ at intermediate mass

Analyses based on SM H->γγ with several categories to enhance sensitivity

CMS: Phys. Lett. B 793 (2019) 320

- CMS: Search in the range 70-110 GeV with 8 TeV (20 fb^{-1}) and 13 TeV (36 fb^{-1}) data
- Observe: A small excess at ~ 95 GeV (local [global] significance 2.8 [1.3])





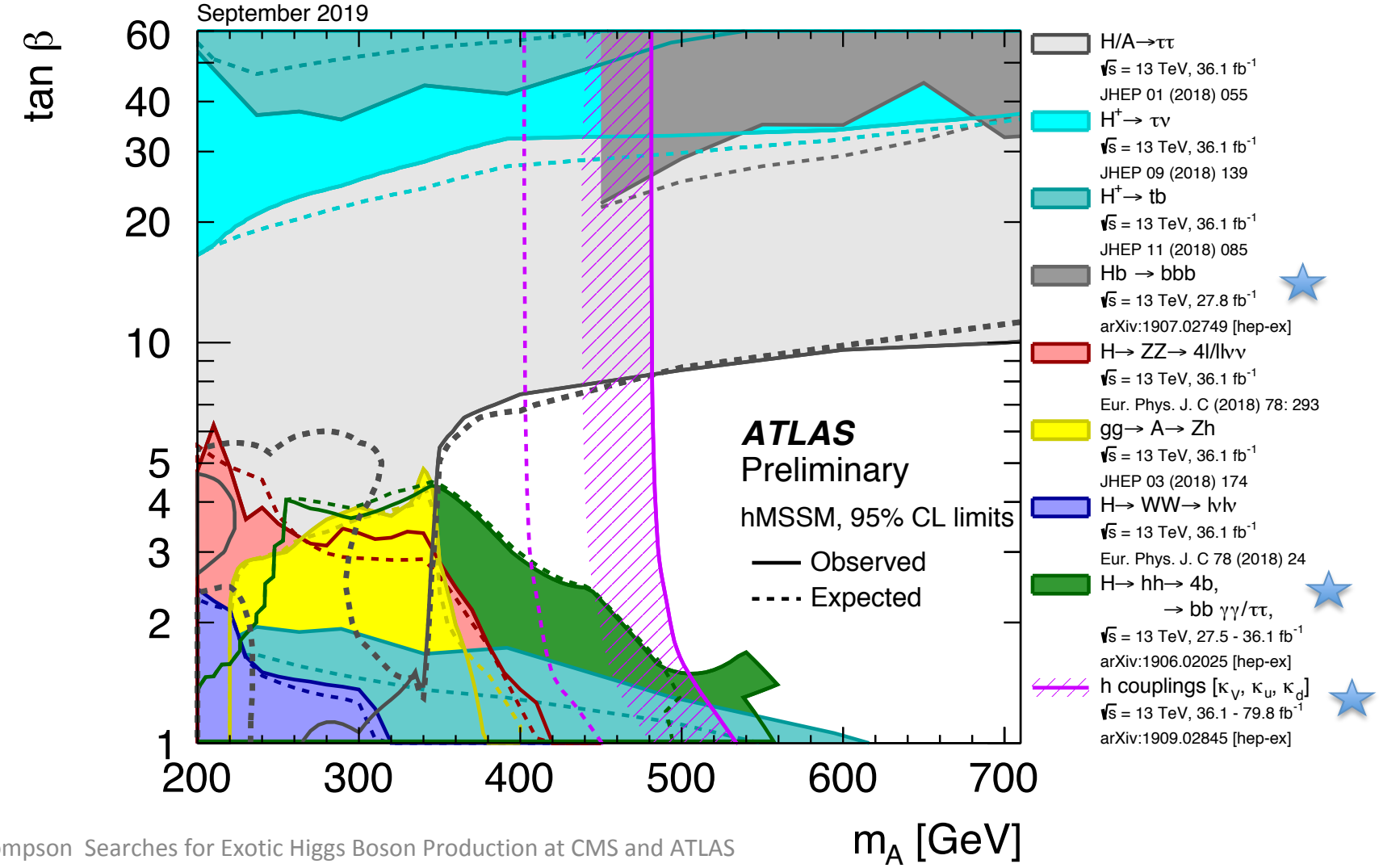
ATLAS:ATLAS-CONF-2018-025

- ATLAS: published Run 1 data: PRL 113 (2014) 171801
- ATLAS Preliminary search in range 65-110 GeV with 80 fb^{-1} 13 TeV data
- No significant excess observed. Keep an eye on full Run 2 analyses from both experiments

Status of 2HDM Benchmark

ATLAS:ATL-PHYS-PUB-2019-034

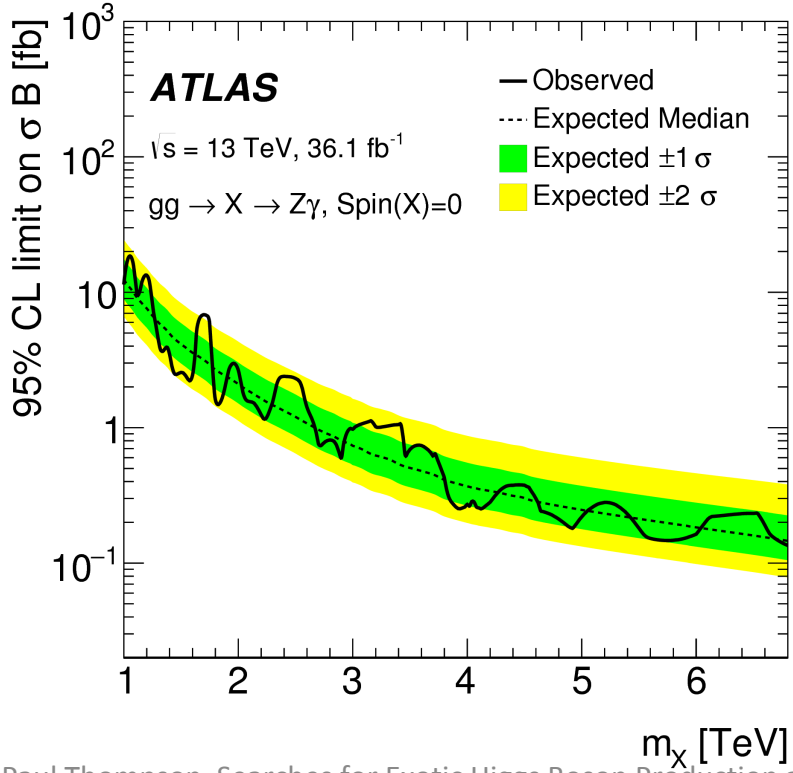
- **hMSSM predictions:** σ with **SUSHI** including ggF+b-associated prod. at NNLO in QCD. Partial widths and decays with HDECAY. Update from October 2018, new analyses and couplings
- Direct searches closing the gaps. Looking forward to rest of Run 2 results plus HL-LHC (see back-up)

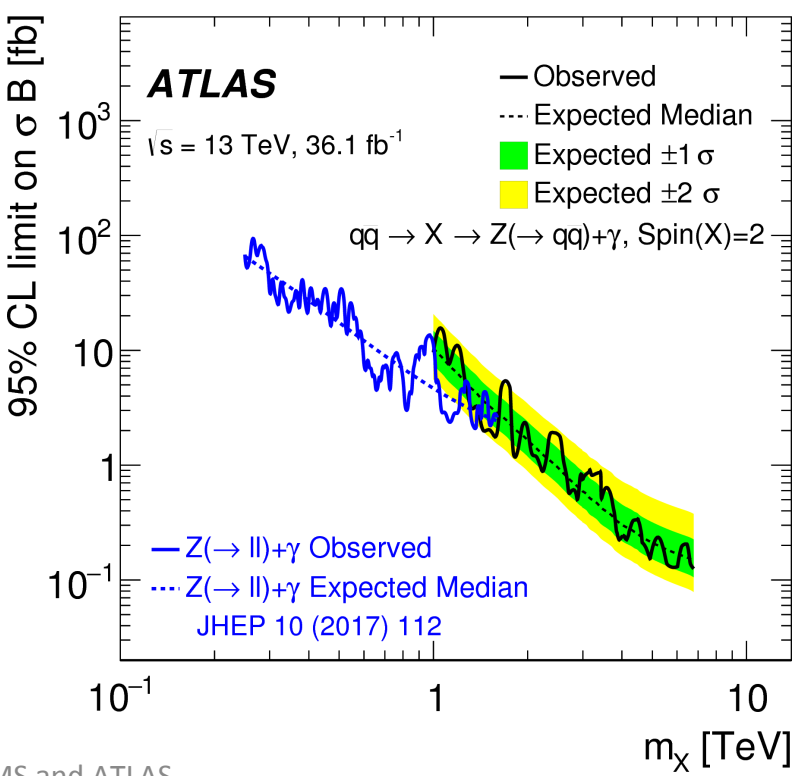


Exotic Higgs Searches in H→Zγ

ATLAS: PhysRevD.98.032015

- H→Zγ proceeds by loop diagrams similar to those in H→γγ and has a similar branching ratio. Due to the branching fraction of Z sensitivity is lower.
- Most recent searches using hadronic Z (BR 70%), extend to higher mass using jet substructure, plus H->Wγ (spin 1) and X->Hγ searches
- Search for new physics:
  - E.g. gg and qq induced production models for spin 0 resonance with narrow width approximation (NWA) and qq induced production models for spin 2 resonance



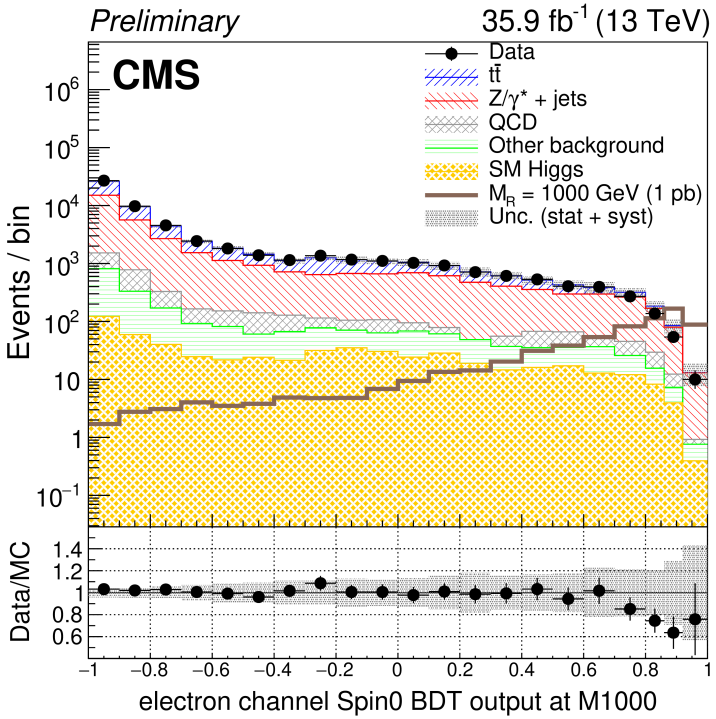


Extending leptonic searches to higher mass

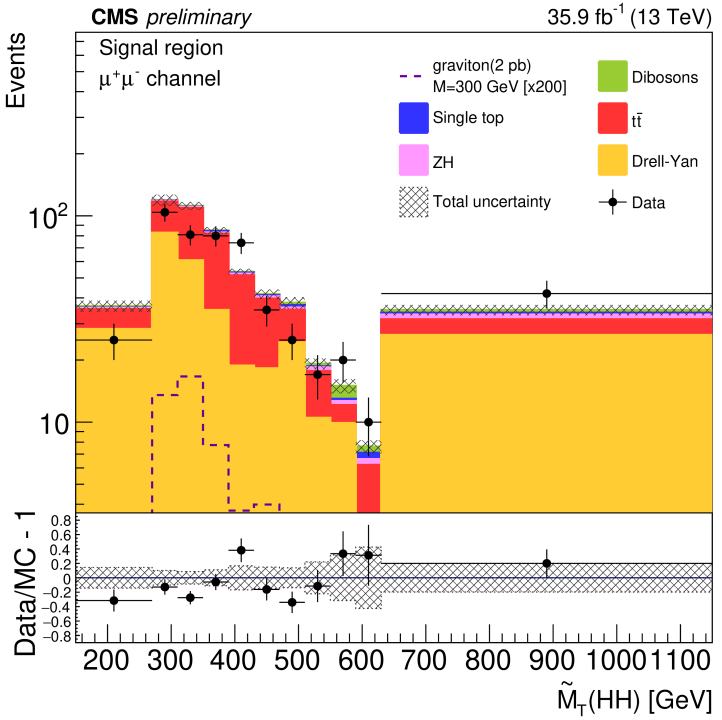
Exotic DiHiggs HH→bbZZ

CMS (July 2019): CMS_PAS_HIG_18_013

- **DiHiggs production** can also be used to search for new Exotic Higgs physics e.g. Warped Extra Dimension formulations (WED) such as Randall-Sundrum (RS)
- Resonant particles produced can be a radion (spin-0) or the first Kaluza-Klein (KK) excitation of a graviton (spin-2).
- **bbZZ** final states considered where one Z decays into **two oppositely charged leptons**, and the other Z decays either **to two neutrinos** (bbllνν) or hadronically into **two or more jets** (bbljj). *First search in bbljj channel*.
- Challenging experimentally V+jet/ttbar backgrounds − use BDTs trained at low or high mass



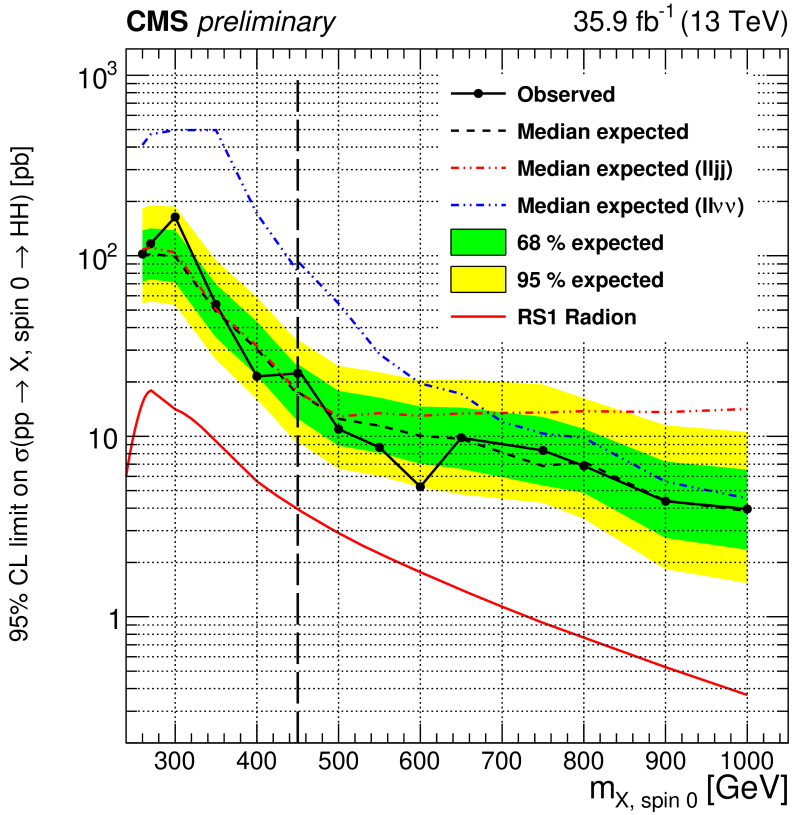
bbeejj

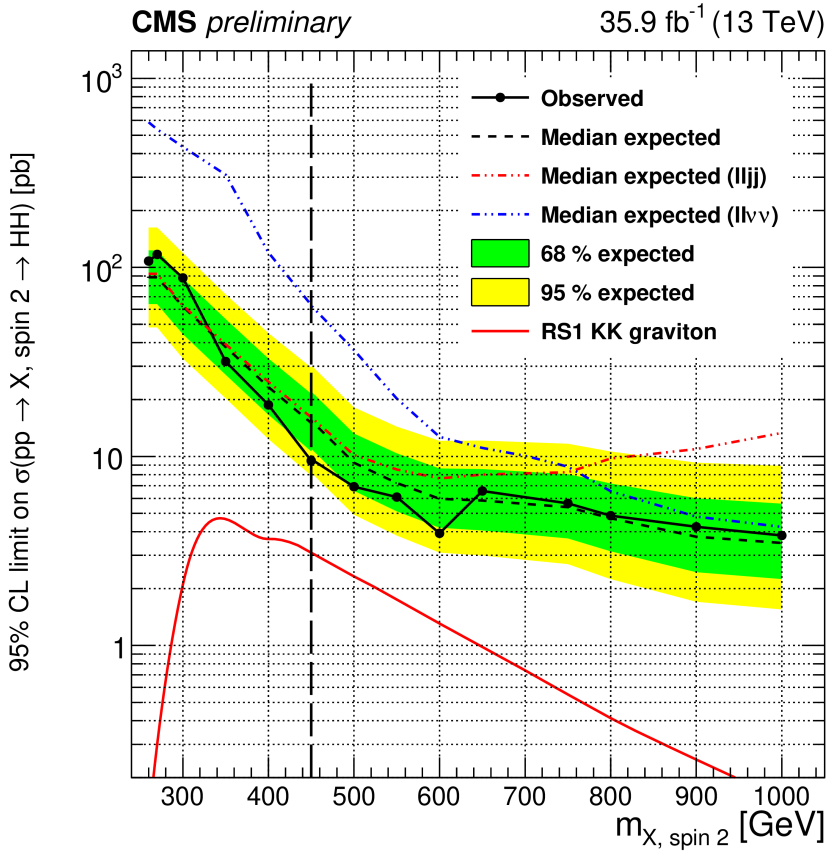


bbμμνν

Exotic DiHiggs HH→bbZZ

- Searches using 36 fb^{-1} of 13 TeV data
- Mass range of search for new particles 300-1000 GeV
- Different channels have complementary sensitivity across the mass range
- Observed limits consistent with SM expectation
- Approaching sensitivity of model parameters

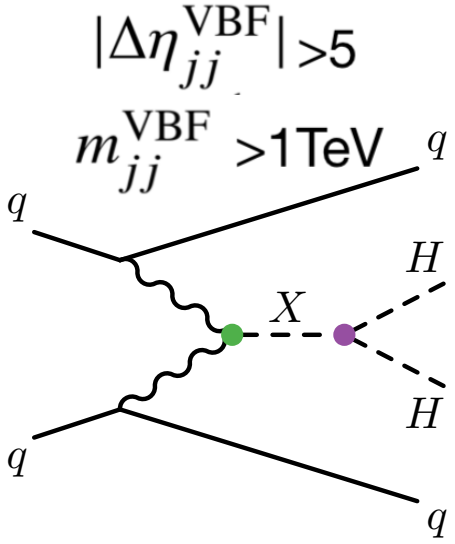


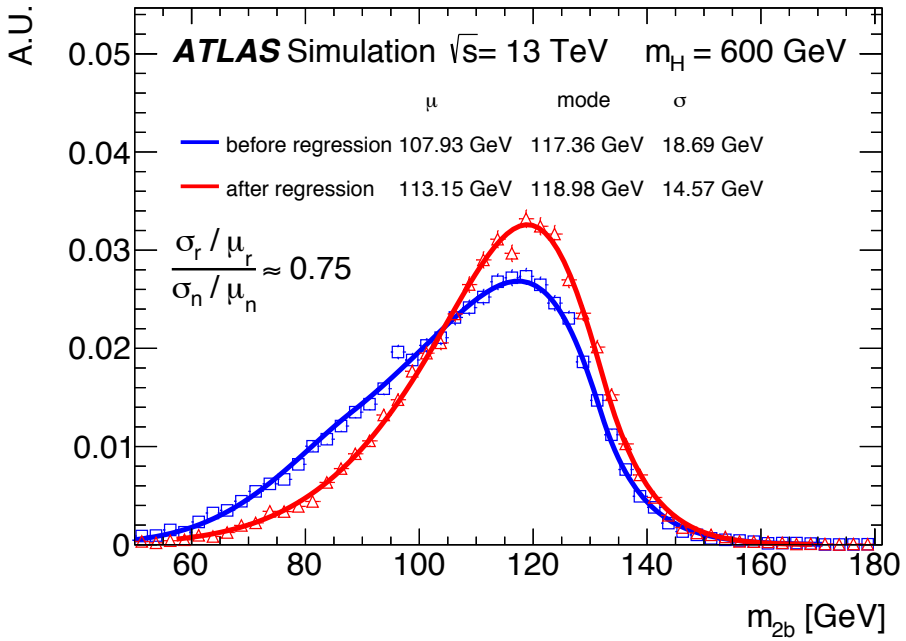


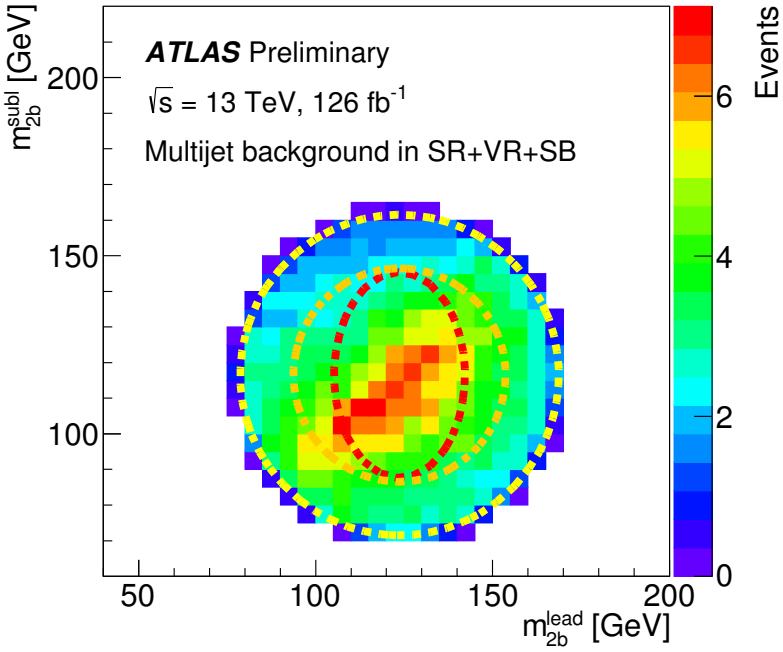
Exotic DiHiggs HH→bbbb(VBF)

ATLAS (July 2019): ATLAS_CONF_2019_030

- **Recent diHiggs production result from ATLAS using bbbb** final states and full Run2 data (126 fb^{-1})
- Sensitive to **VBF production** both resonant and non-resonant (including VVHH coupling – see backup)
- **Regression** using a boosted decision tree improves mass resolution e.g. by 25% for m_H=600 GeV
- Define signal, validation and sideband regions in mass of leading and subleading jet pairs
- Multijet templates **data driven** from 2b-tag region



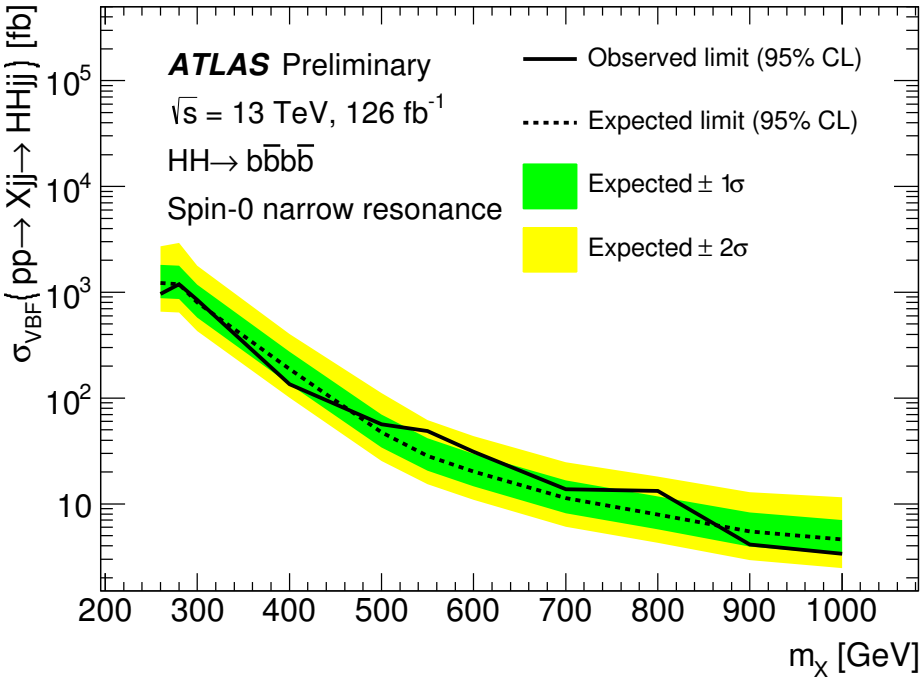


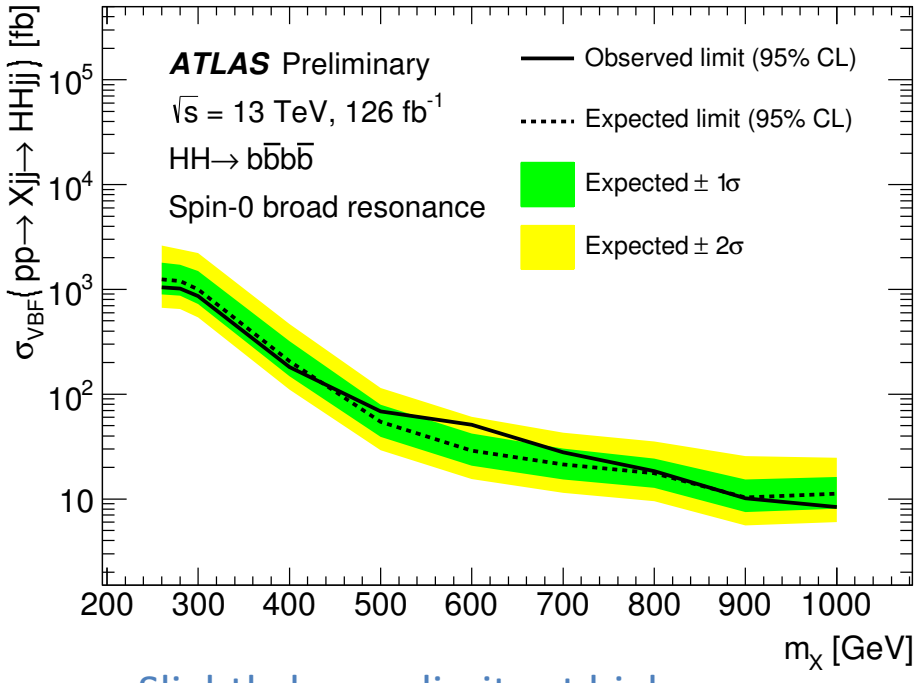


Exotic DiHiggs HH→bbbb (VBF)

- Mass range of search for new particles **260-1000 GeV** for resonant **VBF** production
- Upper limits on the production cross-section for **narrow**- and **broad-width** (tanβ=2.0 and sin(β−α)=0.6) scalar resonances at 95% CL
- Largest deviation from the background-only hypothesis at *550 GeV* with a *local significance* of *1.5 standard deviations.*
- **Non-resonant limit** agrees with expectation with 2 standard deviations:

	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ [fb]	1600	500	700	1000	1400	2100





Slightly looser limits at high mass

Summary

- The SM-like Higgs boson discovery opens a new era of precision physics
- The puzzles of the SM are likely to be related to the Higgs and the scalar sector with many theories predicting Exotic scalars
- ***No signs of deviations from SM so far, but continue to probe the phase space of the parameters of the model***

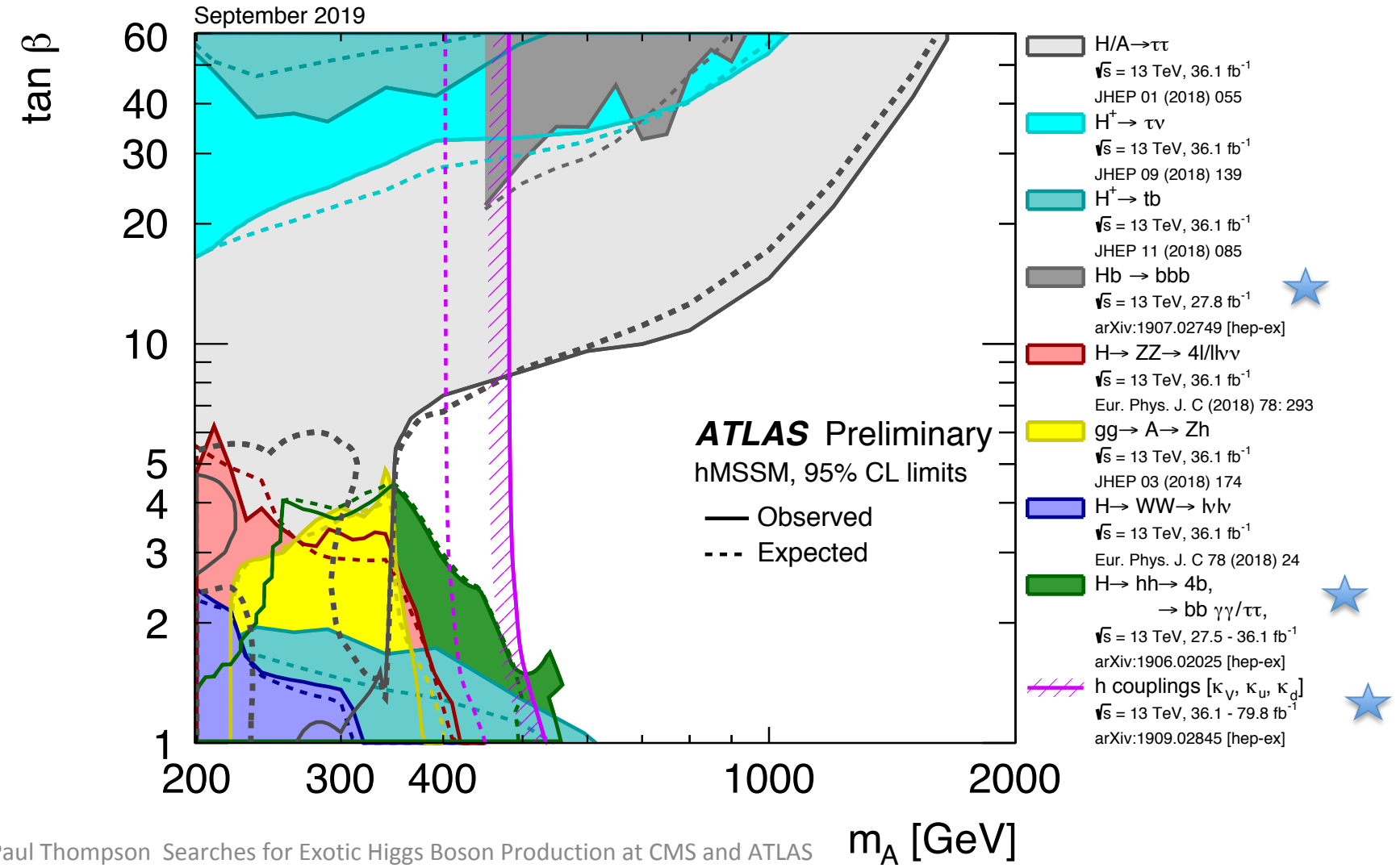
- In many cases LHC full Run 2 potential still to be exploited
- *Looking forward to more results from ATLAS and CMS on the search for Exotics Higgs production…*

Back-up

Status of 2HDM Benchmark

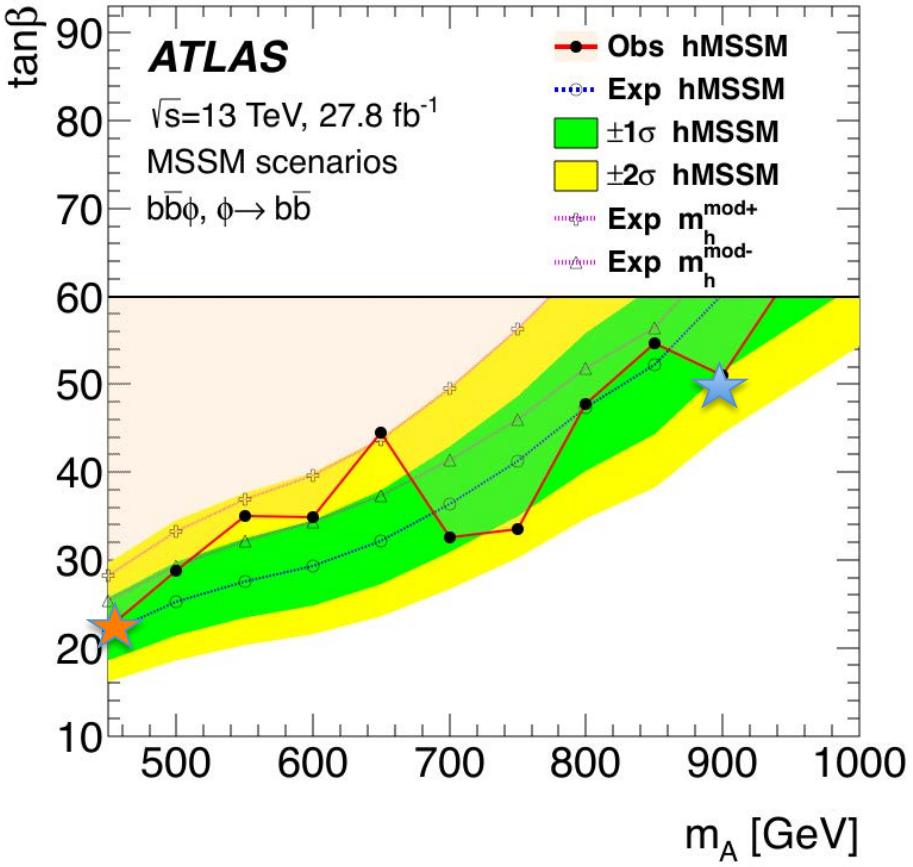
ATLAS:ATL-PHYS-PUB-2019-034

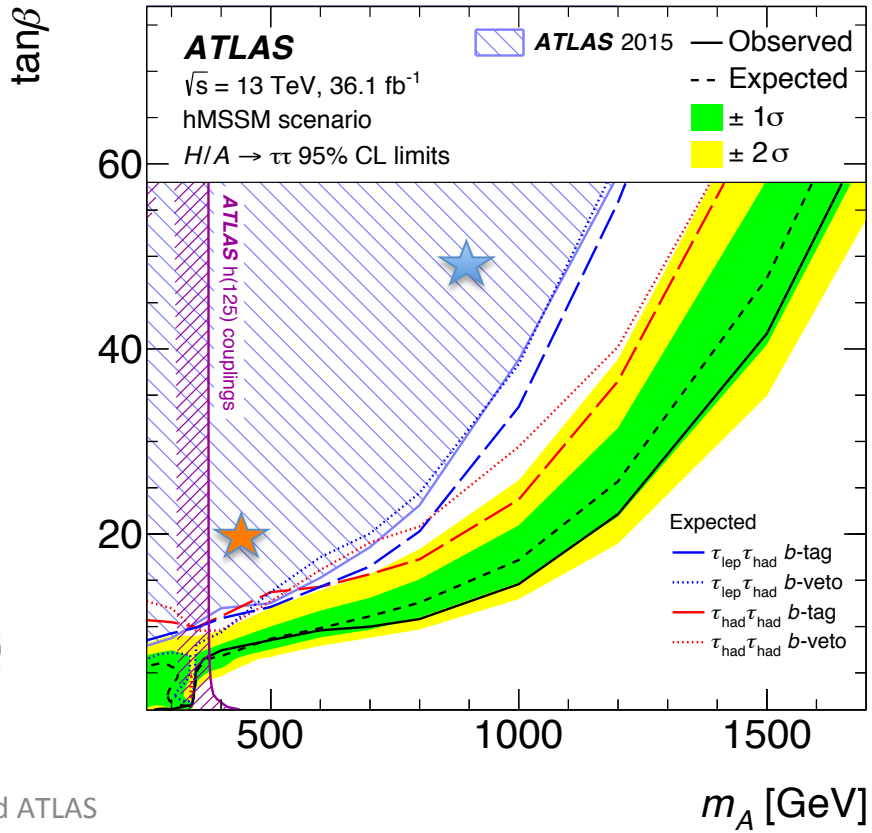
- **hMSSM predictions:** σ with **SUSHI** including ggF+b-associated prod. at NNLO in QCD. Partial widths and decays with HDECAY
- Update from October 2018, new analyses and couplings combination



Compare bH/A->ττ with bH/A->bb

- As example compare ATLAS: JHEP01(2018)055
- Systematic for reconstruction and identification of τ_{had} at high p_T reduced by a factor 2, leading systematic for m_φ>1 TeV.
- Compare with unreduced systematics

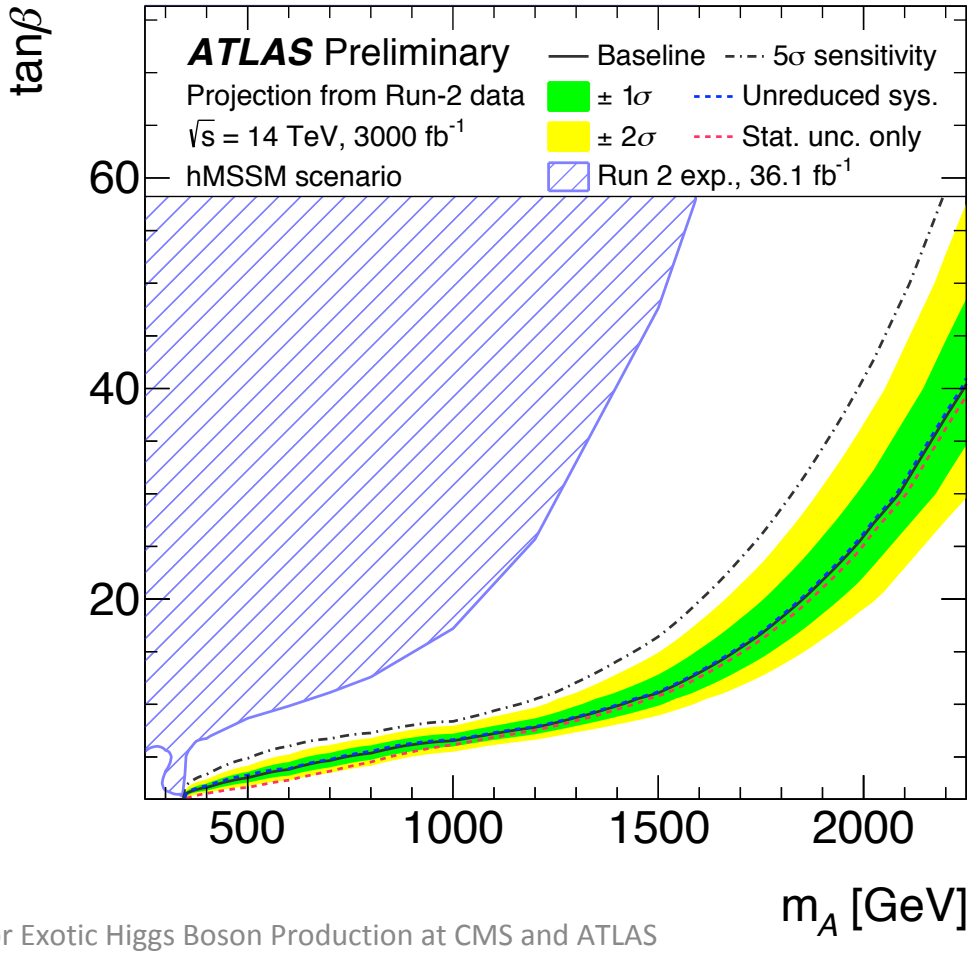




Prospects for H/A->ττ

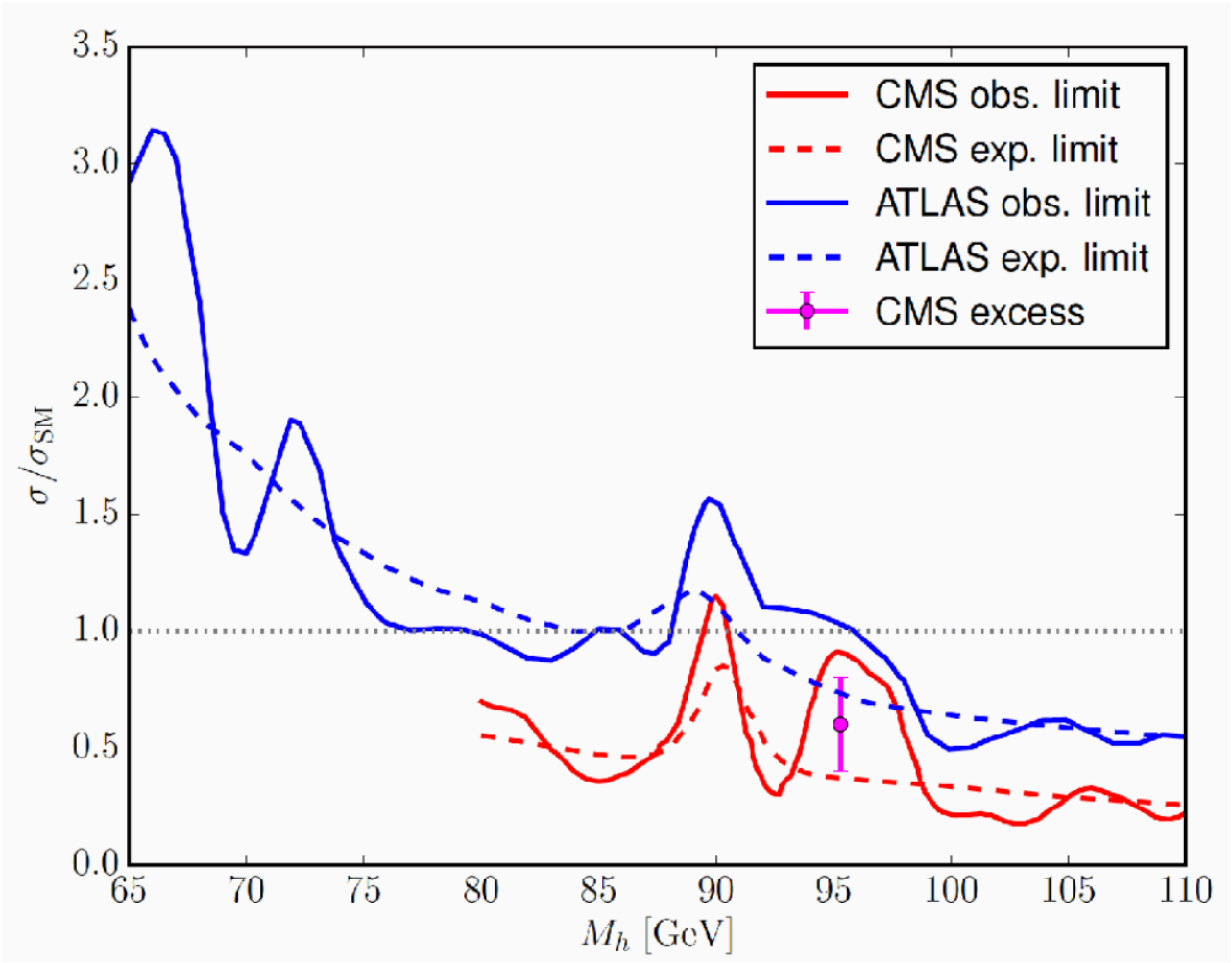
ATLAS:ATL-PHYS-PUB-2018-050

- Use extrapolation of present 36 fb^{-1} (13TeV) analysis to 3000 fb^{-1} at 14 TeV
- Systematic for reconstruction and identification of τ_{had} at high p_T reduced by a factor 2, leading systematic for m_φ>1 TeV.
- Compare with unreduced systematics



H->γγ CMS and ATLAS Comparison

CMS and ATLAS in direct comparison: [S.H., T. Stefaniak '18]



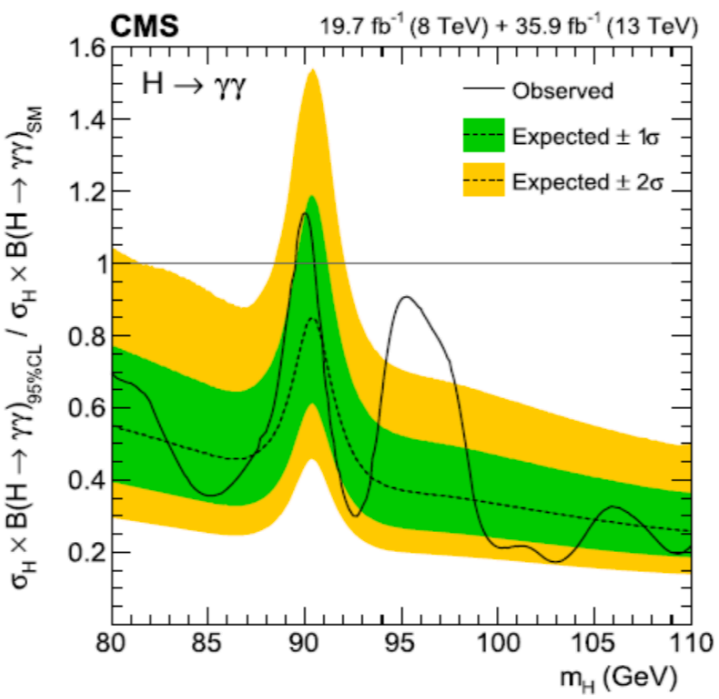
⇒ Can ATLAS and CMS (finally) clarify this?

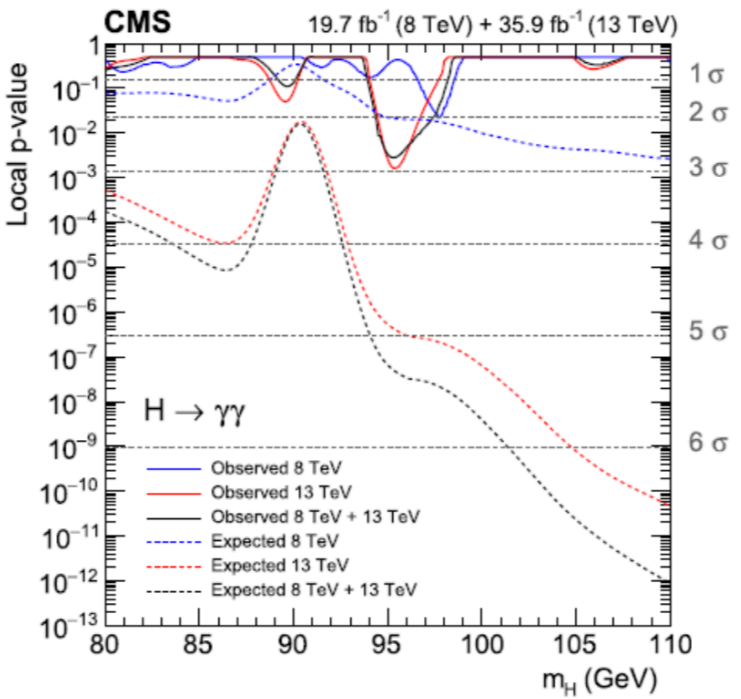
https://indico.lal.in2p3.fr/event/5201/contributions/17281/subcontributions/1466/attachments/14310/17652/sven.pdf 26

H->γγ CMS and ATLAS Comparison

Search for additional low-mass (m<125 GeV) Higgs bosons at CMS, *M.A. Shahzad*

PLB 793 (2019) 320



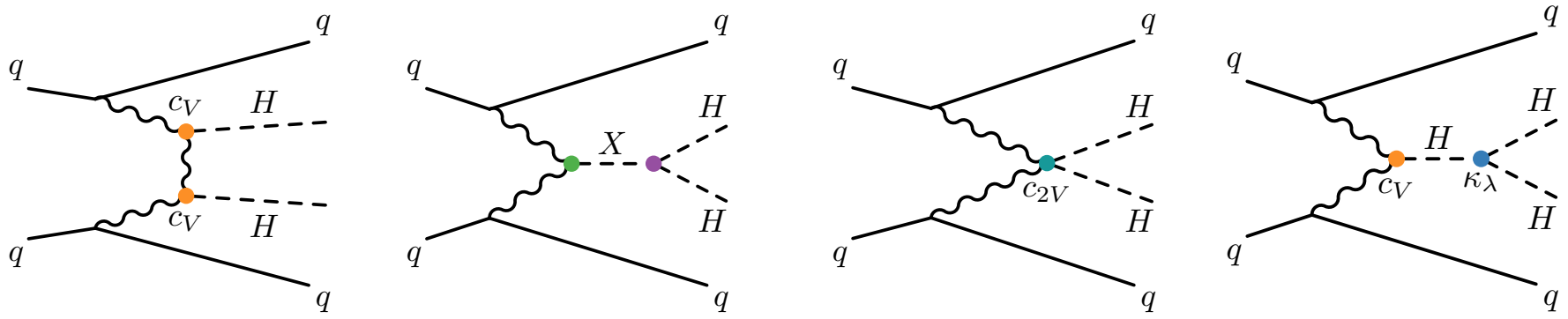


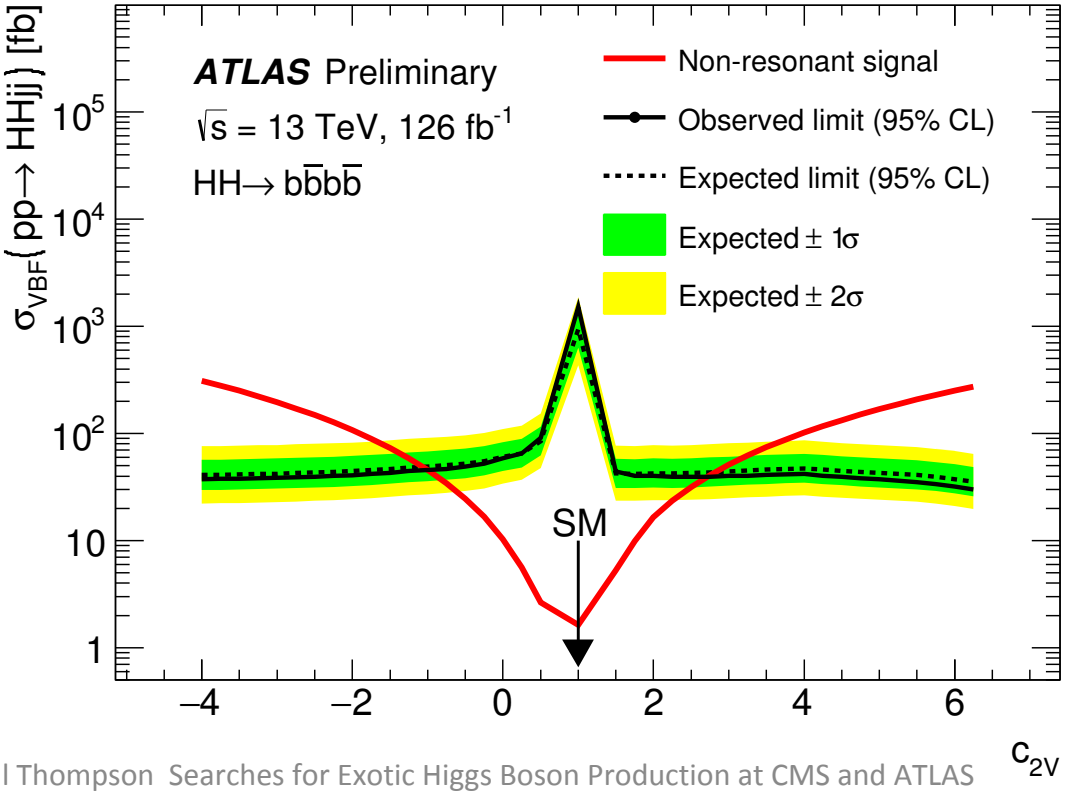
- Limit on σ x BR (H-> γγ) normalized to that of SM.
  - Min. (Max.) limit: 0.17 (1.13) at m_H = 103.0 (90.0) GeV
- Observed significance:
  - 8 TeV: ~2.0 σ local significance at m_H = 97.6 GeV
  - 13 TeV: ~2.9 σ local (1.47 σ global) significance at m_H = 95.3 GeV
  - 8 TeV + 13 TeV: ~2.8 σ local (1.3 σ global) significance at m_H = 95.3 GeV
- Need more data to ascertain the origin of this excess.

Exotic DiHiggs HH→bbbb (VBF)

ATLAS (July 2019): ATLAS_CONF_2019_030

- VBF sensitivity to *VVHH coupling* c_{2V}





Excluded at 95% CL:

$c_{2V} < -1.02$ and $c_{2V} > 2.71$