BSM HIGGS @ LHC

MARÍA CEPEDA, CERN

XLIV International Meeting on Fundamental Physics, Madrid, April 2016

Why search for BSM Higgs?

The Run I of the LHC brought the discovery of a new particle, and opened the quest for understanding its properties and decays, in the SM context, and beyond.

Is the new boson *really* the *minimal* SM Higgs?

- Is the ***signal strength***, where seen, at the expected SM level?
- Is this a ***scalar***, and not a pseudo-scalar or tensor?
- Does it ***couple*** to the SM particles at correct level? t,b,τ,μ
- Does it ***couple to itself*** ?
- Is this the ***only*** new non-vector boson, and not one of several?
- Does it ***couple*** unusually ?

MSSM ?

2HDM+S?

2HDM ?

EWK Singlet?

Higgs Triplet?

What has 13TeV data said so far?

Outline

- Summary of Run I coverage
- 13TeV search for MSSM H→ττ
- DiHiggs results
- 2HDM
- Charged Higgs
- Exotic decays
- Invisible Higgs

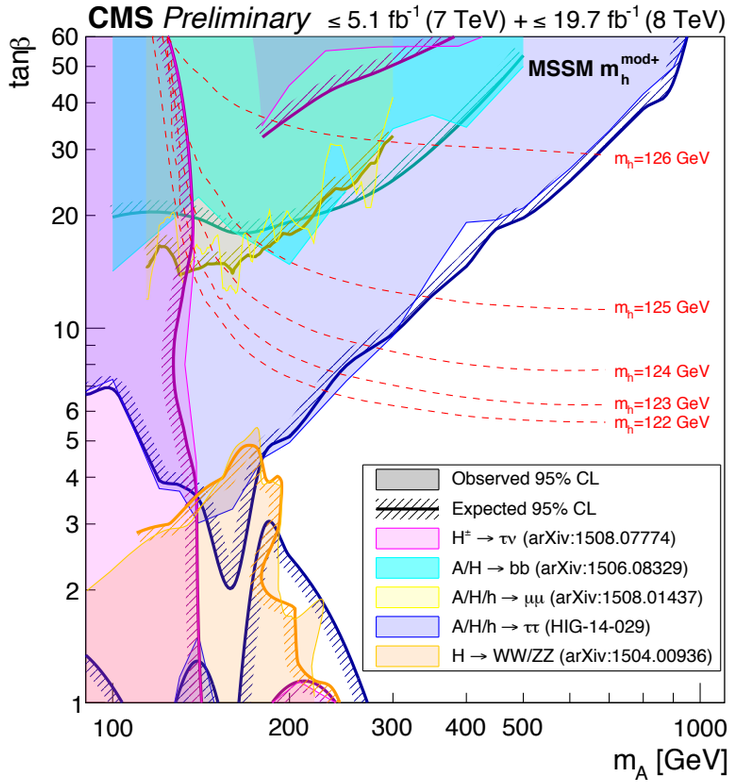
Only recent results shown! For the full picture:

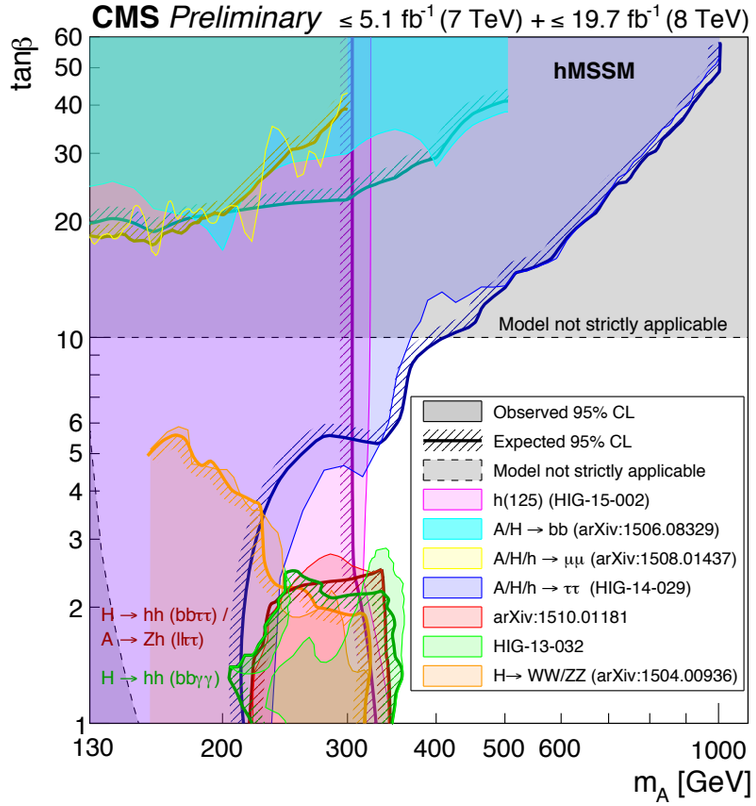
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

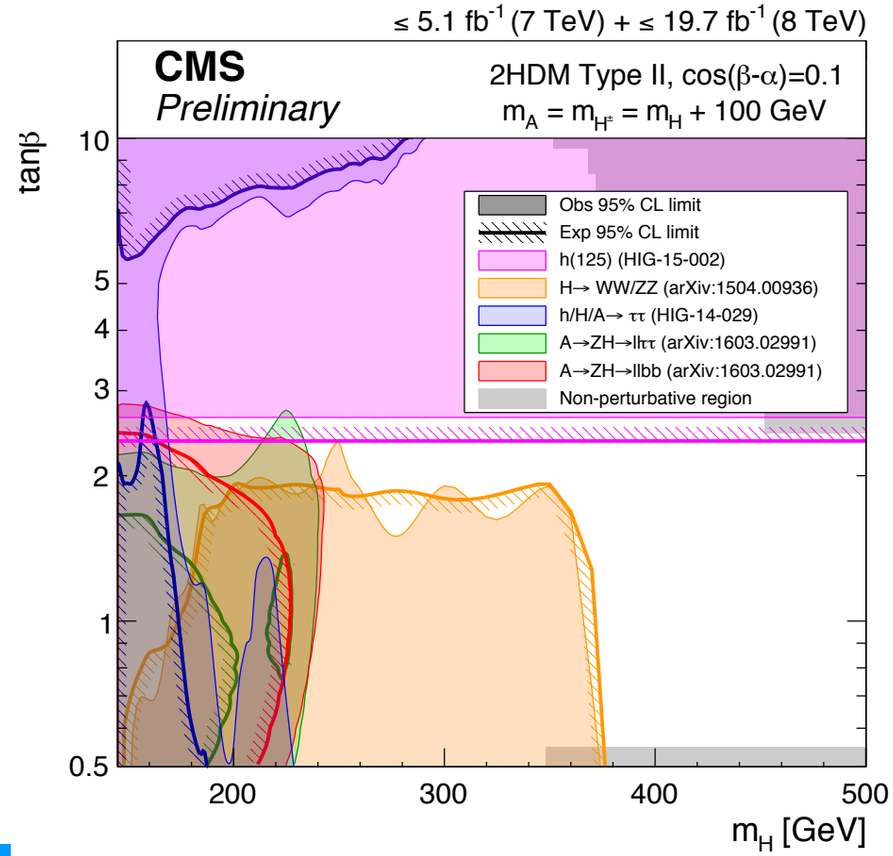
What was the landscape at the start of Run II?

Before exploring 13TeV, a small stop to explore the view from the top of Run I:

- Many extra scalar searches performed at 7&8TeV by both experiments
- No hints of new physics in Run I
- But there is still a lot of uncovered phase-space - specially at high mass!







CMS-PAS-HIG-16-007

2015 dataset already competitive for some of these

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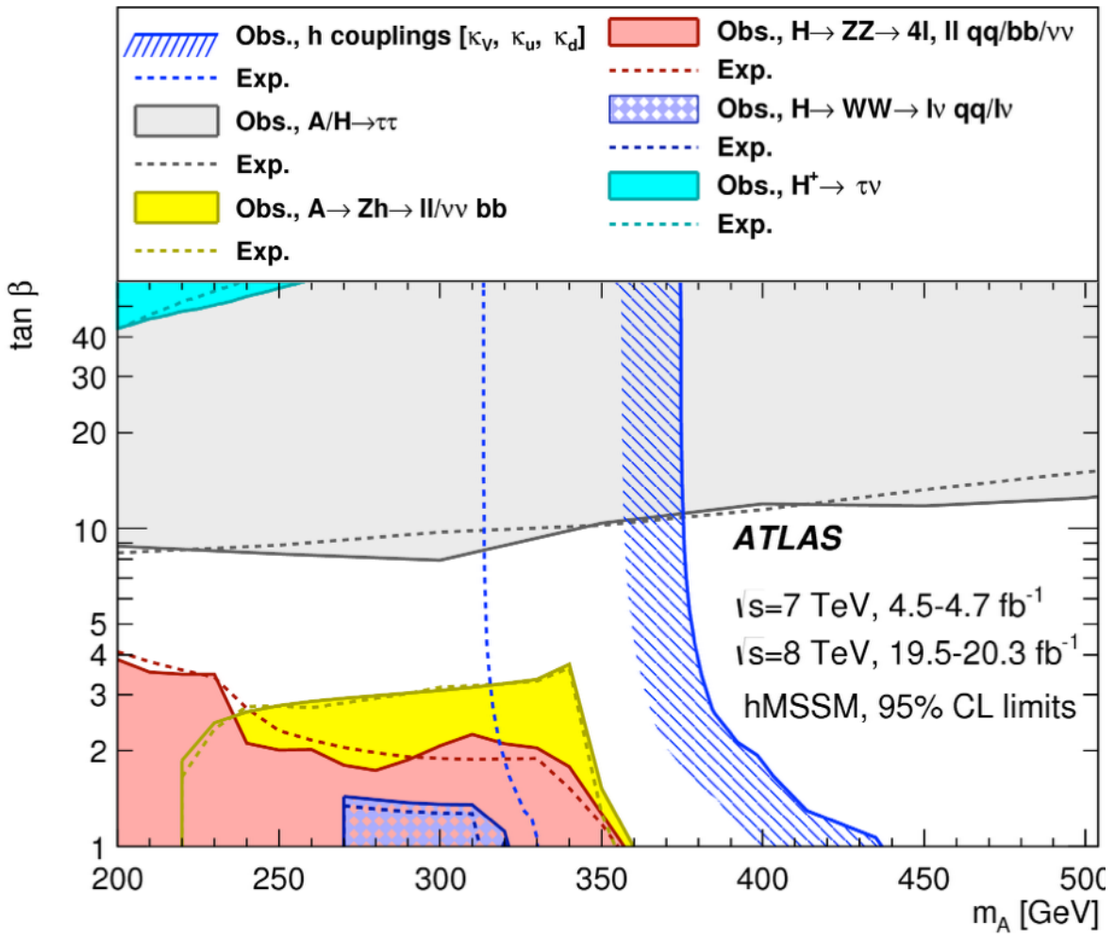
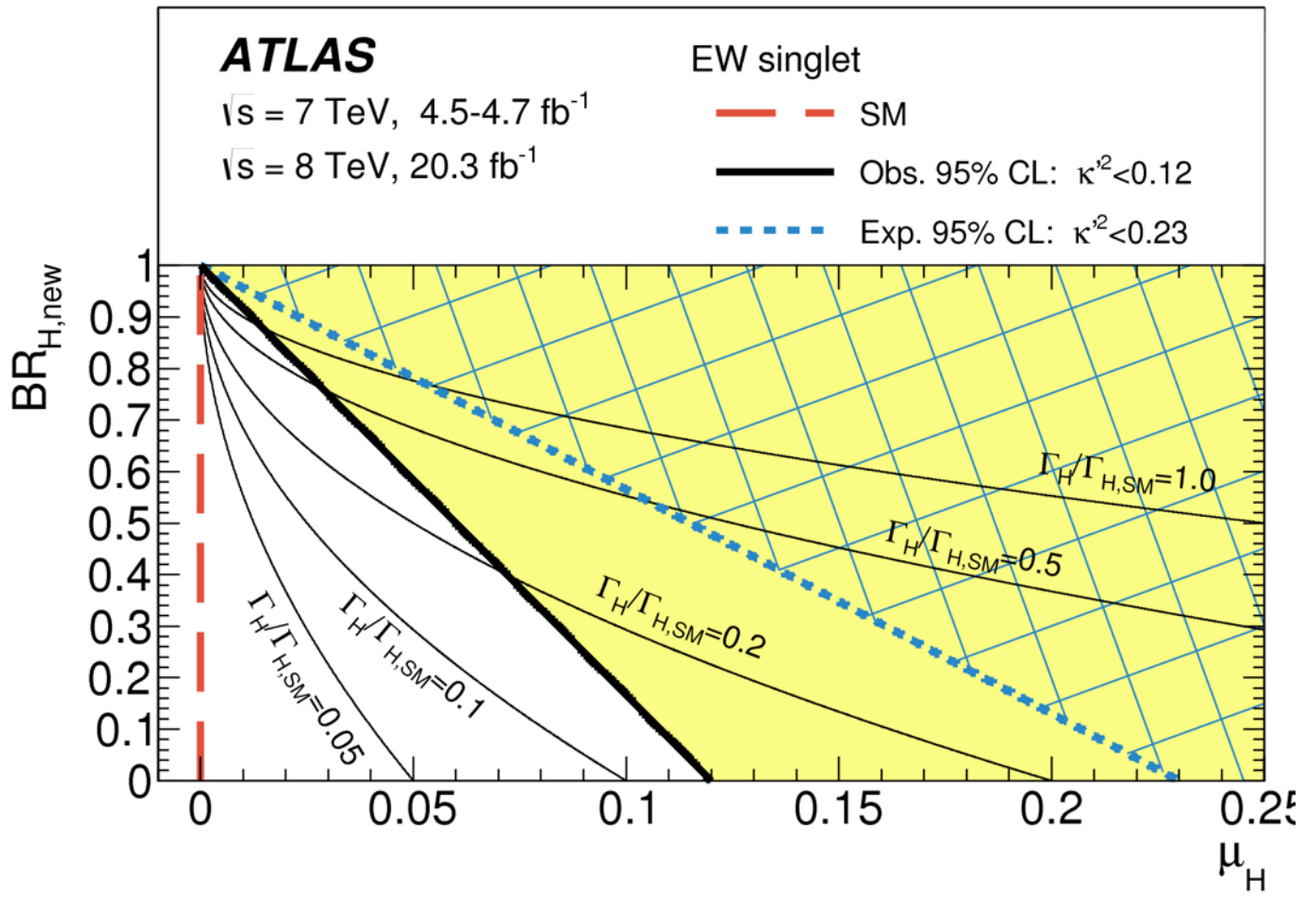


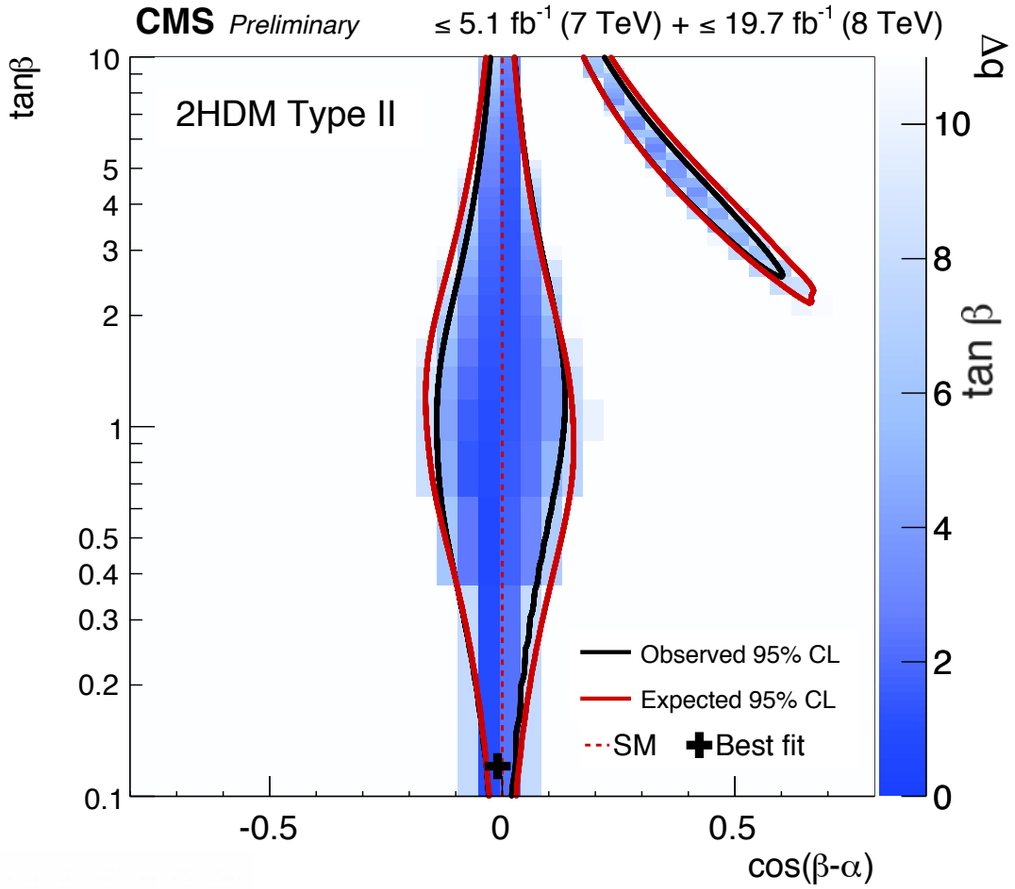


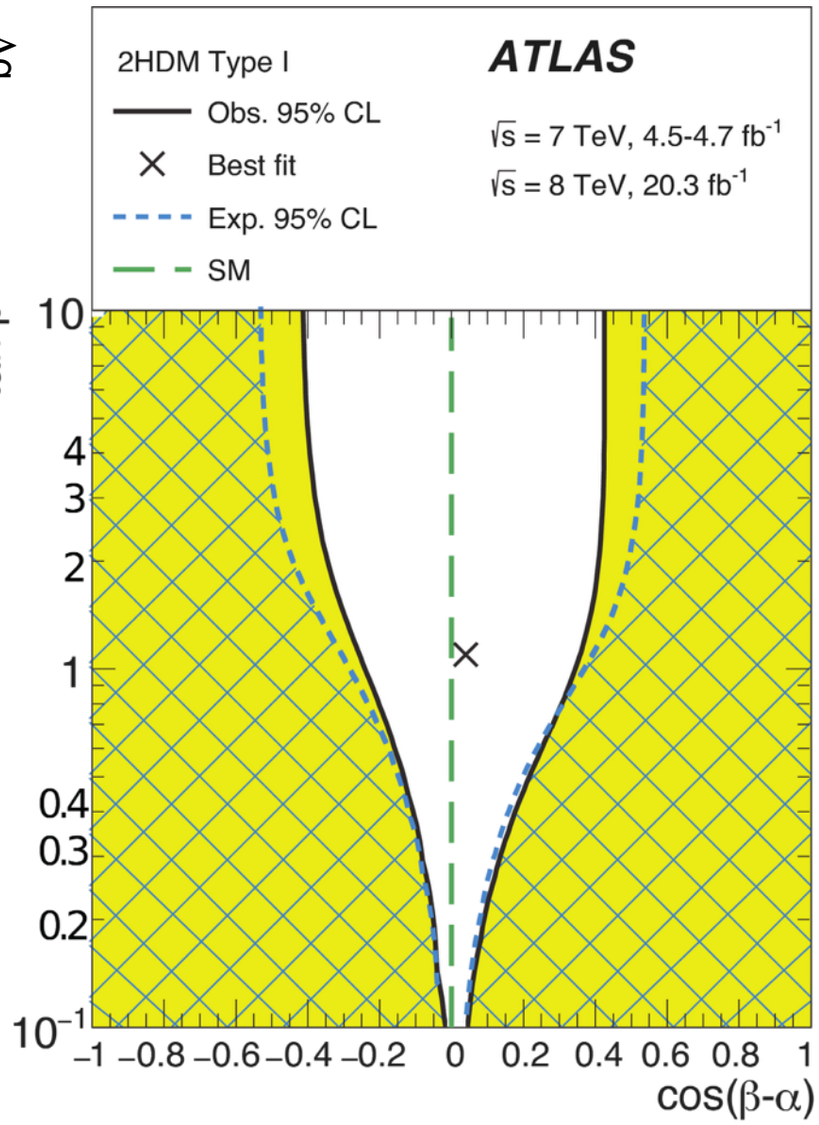
ATLAS: JHEP11(2015)206

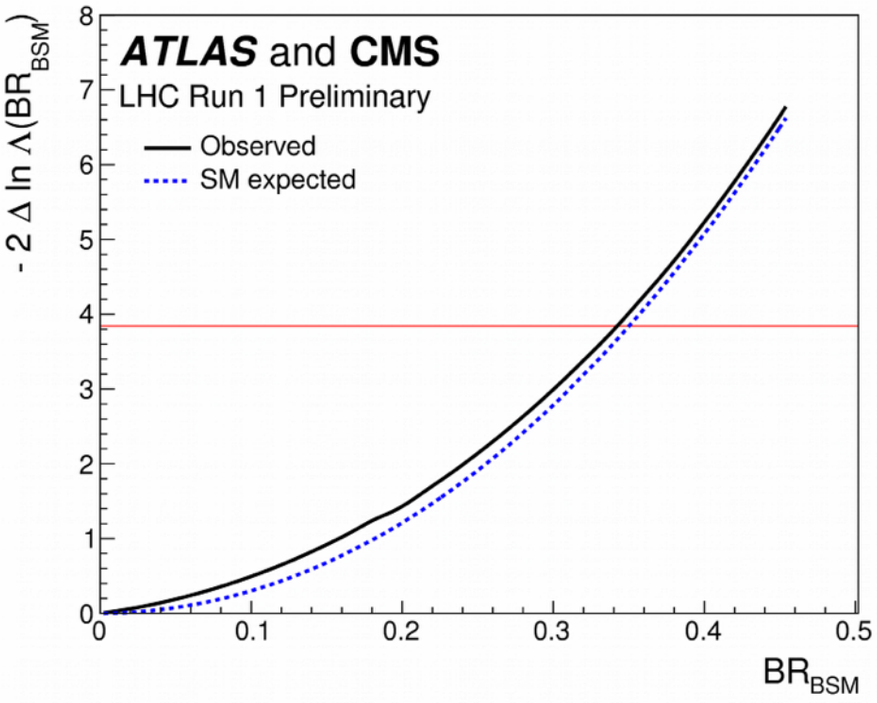
2015 dataset already competitive for some of these

What was the landscape at the start of Run II?

- Also, the h(125) observation gives us indirect constraints on new models







$BR_{BSM} < 0.34$ at 95% C.L. (assuming $k_V \leq 1$)

ATLAS-CONF-2015-044 **CMS-PAS-15-002**

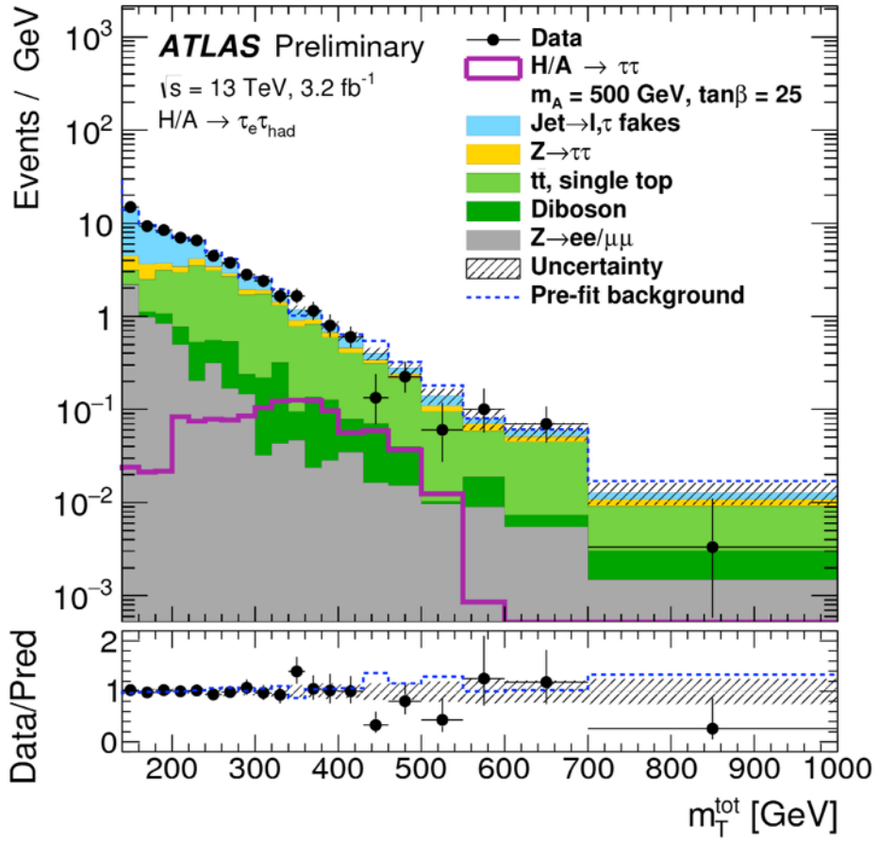
MSSM H→ττ

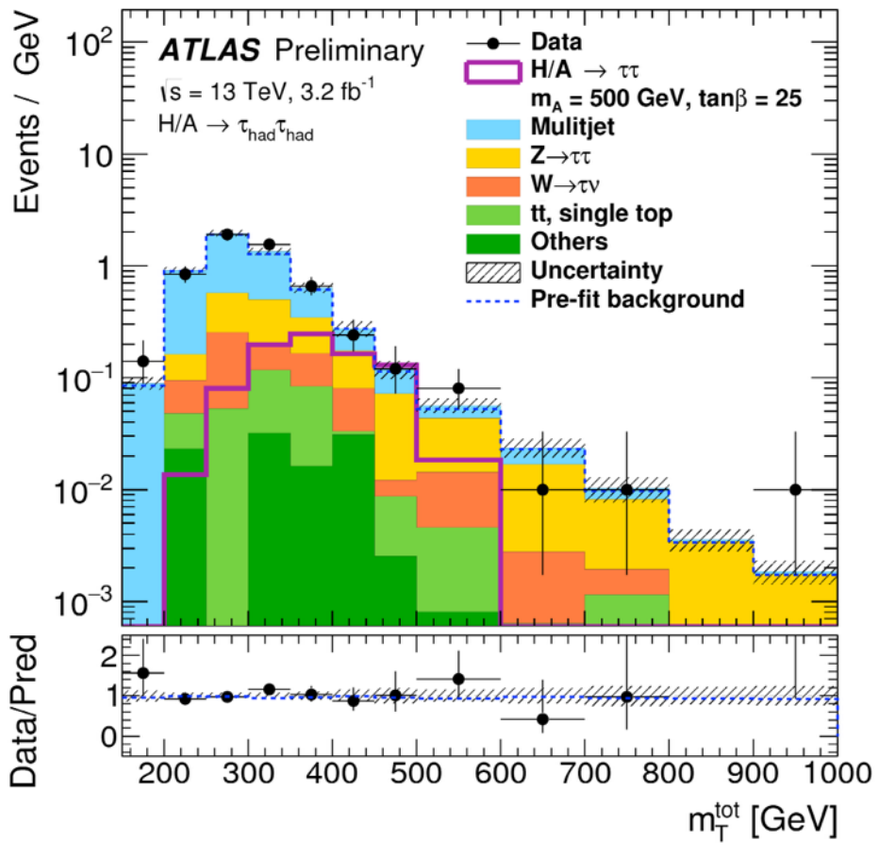
- 13 TeV !
- **Key channel: Hττ provides sensitivity in MSSM at high tanβ, and in 2HDM at the alignment limit**

ATLAS-CONF-2015-061

- Analysis targets three channels with different τ decay modes:
  - $\tau_{had}\,\tau_{had}$ (Single τ_{had} trigger , OS candidates, DeltaPhi>2.7)
  - $\tau_{l}\,\tau_{had}$ (Single lepton trigger, OS candidate DeltaPhi>2.4, M_T range)
- Misidentified leptons estimated on data
- Discriminant variable: total M_T of the system

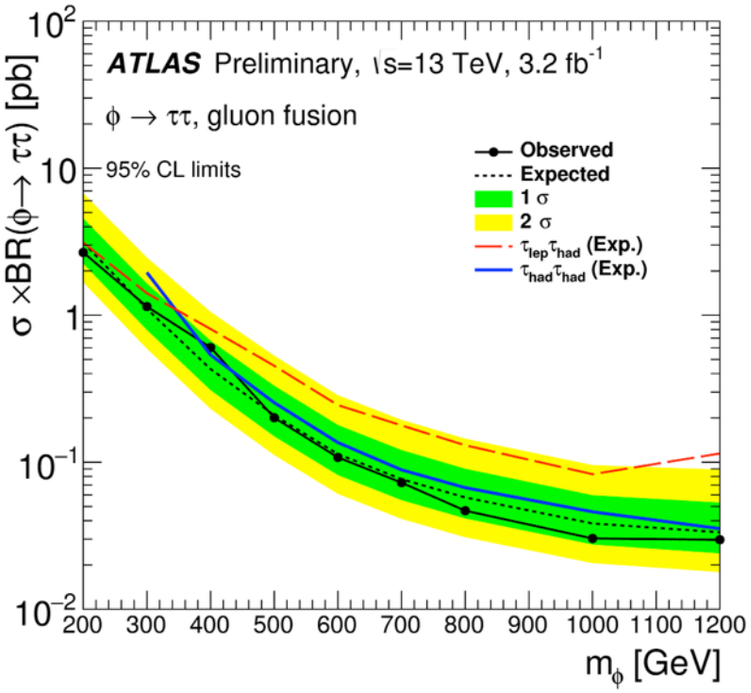
$$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) \equiv \sqrt{2 p_{\mathrm{T}}(\ell) E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}}))}.$$

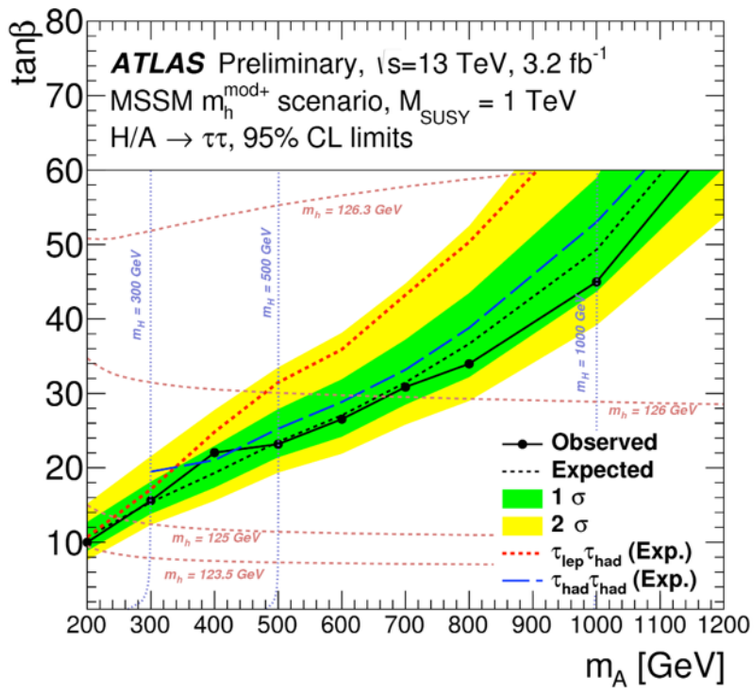


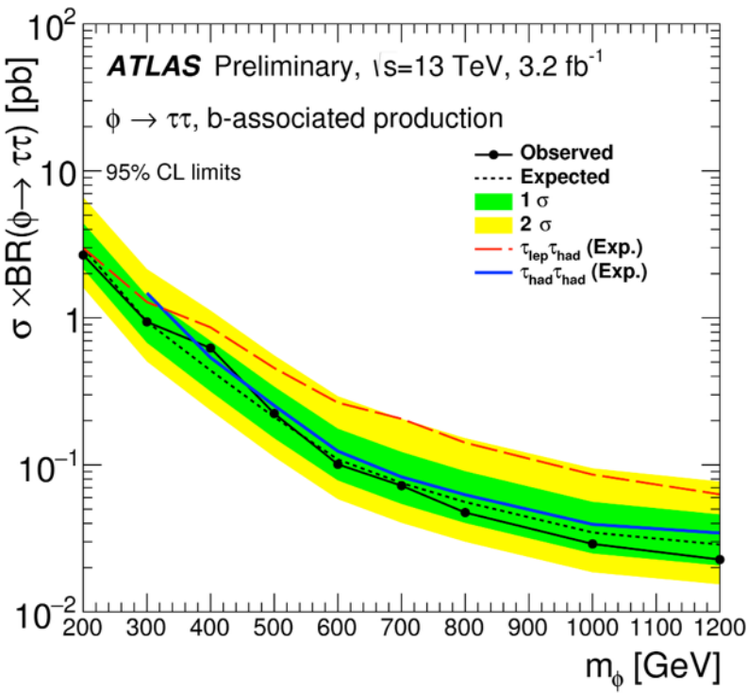


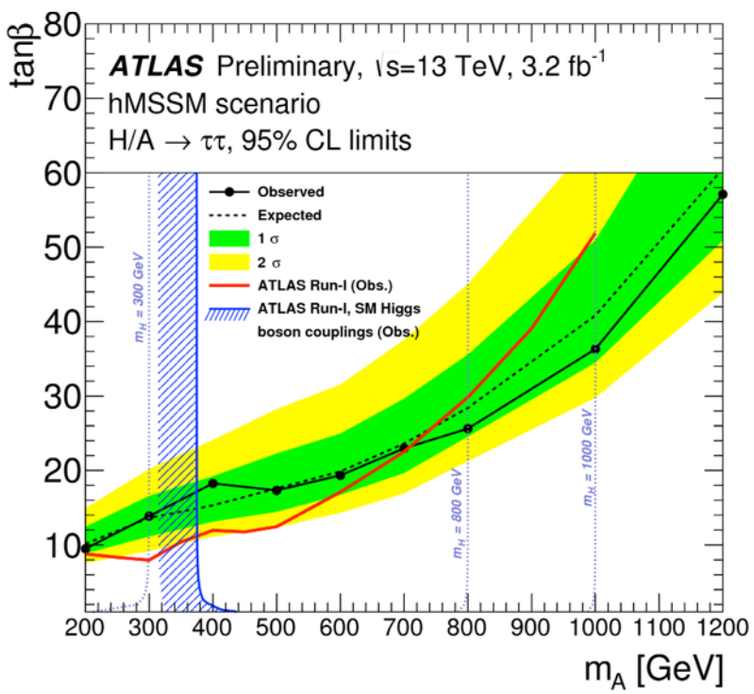
MSSM H→ττ

- Model independent and model dependent results in several MSSM benchmarks









No evidence for BSM Higgs

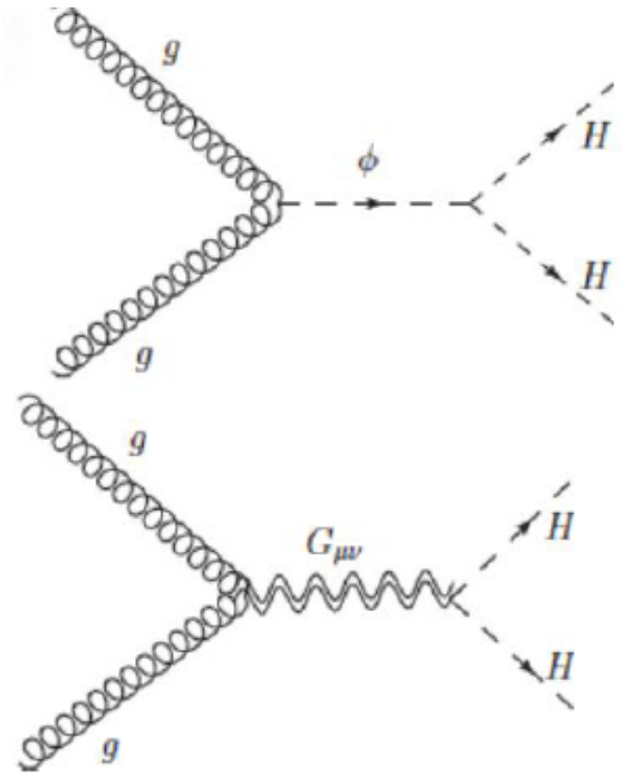
Sensitivity already exceeds ATLAS Run-1 for m_A>700 GeV.

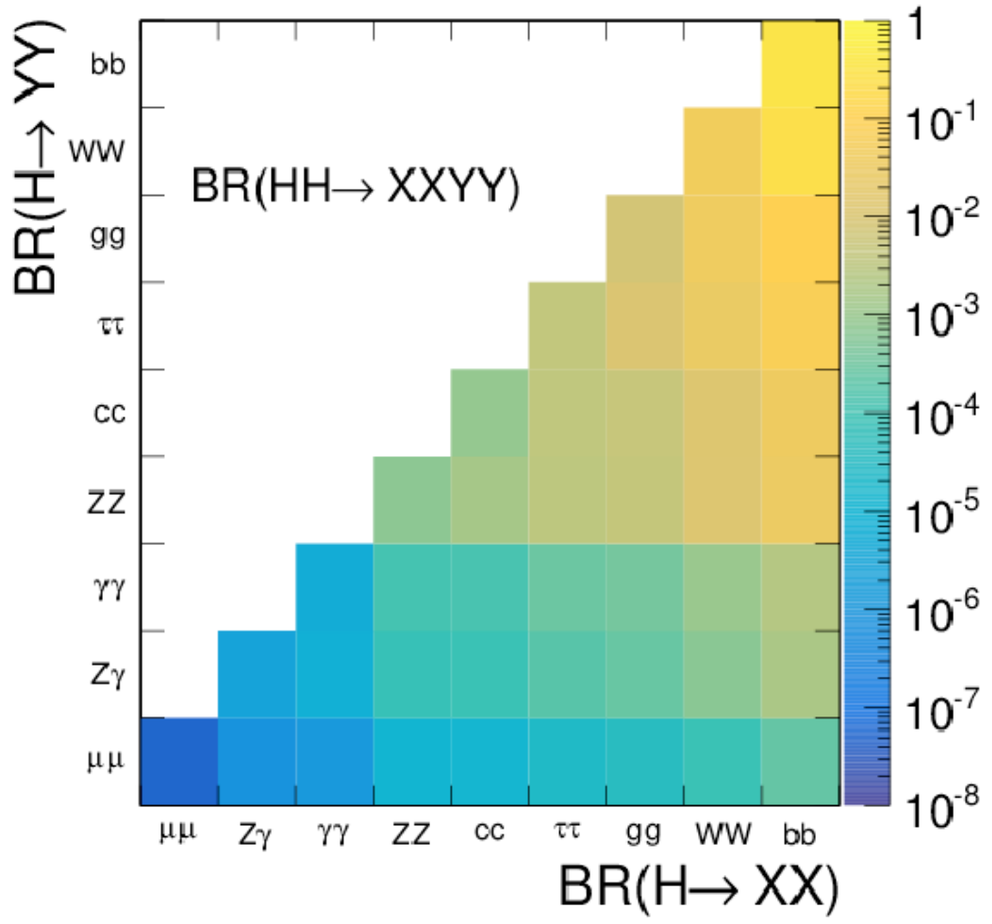
The most stringent constraints on tanβ for the search excludes tanβ>10 for m_A=200 GeV

ATLAS-CONF-2015-061

DiHiggs Searches

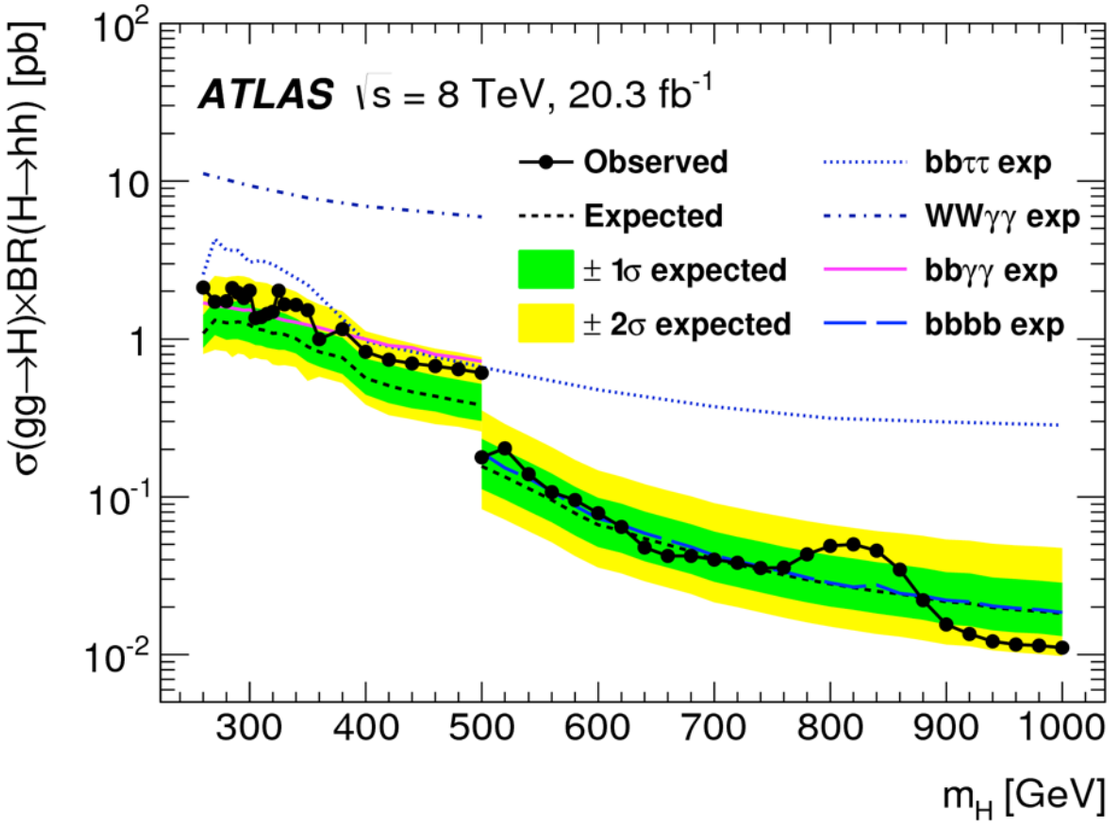
- **Non-Resonant production (self-coupling)**
  - First results starting to arrive
  - SM production requires ~O(3/ab)@14TeV
  - Excesses of non resonant hh production —> new physics
- **Resonant production**
  - Predicted in the 2HDM: for some parameters of these models H—>hh is the dominant decay channel (low tanβ and $2m_h<m_H<2m_t$)
  - Radion (spin-0) and Graviton (spin-2) interpretation (M>250 GeV)



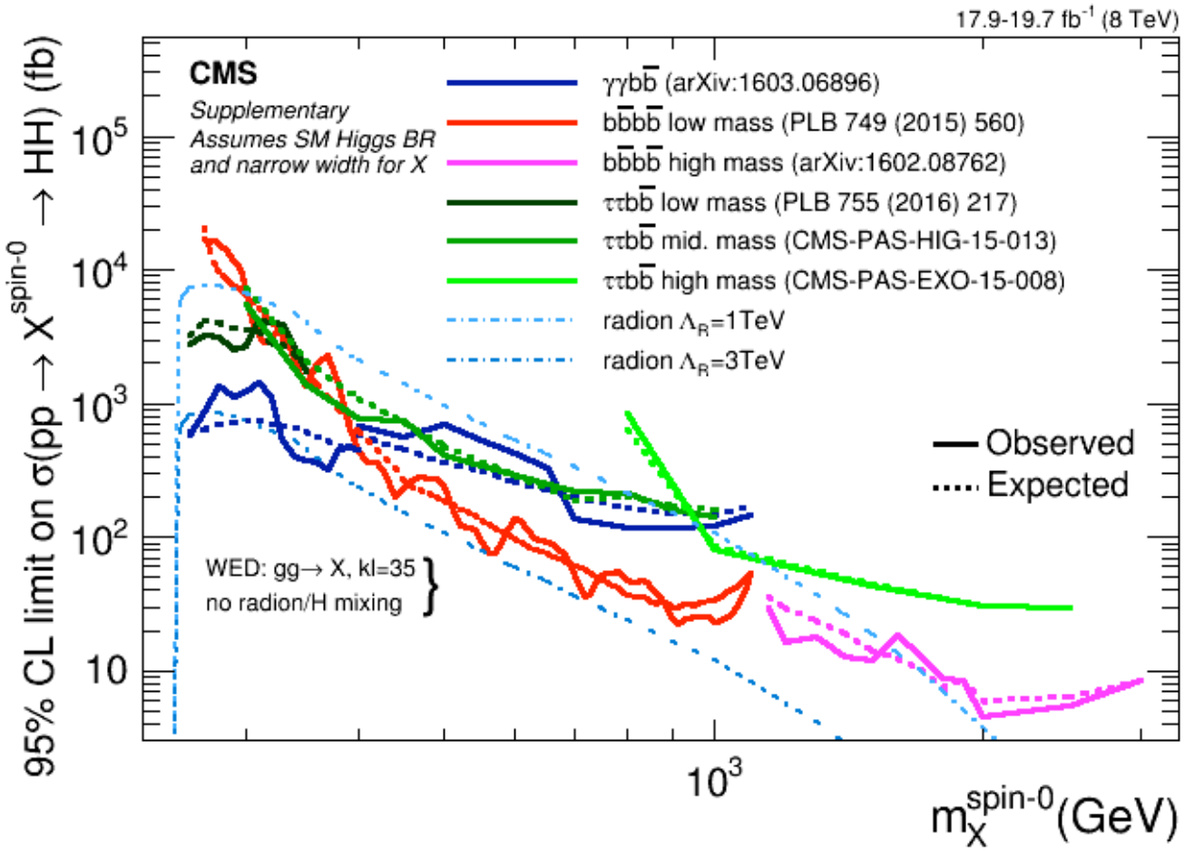


DiHiggs Searches

Large number of final states being probed



ATLAS: Phys. Rev. D 92, 092004 (2015)



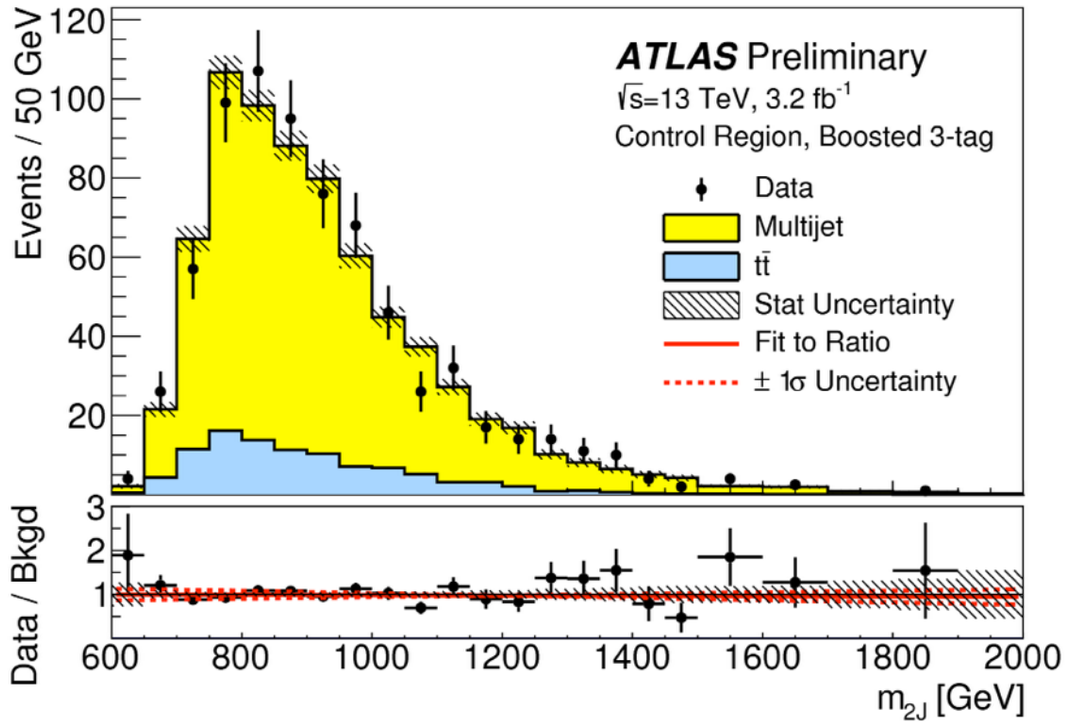
CMS: arXiv:1603.06896

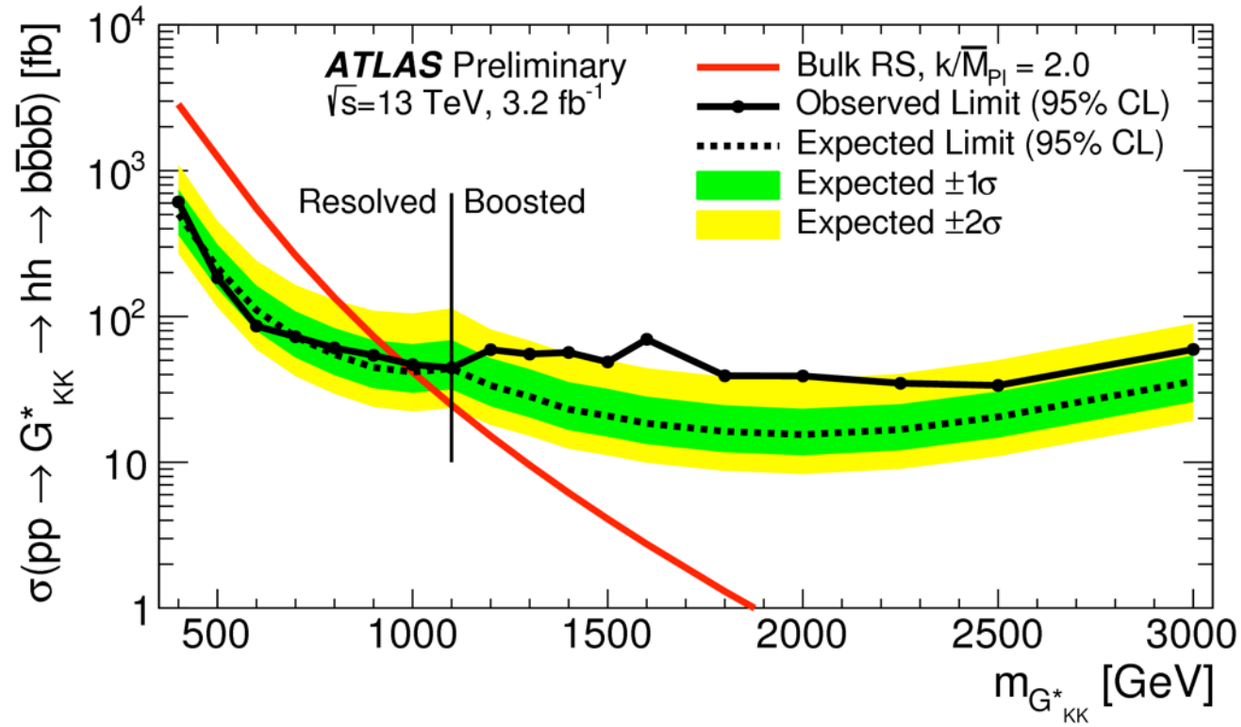
hh→4b

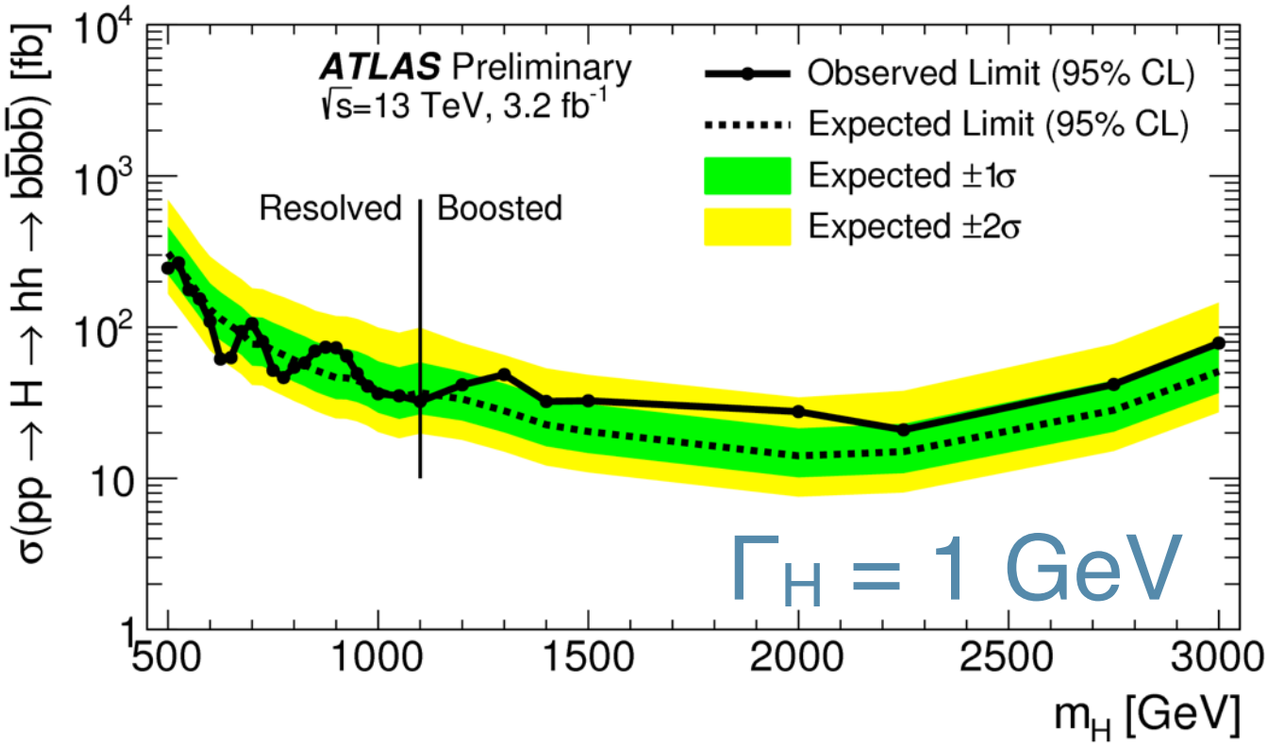
ATLAS-CONF-2016-017

CMS-PAS-HIG-16-002

- Targets different mass regimes (resolved 4b /boosted 2j)
- Event selection selects 3/4 b-tagged jets such that two di-jet pairs are consistent with the Higgs mass.
- Data driven background estimations
- Non-resonant production of Higgs-boson pairs —> less than 1.22 pb @ 95%CL





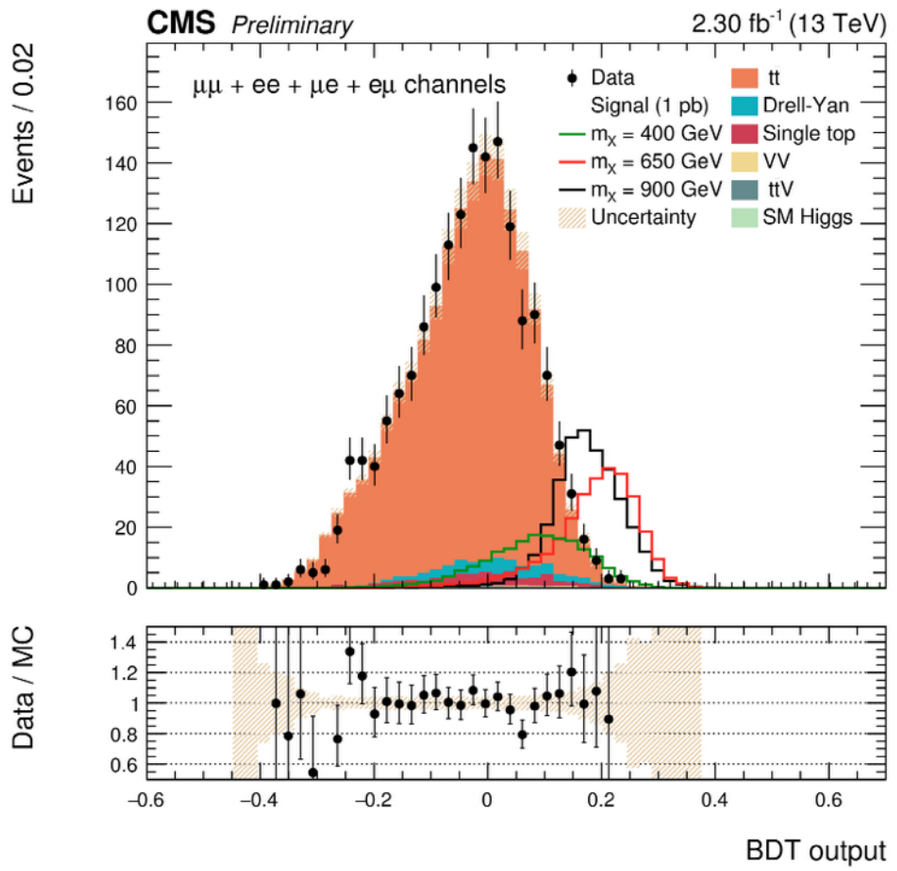


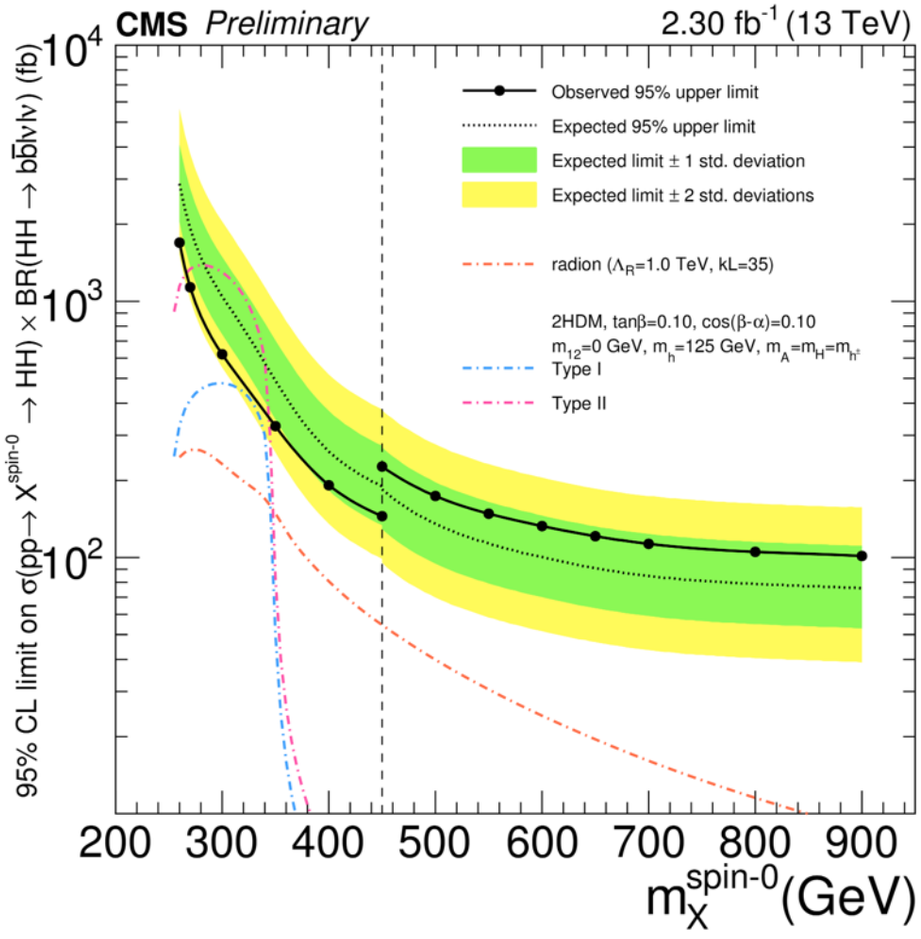
CMS: upper limits at a 95% confidence level in the mass range from 260 to 1200 GeV

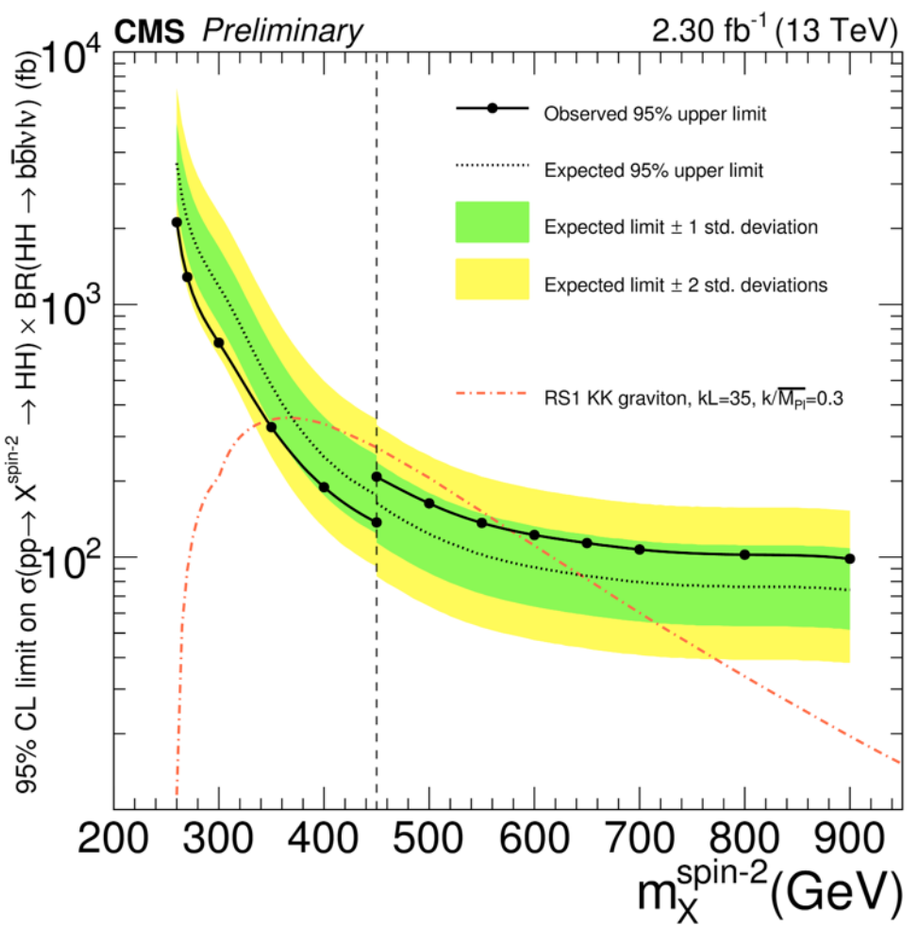
hh→WWbb

- Final state: 2l + 2b (m_{ll} not in the Z mass range)
- Based on the invariant mass distribution of the b-jet pair
- S/B discrimination through a BDT with kinematic variables

CMS-PAS-HIG-16-011





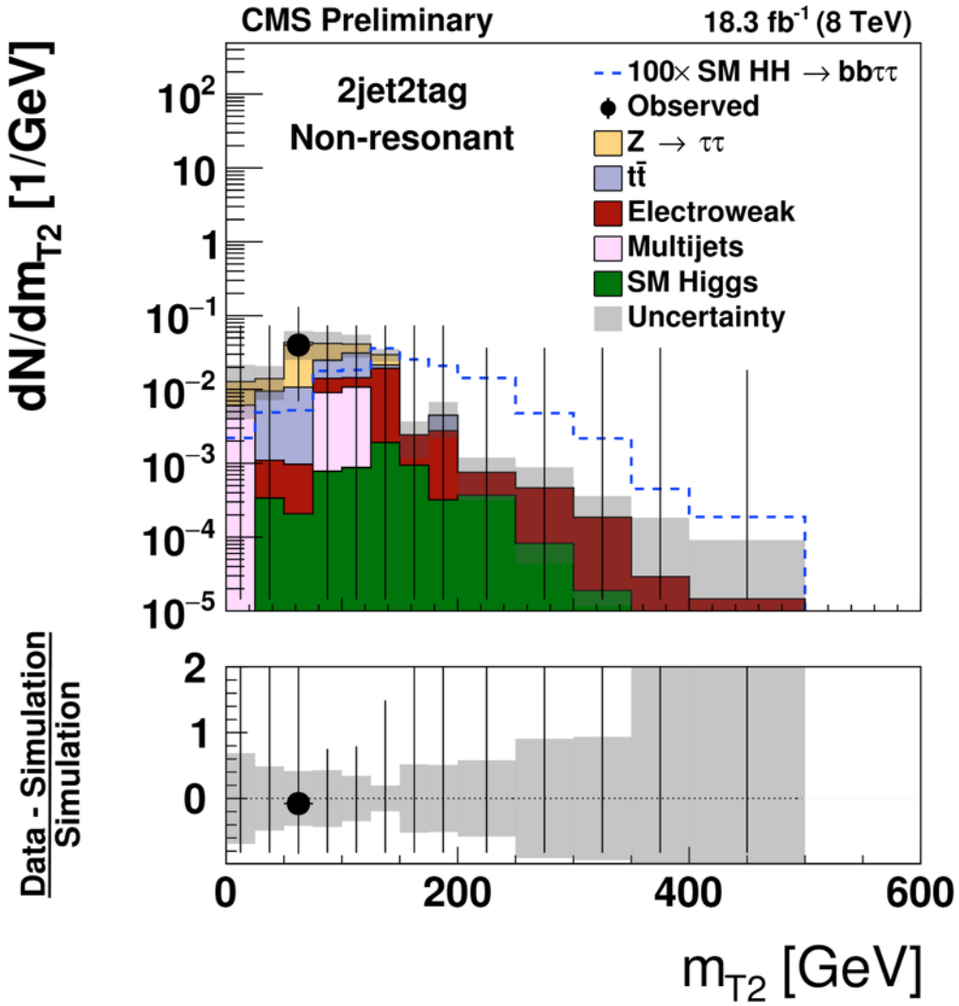


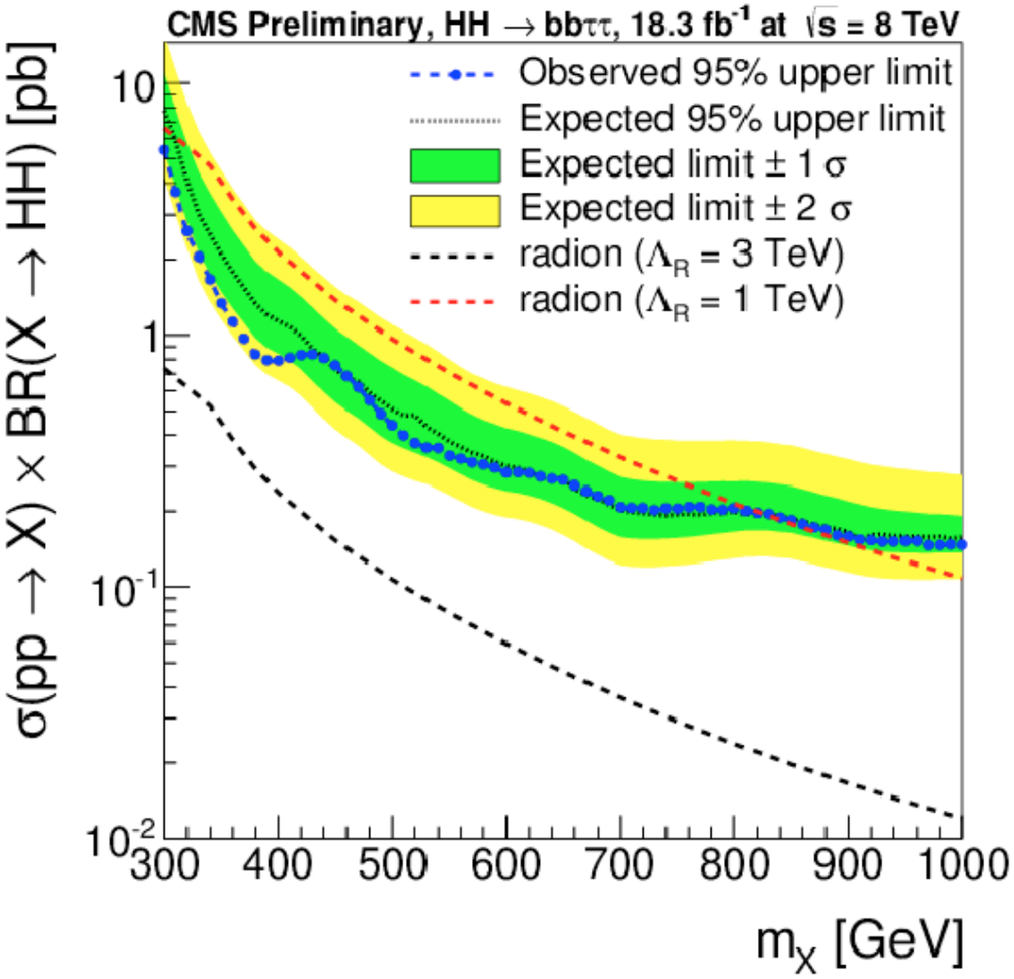
hh→bbττ

CMS-PAS-HIG-15-013

8TeV

- New resonant and non-resonant interpretations
- Categories: bbτ$_h$τ$_h$ x (0-1-2 bjets)
- Best single observed limit on non-resonant di-Higgs production @ 8TeV, 0.59(0.94) pb → 53 (84) x SM (*)





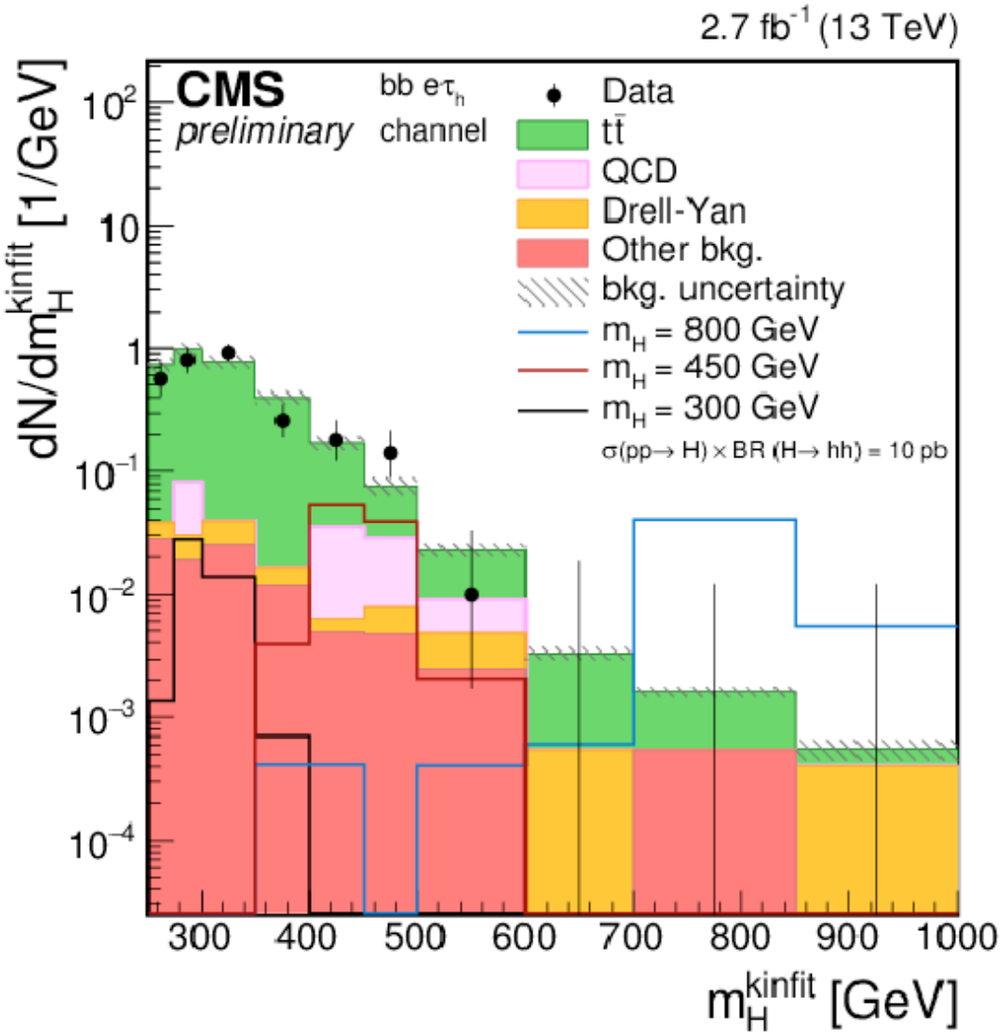
(*) ATLAS combination of Run I HH: 70 (48) x SM

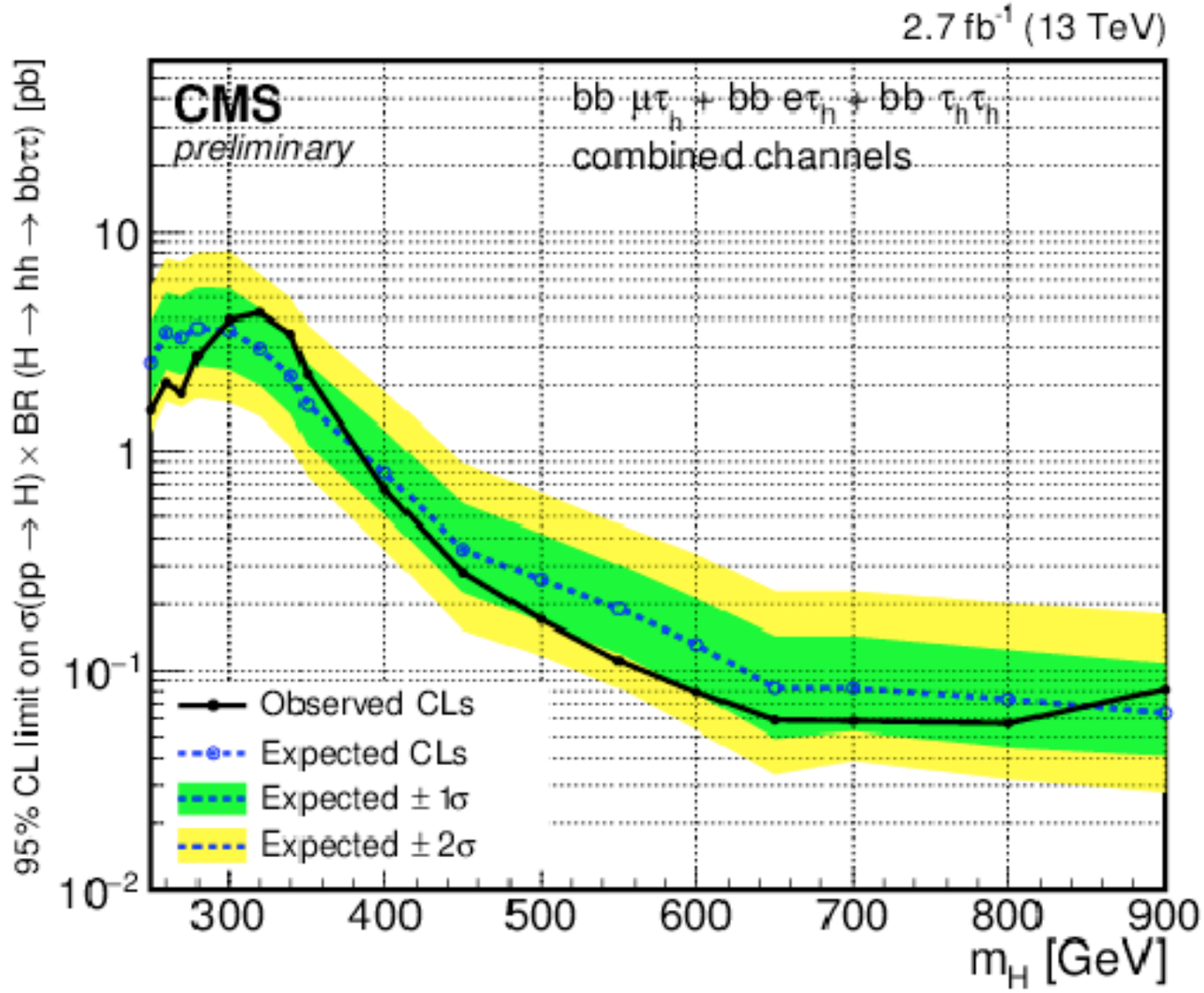
hh→bbττ

CMS-PAS-HIG-16-012

CMS-PAS-HIG-16-013

- Resonant and non-resonant interpretations
- Categories: $bb\tau_e\tau_h$, $bb\tau_\mu\tau_h$, $bb\tau_h\tau_h$
- Model independent search: Resonant limit: <1.53-0.082 pb (2.53-0.063) @95%CL
- Non Resonant limit as a function of κ_λ. 8.8 (7.2) pb (200xSM) for κ_λ=1

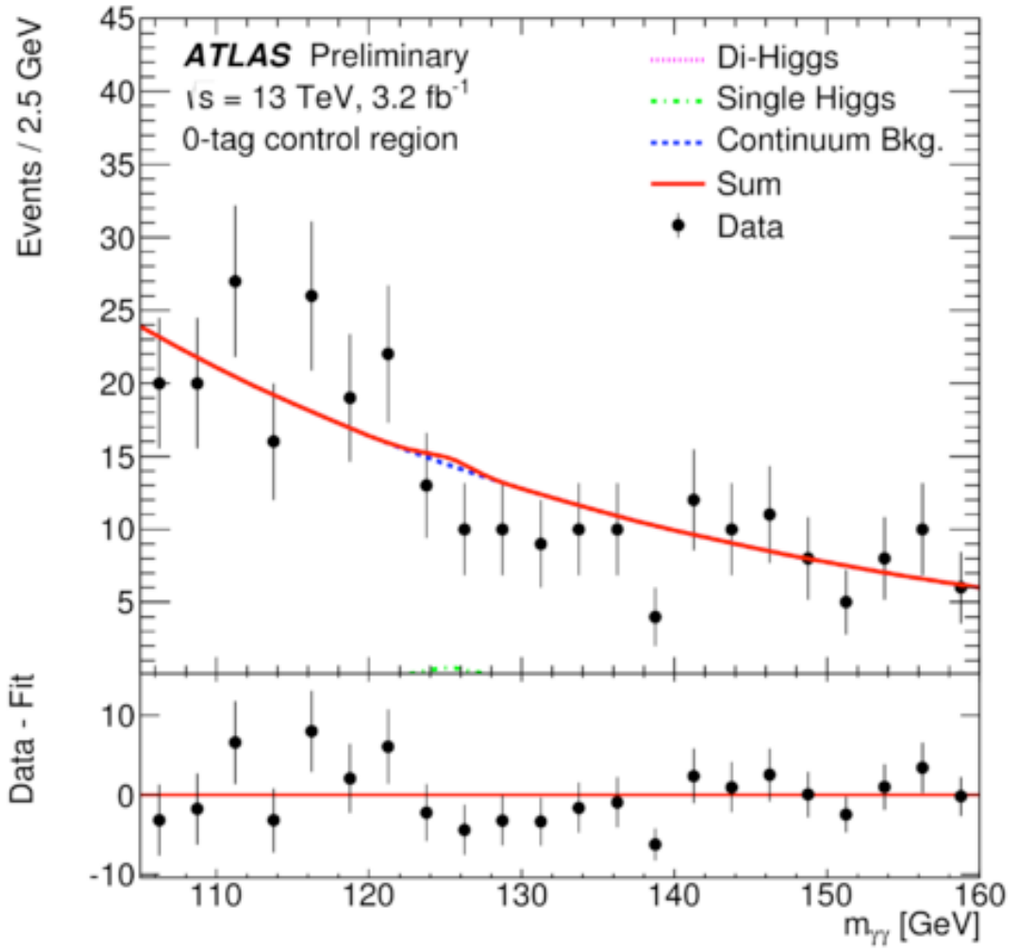




hh→bbγγ

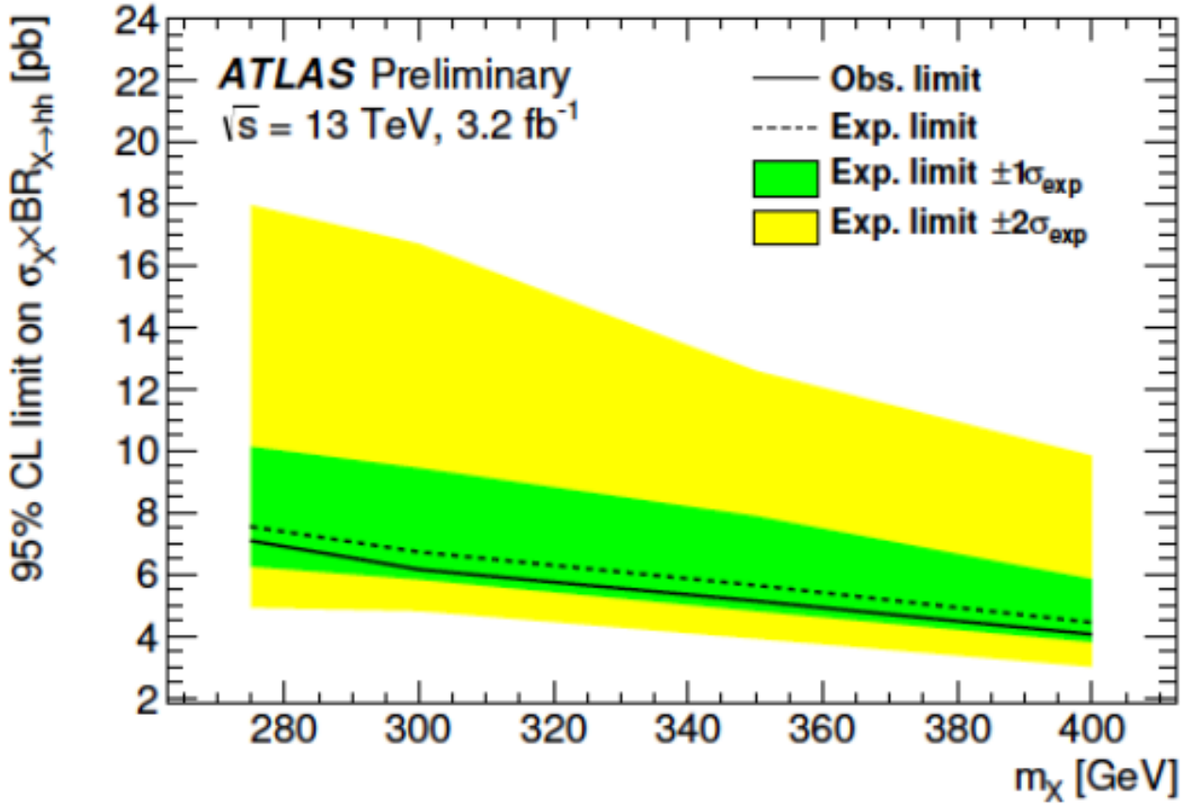
ATLAS-CONF-2016-004

- high bb branching ratio + excellent γγ mass resolution



Non-Resonant Analysis:
< 3.9(5.4) pb @ 95 % CL

POSTER BY **LEONOR CERDÁ ALBERICH**



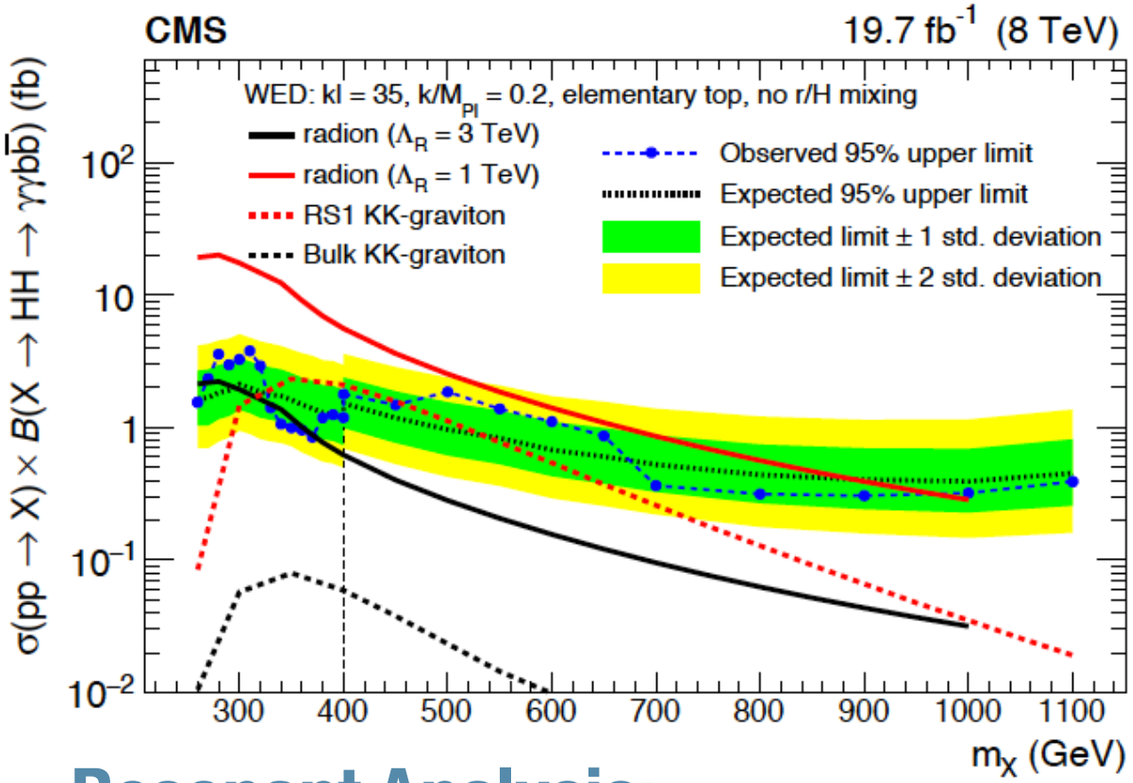
Resonant limit (narrow resonance):
ranges between 7.0 pb and 4.0 pb (7.5 pb, 4.4pb expected) @ 95%CL for masses of the resonance between 275 and 400 GeV

hh→bbγγ

CMS: arXiv:1603.06896

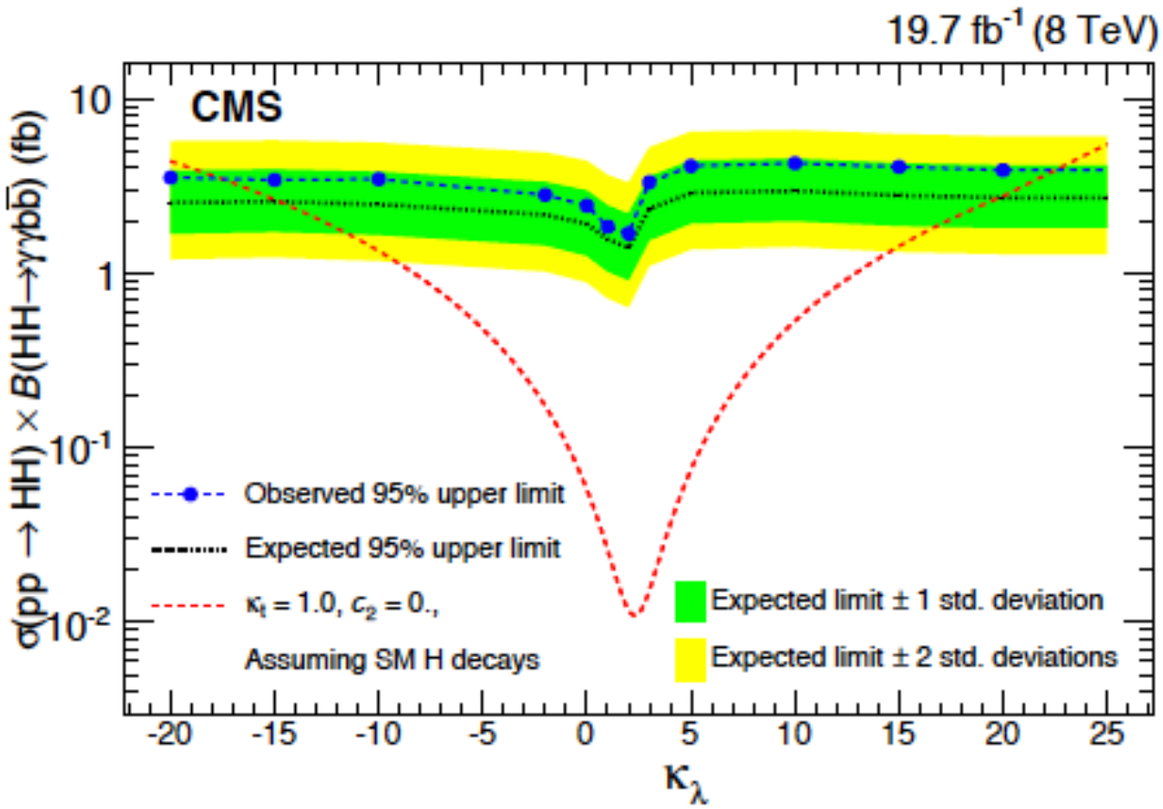
8TeV

- high bb branching ratio + excellent γγ mass resolution



Resonant Analysis:

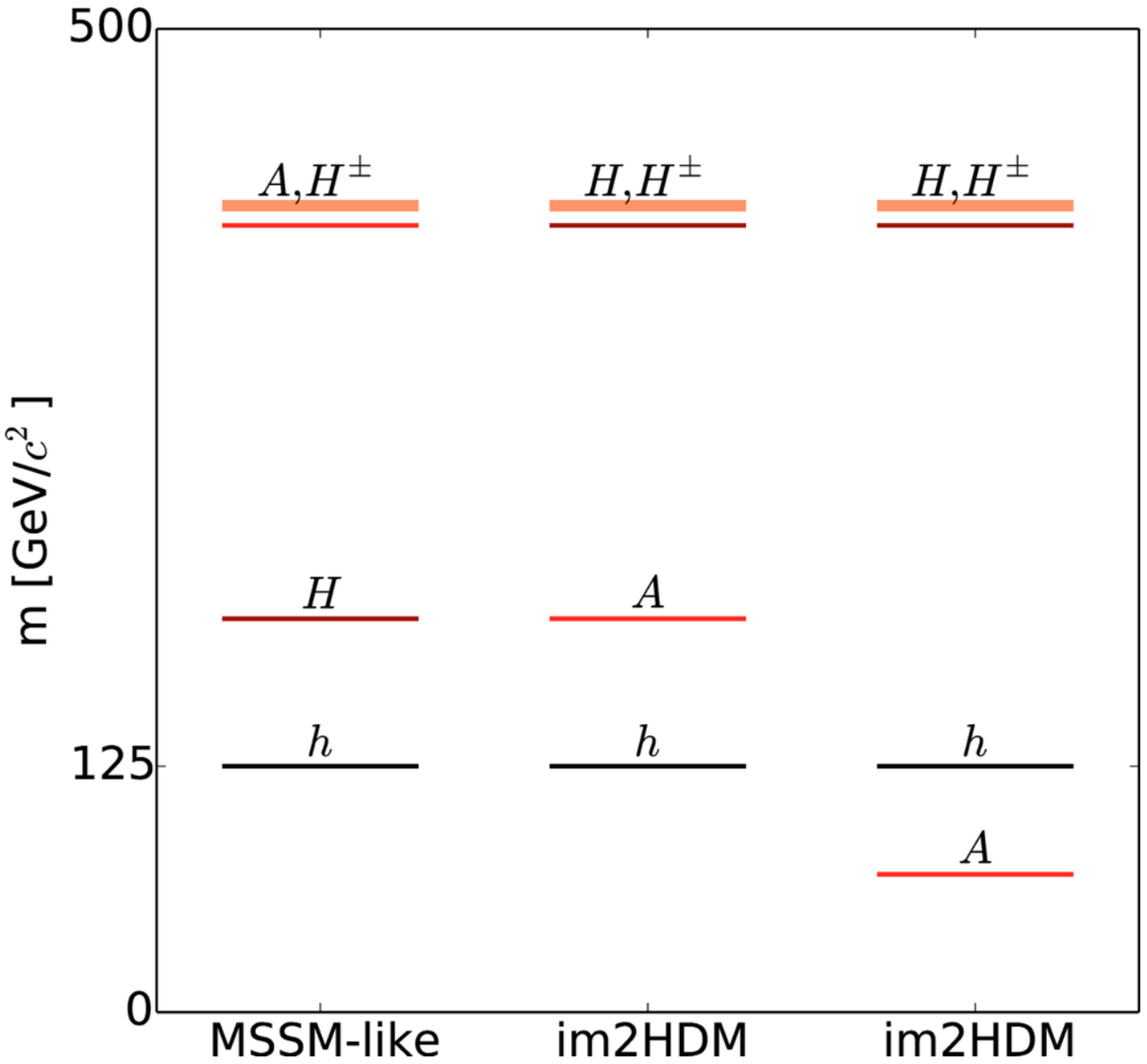
- radion (ΔΓ=1TeV) excluded for M<980 GeV
- RS1 KK graviton excluded for 325 GeV-450 GeV (k/MPI=0.2)



Non-Resonant Analysis:

- SM-like limit on the σ(gg→HH→bbγγ)<1.85(1.56)fb (74xσ$_{SM}$)
- Anomalous couplings interpretation: values of the self coupling excluded for κλ<-17 and κλ>25

2HDM searches

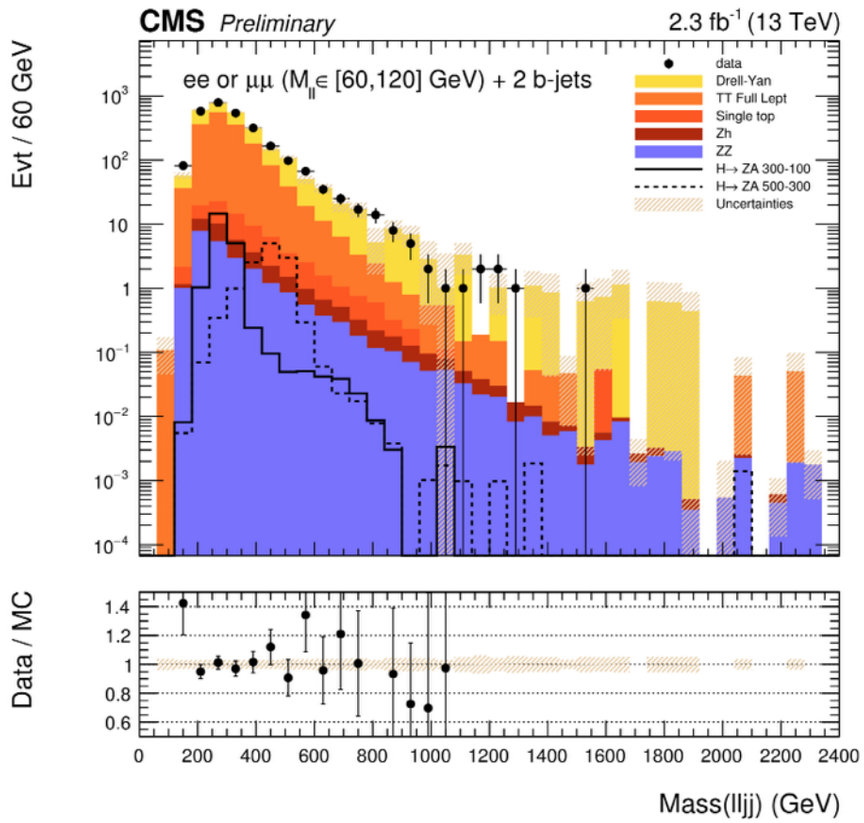


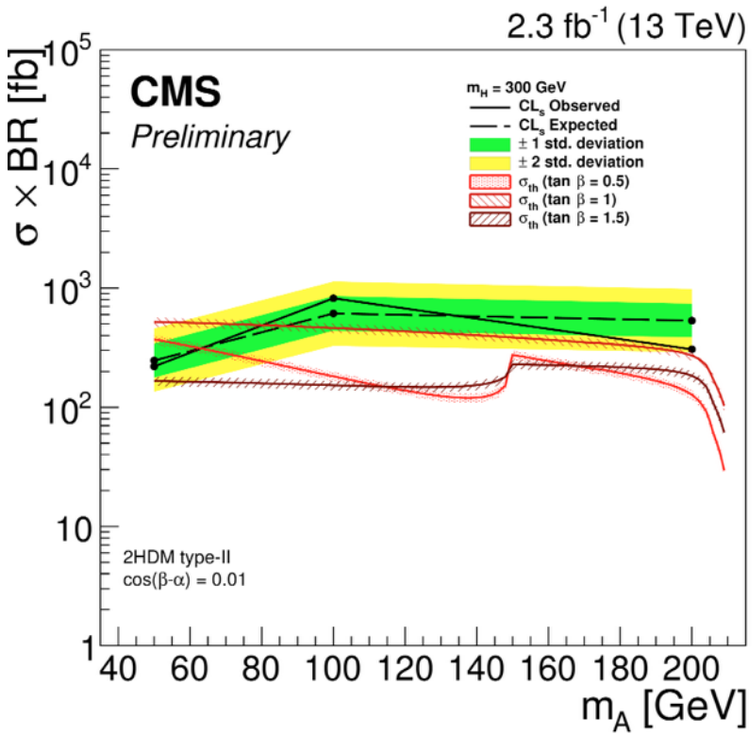
- Most of the analyses in this talk can be interpreted in terms of 2HDM, but the following target these models specifically

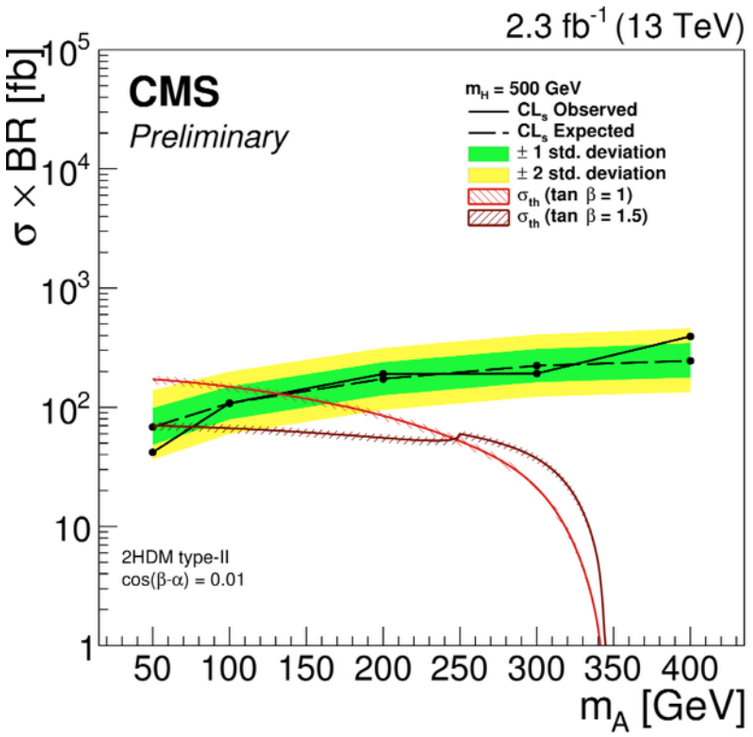
H→ZA

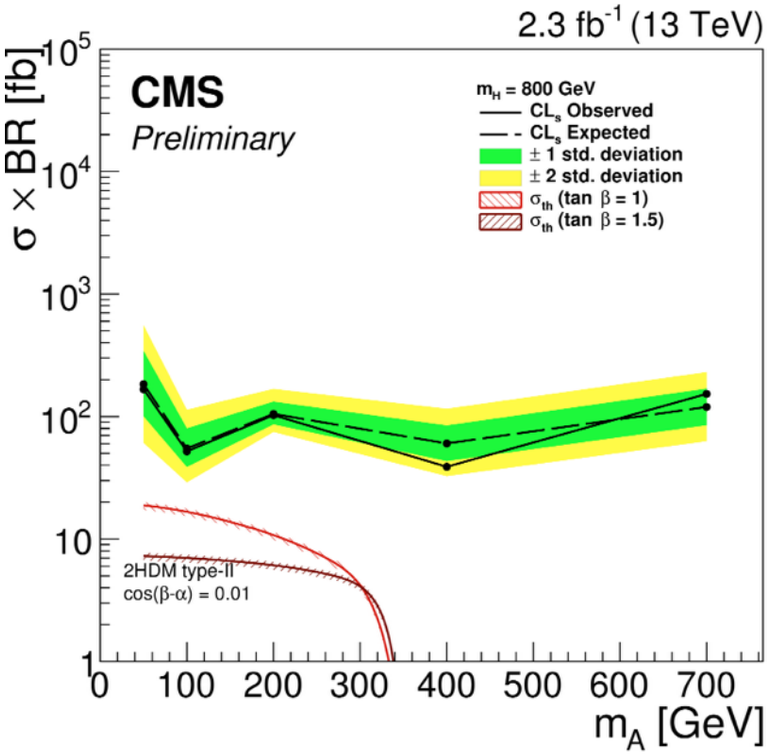
CMS-PAS-HIG-16-010

- **Interpretation in the context of Higgs-doublet-model with twisted custodial symmetry, leading to a mass triplet $m_{H^{\pm}} \sim m_H$, and pseudoscalar A**
- 2l+2b final state
- Final discriminant: mass of the full system (llbb)
- Limits are set on cross section times branching ratio for three m_H hypotheses, as a function of m_A.





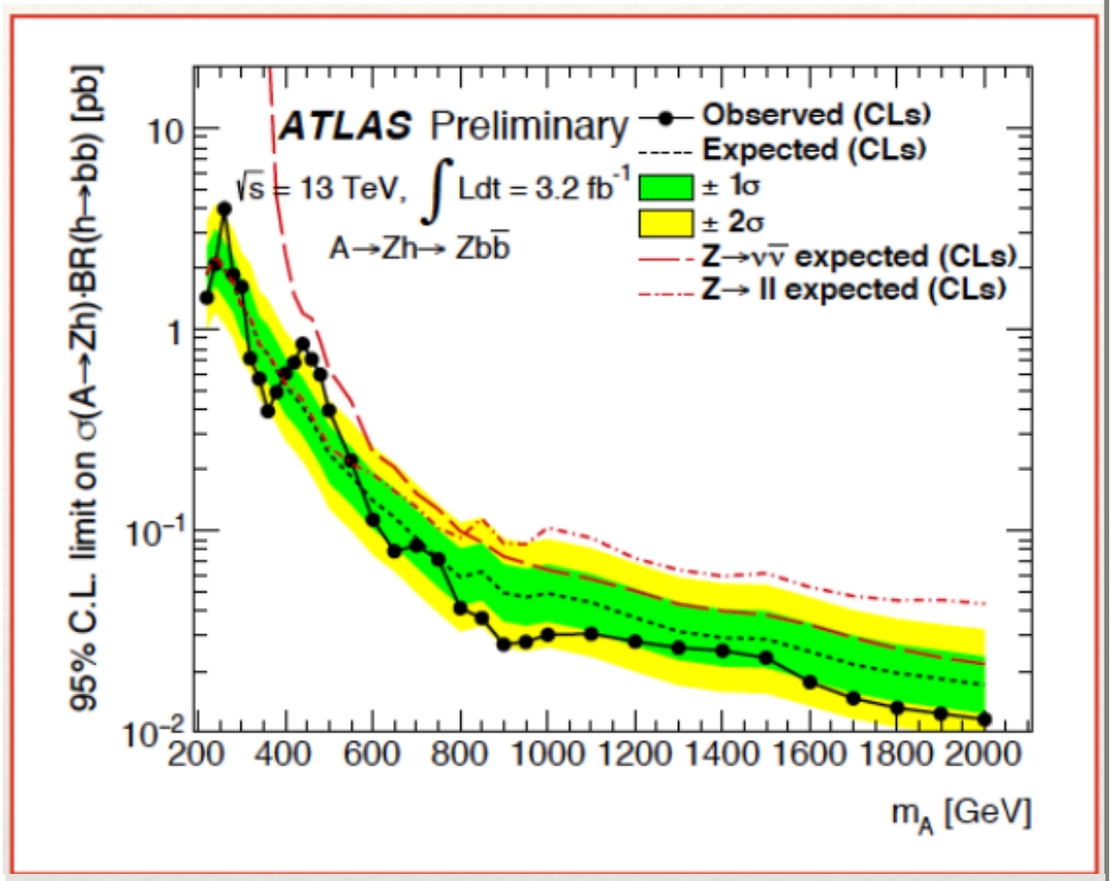


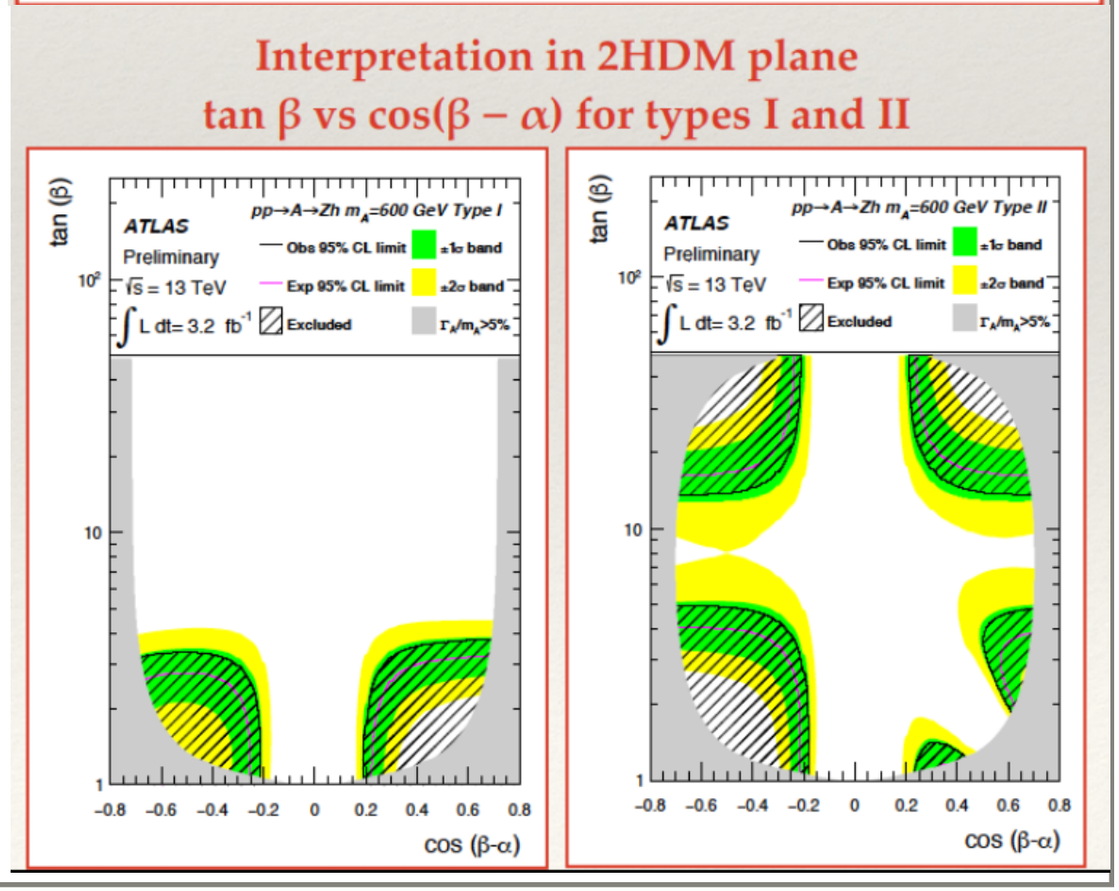


A→Zh

- 2l+2b and 2v+2b final states
- 2l+2b is similar final state to the CMS search, but different interpretation and analysis! CP odd scalar decaying to Z h(125)
- Categorised as a function of #leptons, #bs, and divided in resolved/boosted
- Final discriminant: mass of the full system (2l2b) or transverse mass of the system (2v2b)
- Interpretation in the 2HDM plane

ATLAS: SHOWN IN MORIOND

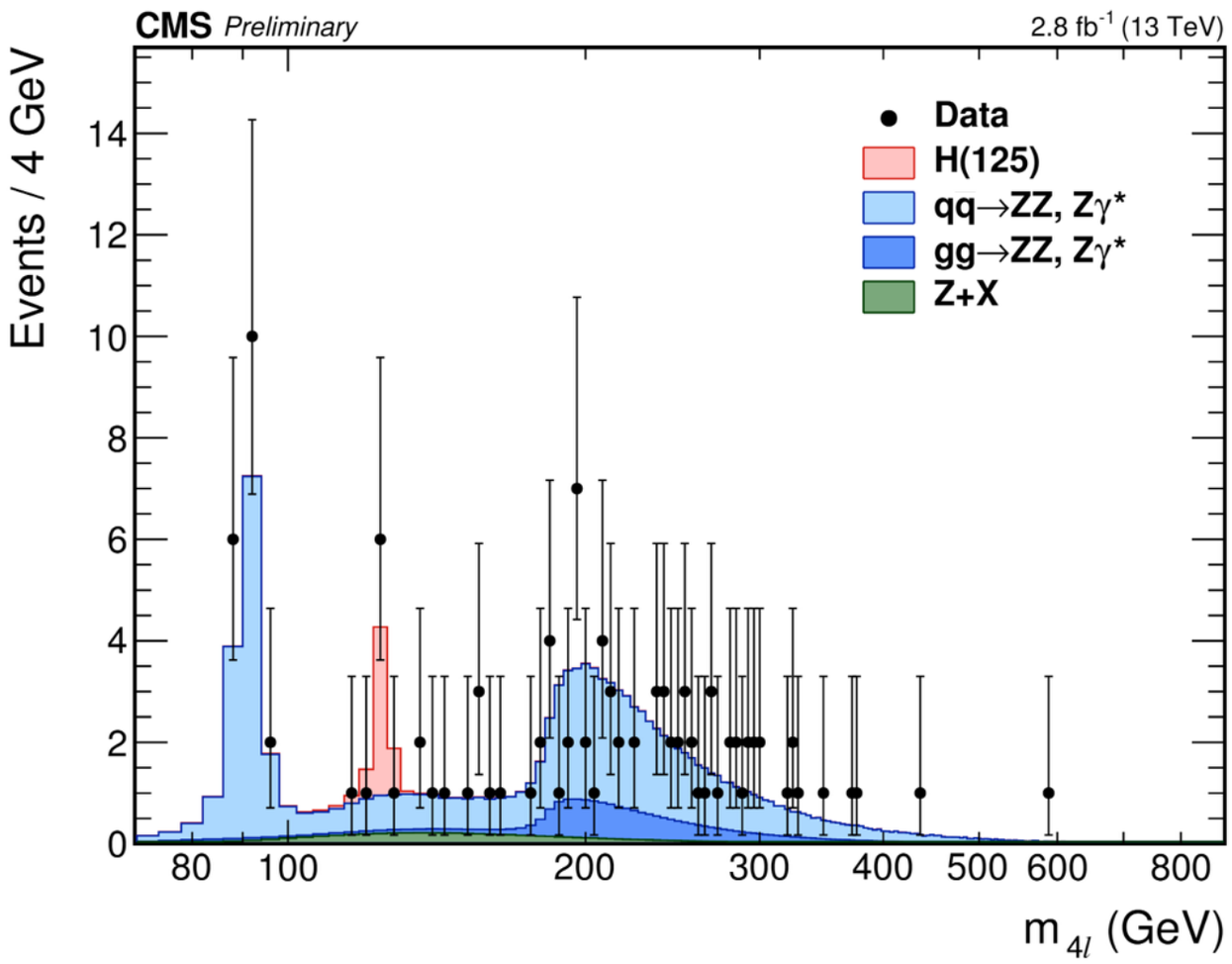


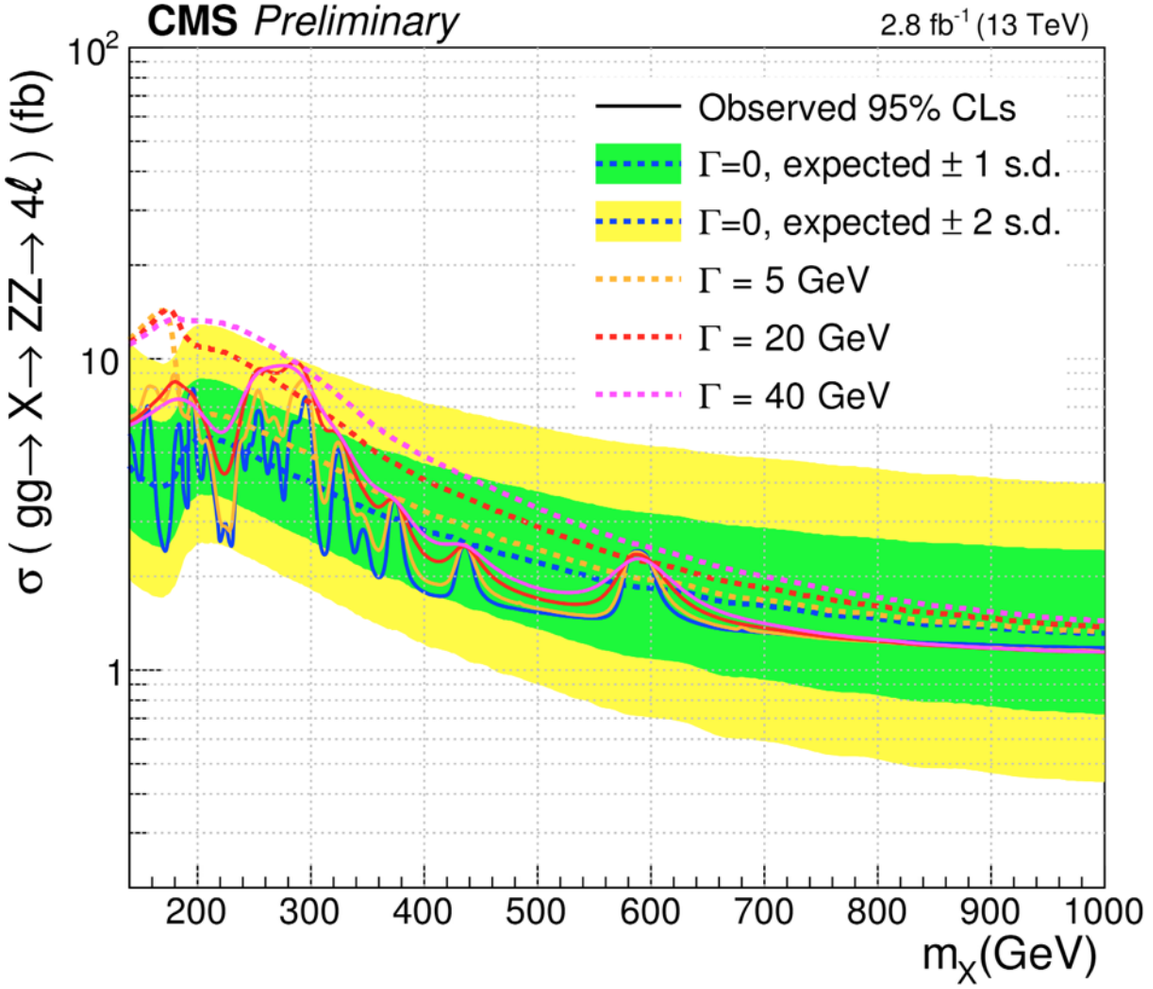


H→ZZ→4l

CMS-PAS-HIG-15-004

- Extension at high mass of the SM analysis shown yesterday by **Luca Fiorini**
- Narrow resonance search: up to 1 TeV
- Includes interpretation in 2HDM (m_H vs tan(β), type1 and type2)





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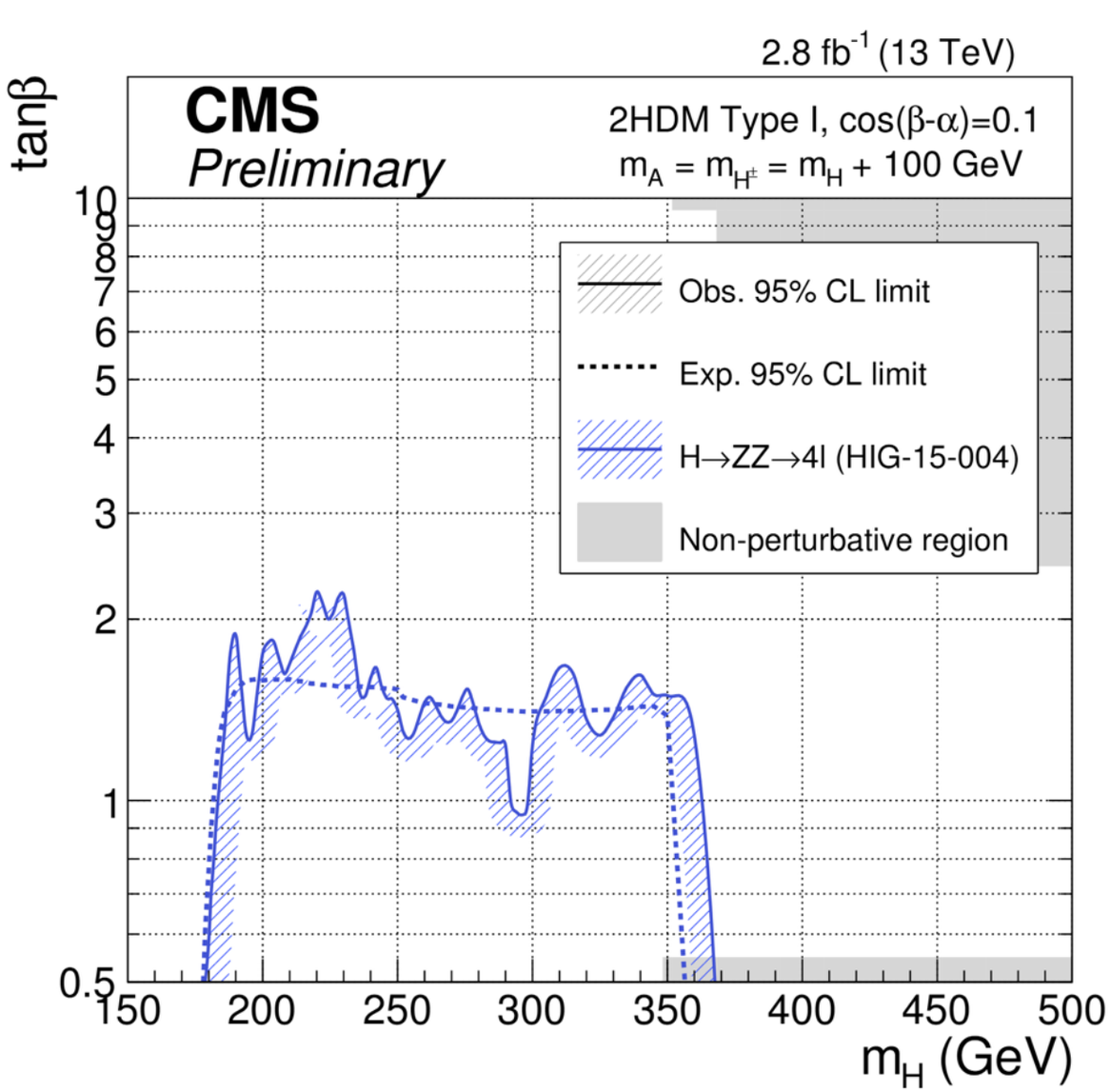
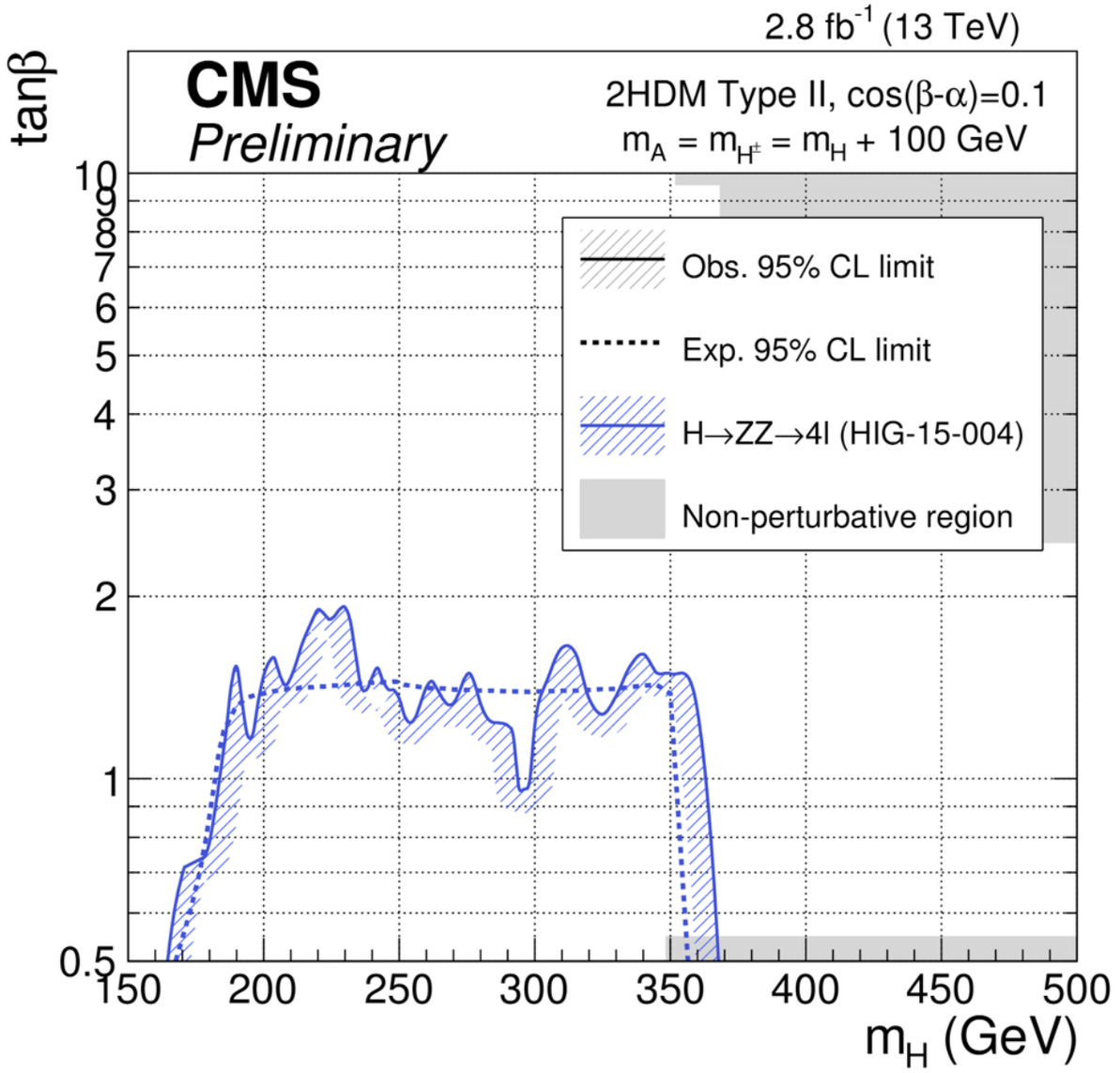


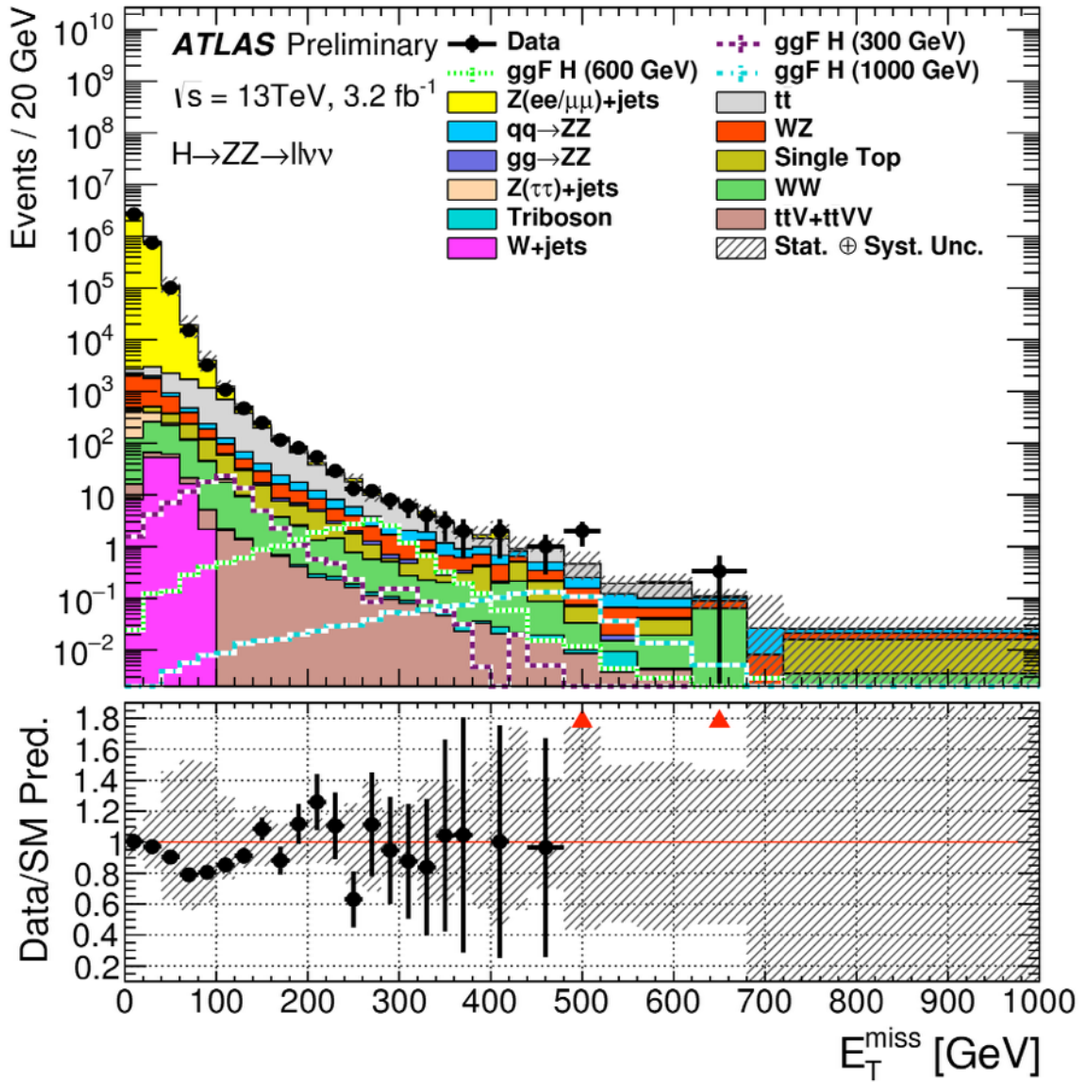


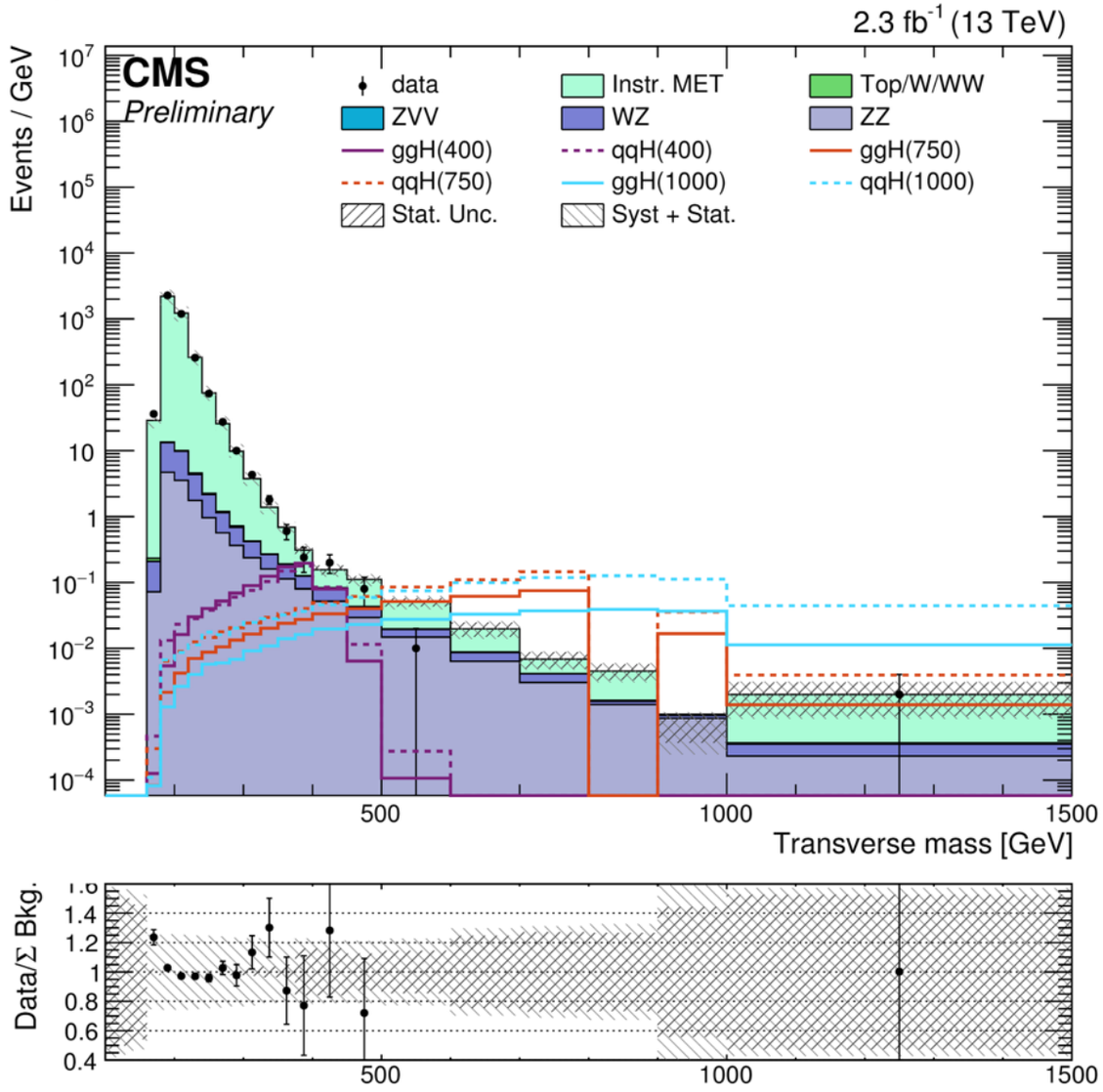
H→ZZ→2l2ν

CMS-PAS-HIG-16-001

ATLAS-CONF-2016-012

- 2 leptons + E_T^{miss} / M_T
- Data driven modelling of backgrounds —> good prediction of tails
- ATLAS: Limits on narrow width high mass resonance and RS graviton
- CMS: high mass resonance + EW Singlet and 2HDM



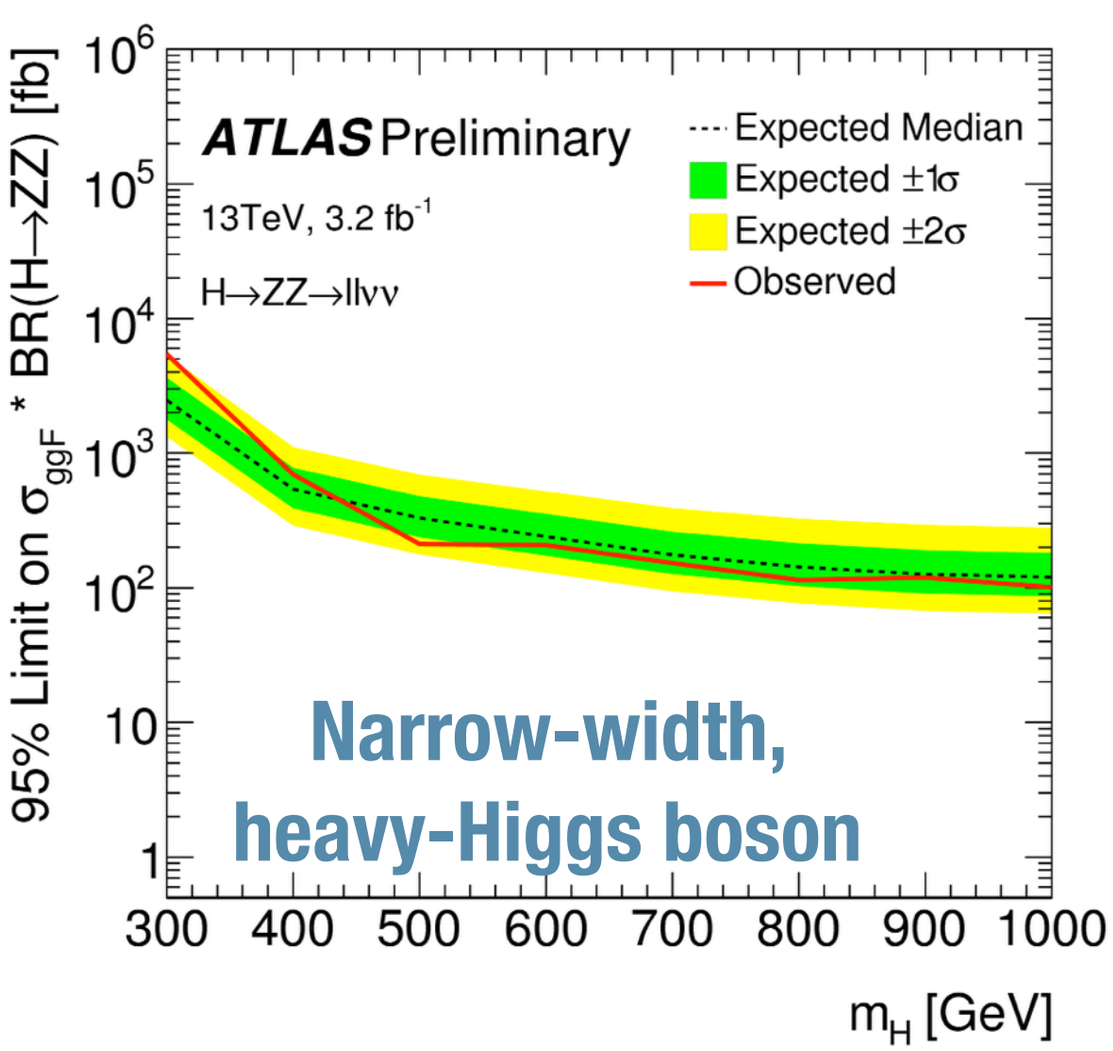


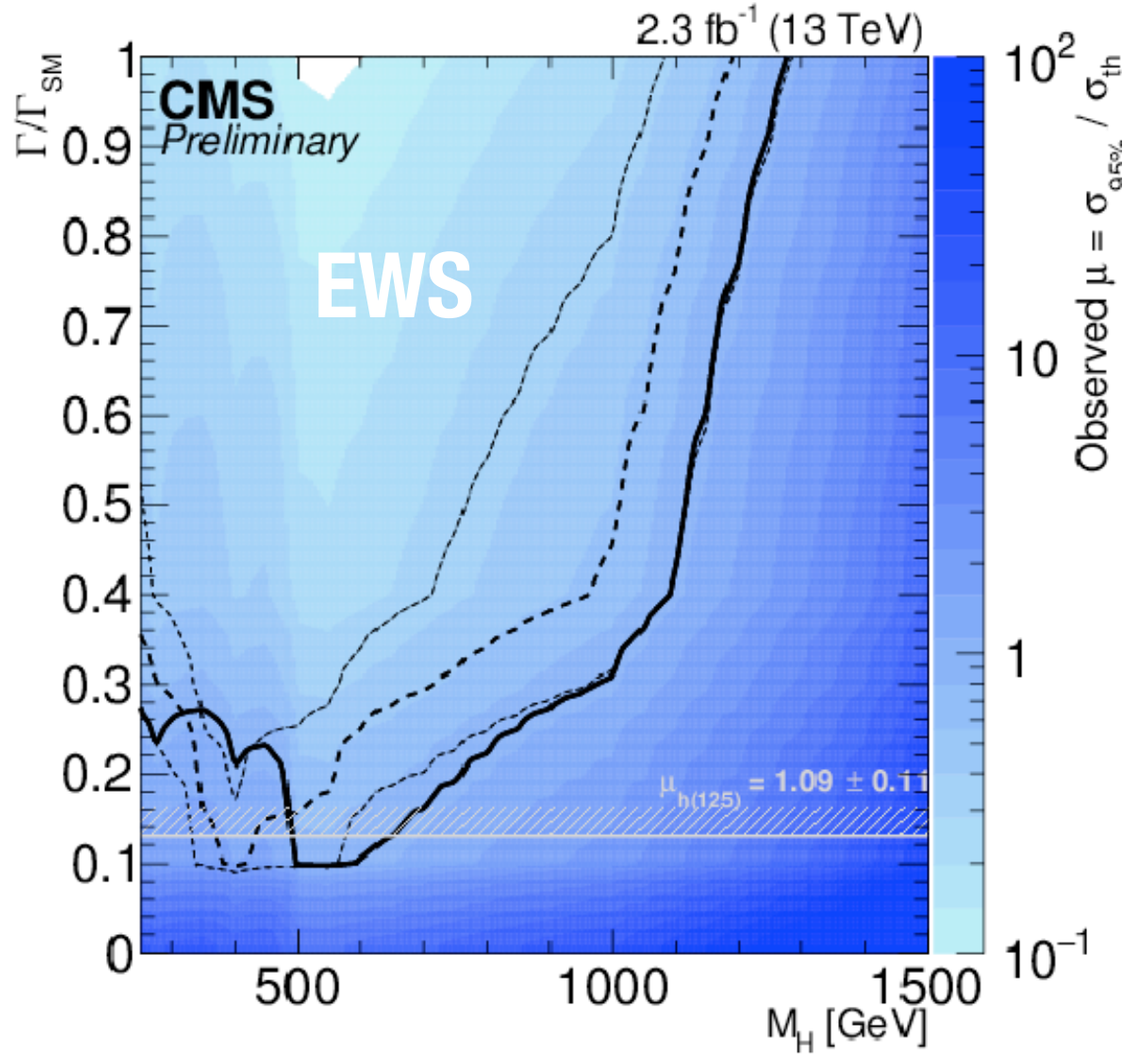
H→ZZ→2l2ν

CMS-PAS-HIG-16-001

ATLAS-CONF-2016-012

- 2 leptons + E_T^{miss} / M_T
- Data driven modelling of backgrounds —> good prediction of tails
- ATLAS: Limits on narrow width high mass resonance and RS graviton
- CMS: high mass resonance + EW Singlet and 2HDM

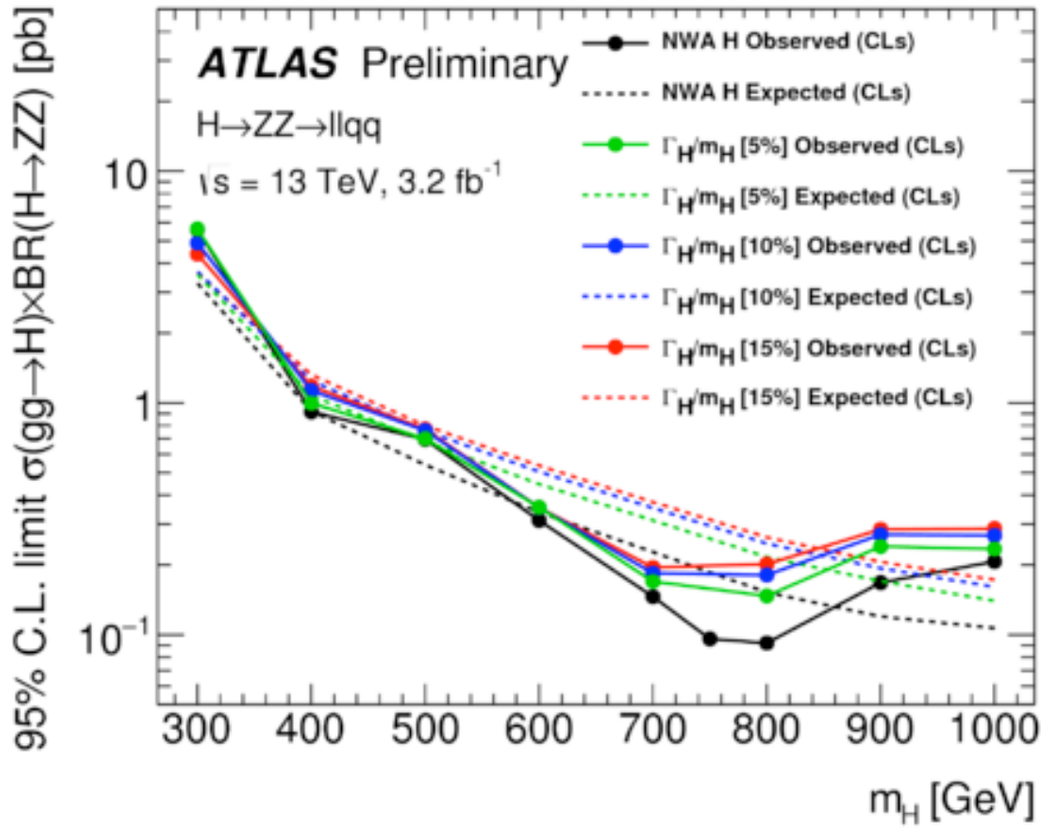


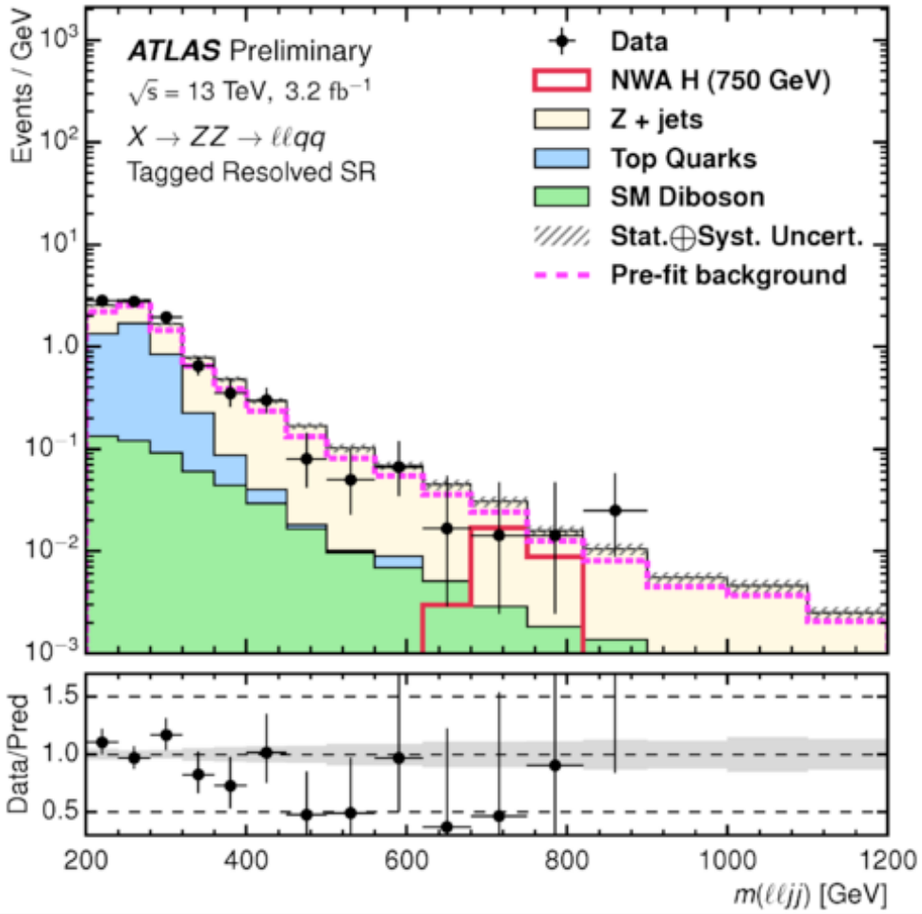


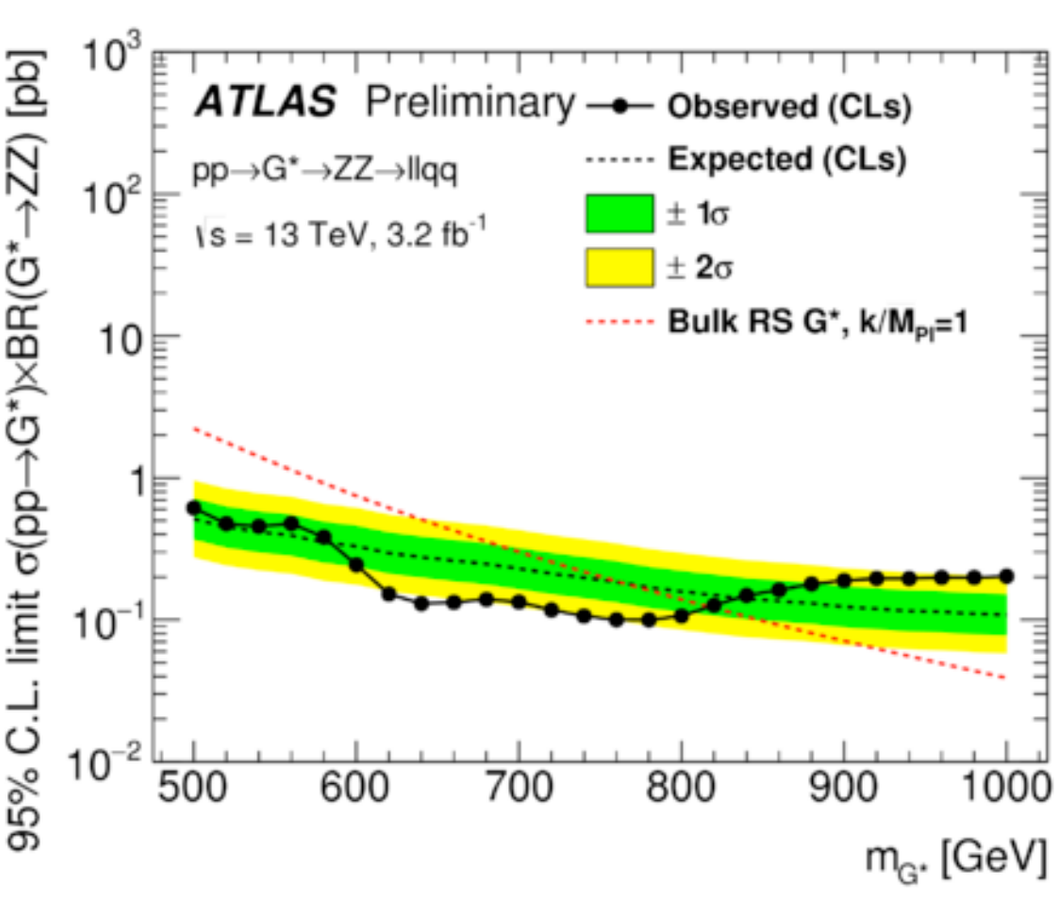
H→ZZ→2l2q

- Search for high mass Spin0 and Spin2 resonances
- Competitive above 500 GeV
- Both resolved (jj, tagged and untagged) and boosted (J) analysis
- Simultaneous fit to m_{llj} and m_{lljj} SR and CR for merged and resolved analysis

ATLAS-CONF-2016-016







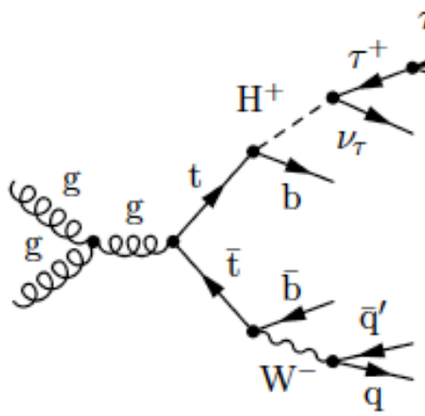
Charged Higgs

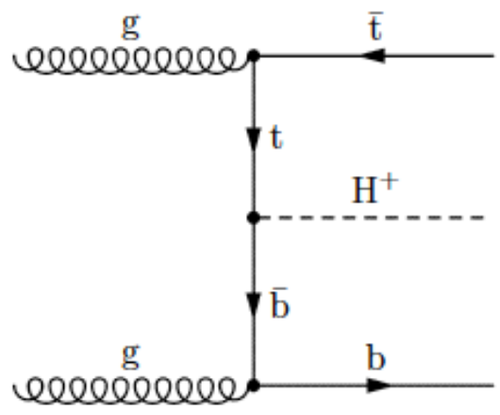
ATLAS: JHEP03(2016)127 ; JHEP 03 (2015) 088; Phys. Rev. Lett. 114, 231801 (2015)

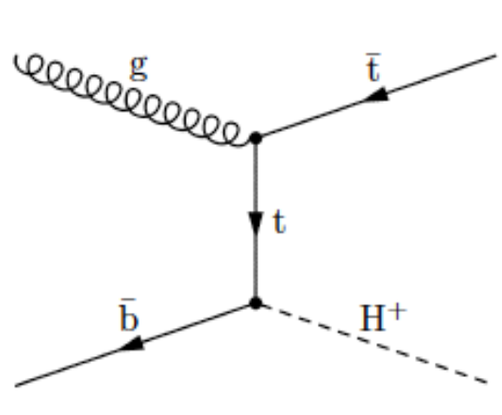
CMS: JHEP11 (2015) 018
JHEP 12 (2015) 1

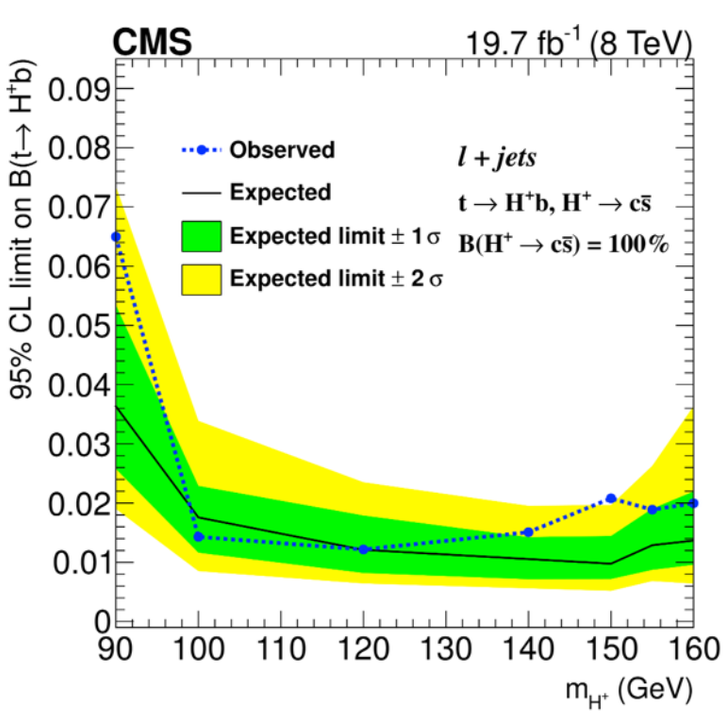
- **Predicted in 2HDM/MSSM:**
- Dominantly produced in association with a top quark
  - Direct production searches for $m_{H^\pm} > m_t - m_b$
  - Top quark decay searches for $m_{H^\pm} < m_t - m_b$

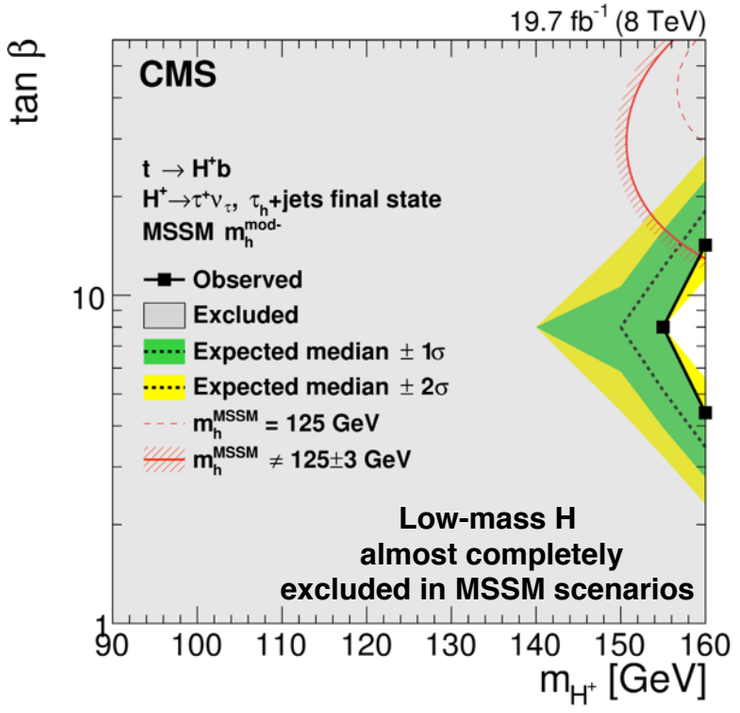
- Large variety of $H^\pm$ decays probed in Run I: tb, cs, τν ; VBF $H^\pm \to W^\pm Z$ —> No surprises

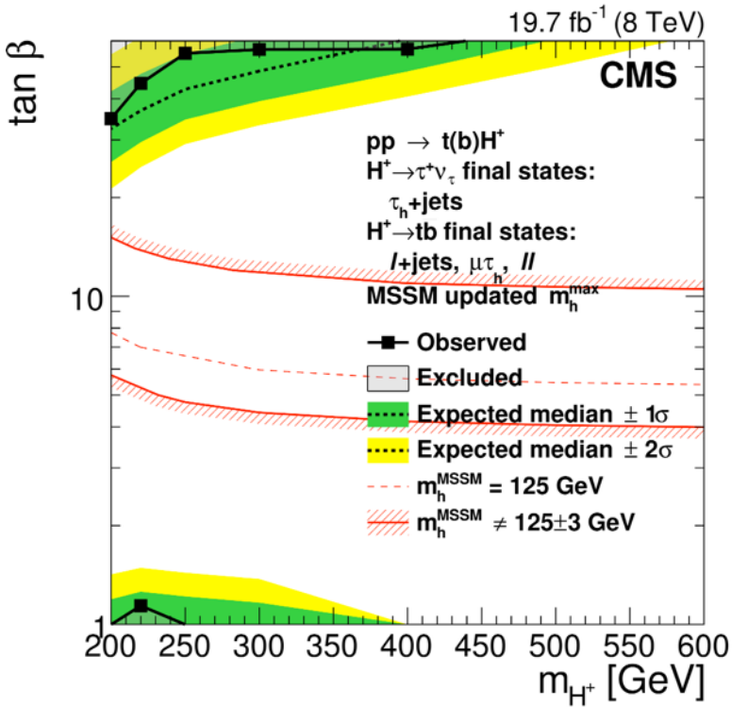










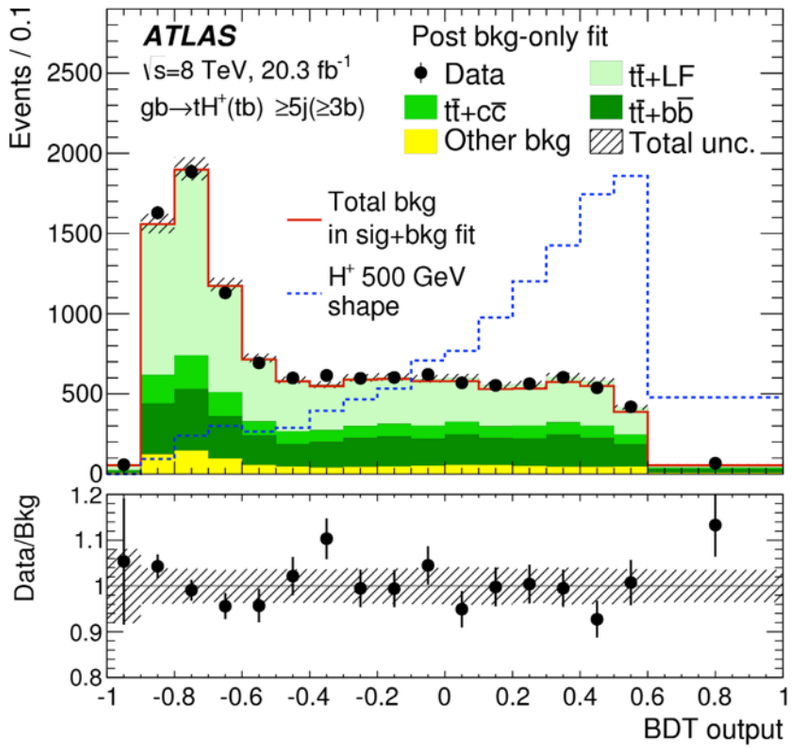


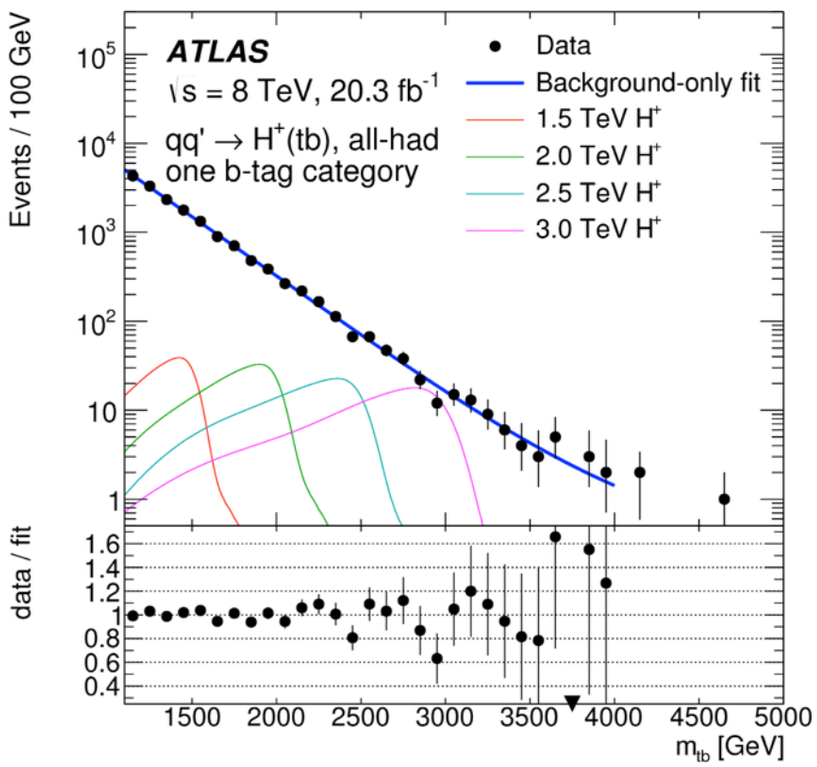
$H^{\pm} \rightarrow tb$

ATLAS: JHEP 03(2016)127

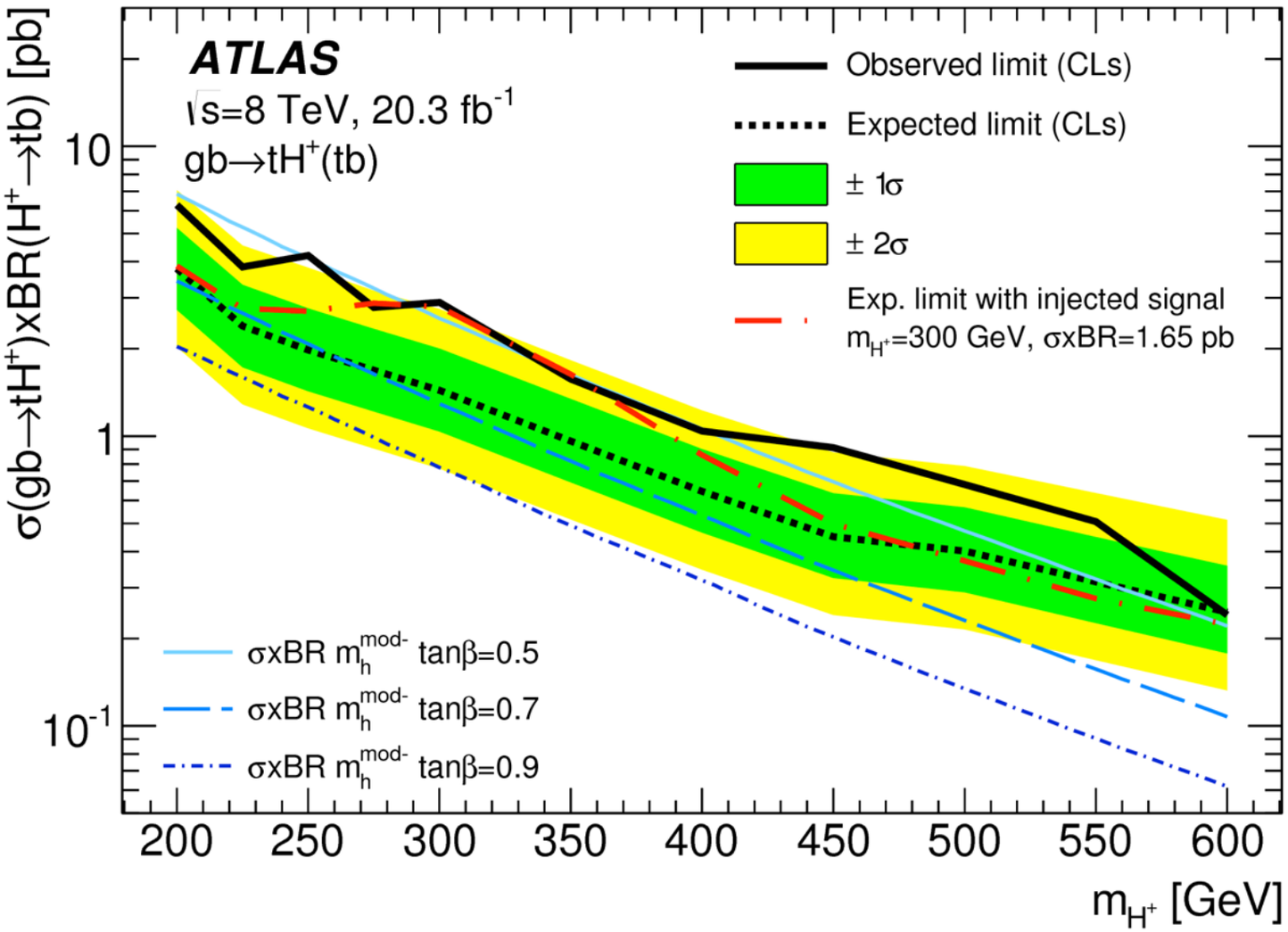
CMS: JHEP 11(2015)018

8TeV





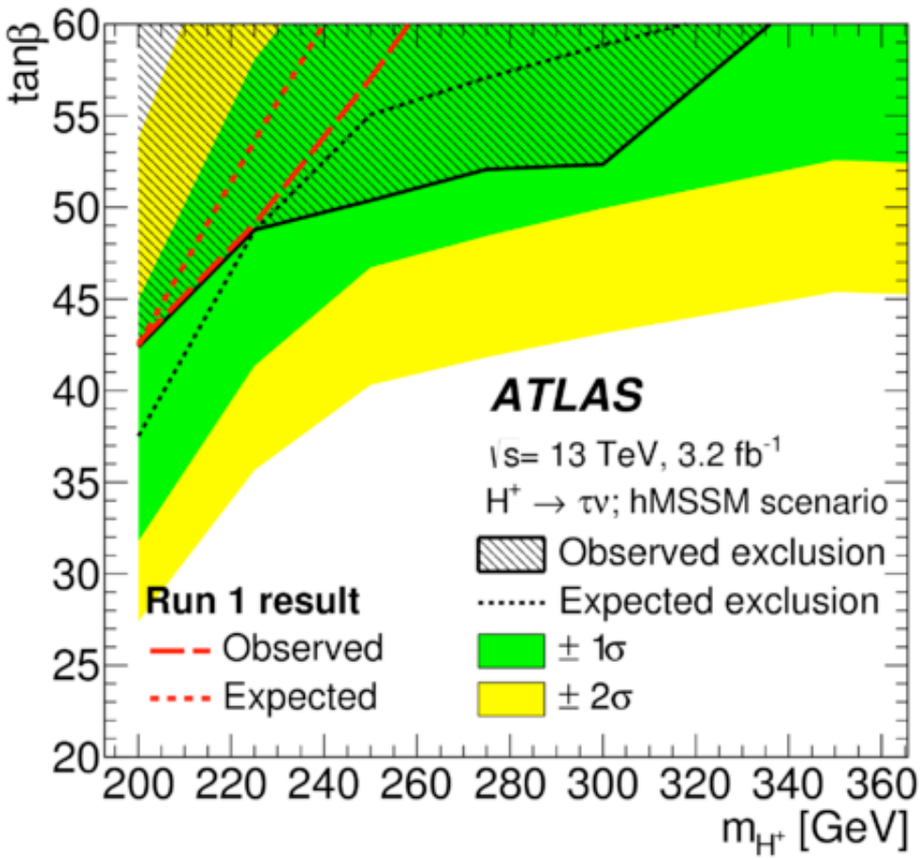
- Dominant decay mode at High Mass
- Lepton+Jets final state → Fit to 5 regions (4 control regions based on #jets/bjets + 1 signal region)
- Signal/Background discrimination through a BDT trained for $M_{H^{\pm}}$=300 GeV, 500 GeV

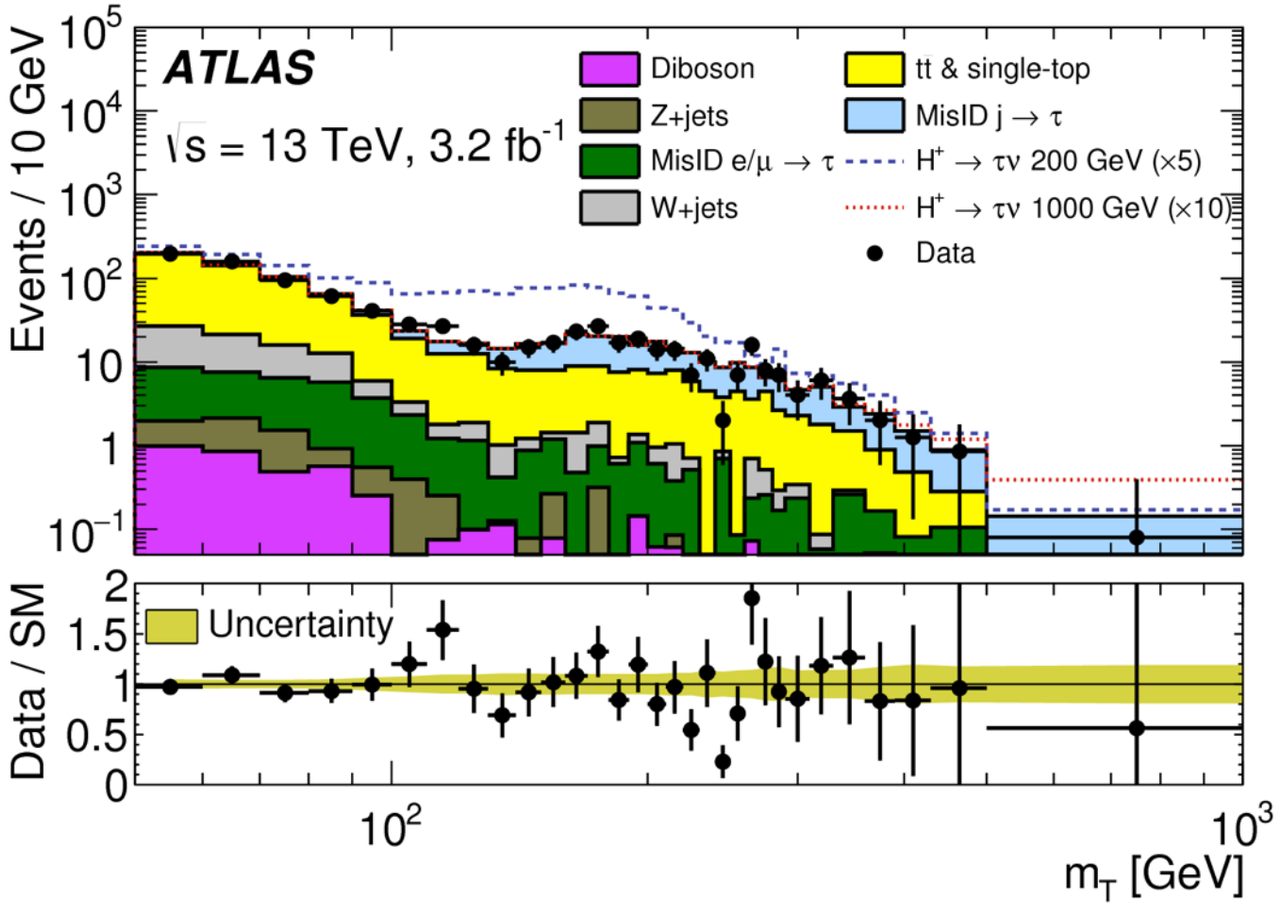


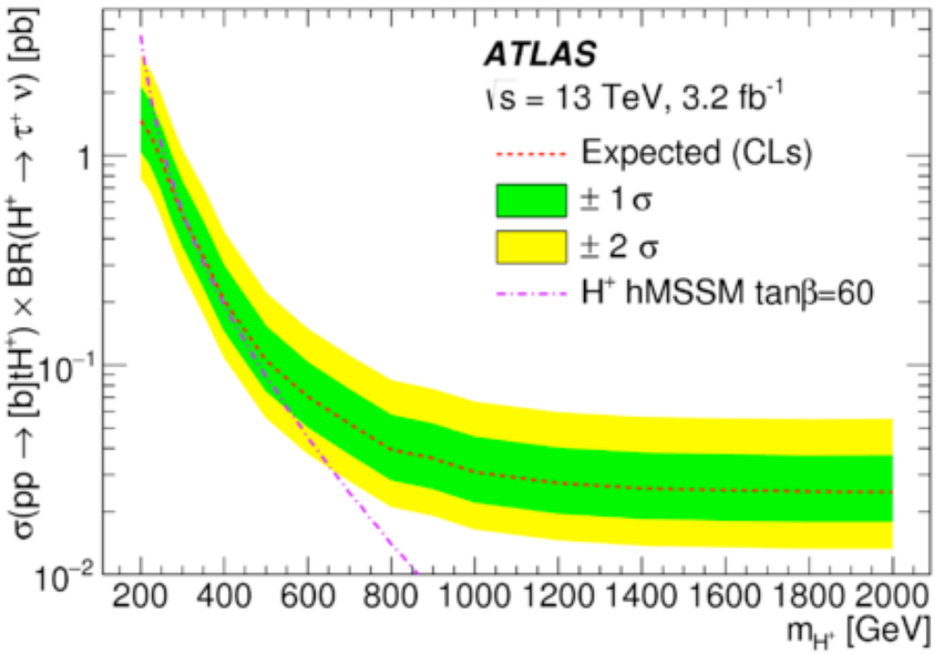
$H^{\pm} \rightarrow \tau\nu$

ATLAS: arXiv:1603.09203

- H—>τν decay channel represents a clean signature and substantial BR (~10%) in several MSSM benchmarks.
- **Event Selection**
  - E_T^{miss} trigger & $E_T^{miss} > 150$ GeV
  - ≥3 jets including ≥1 b-tagged jet
  - 1 τ and no e or μ ; $m_T > 50$ GeV



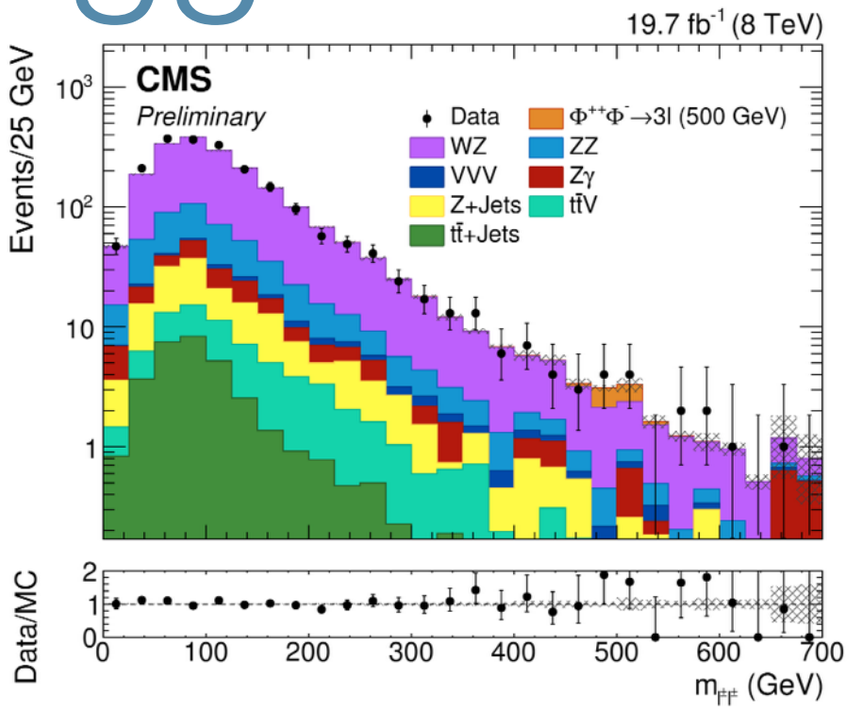




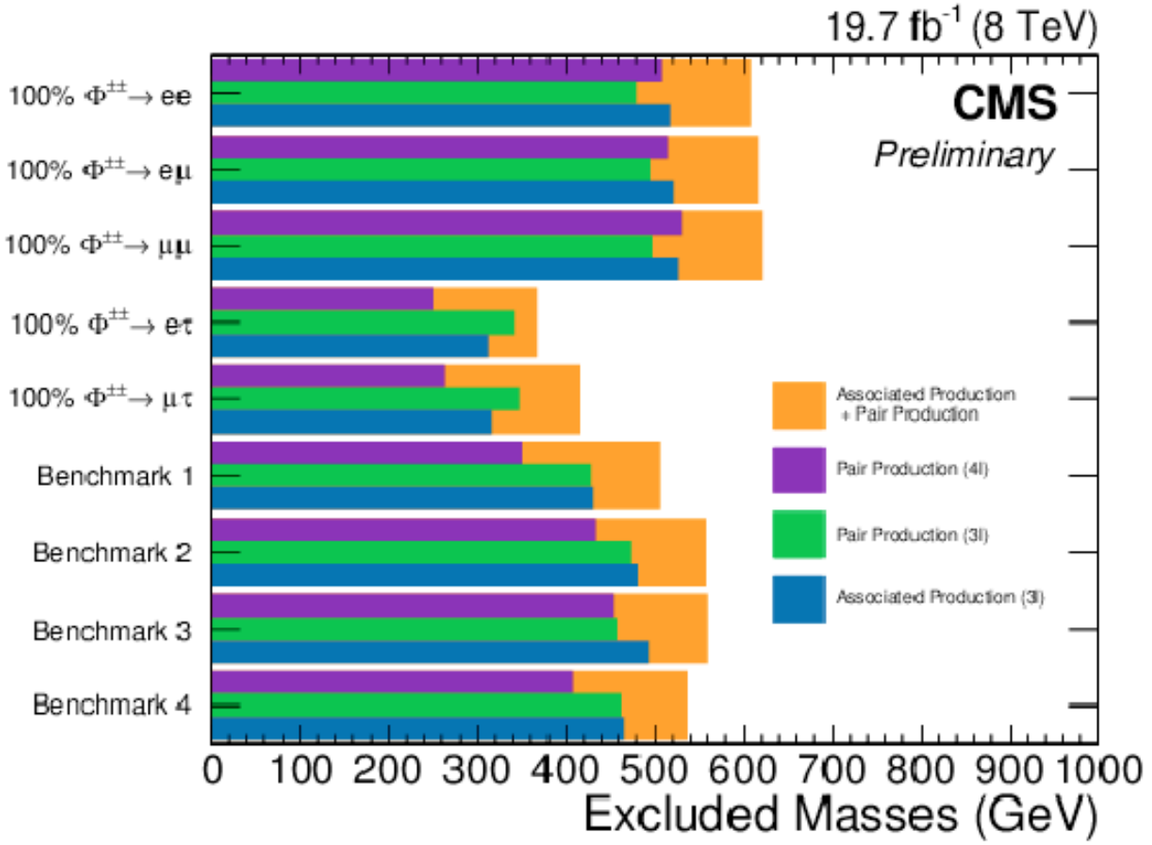
Doubly Charged Higgs

8TeV

- Predicted in Higgs triplet models
- Final state: three or four leptons probing associated production ($\Phi^{\pm\pm}\Phi^{\mp}$) and pair production ($\Phi^{\pm\pm}\Phi^{\pm\pm}$).
- Two sets of results:
  - Model independent search for narrow resonances assuming 100% decay Br to μμ, ee, eμ, τμ, τe
  - Four benchmark points that target different neutrino mass hierarchies



Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6



CMS: CMS-PAS-HIG-14-039

CMS: EPJC 72 (2012) 2189

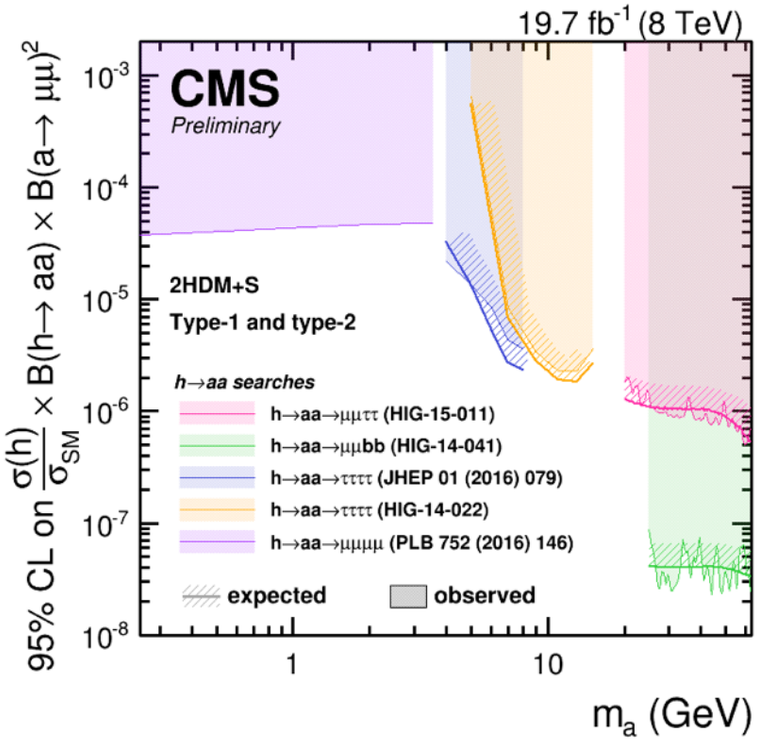
ATLAS: JHEP 03 (2015) 041

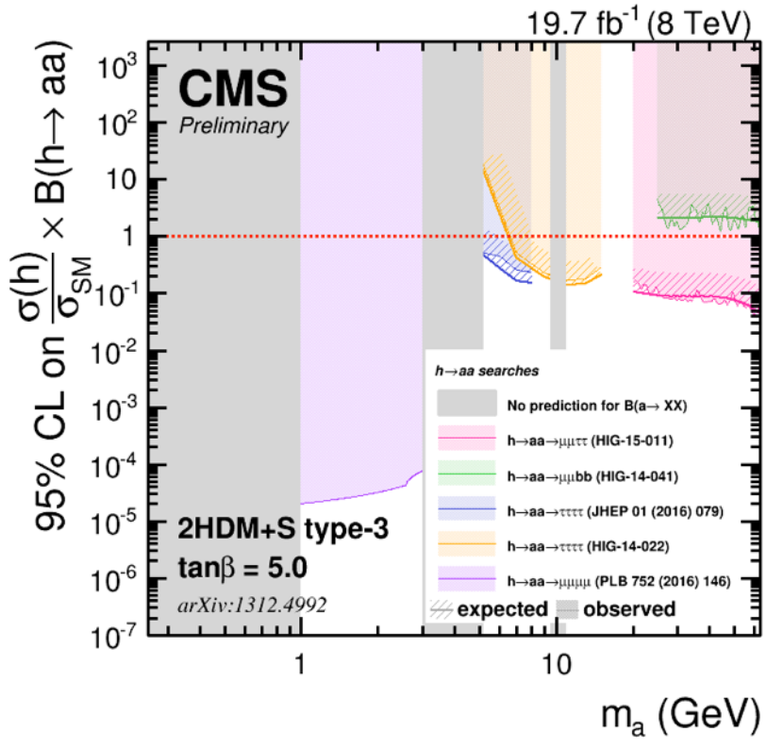
ATLAS: arXiv:1411.2921

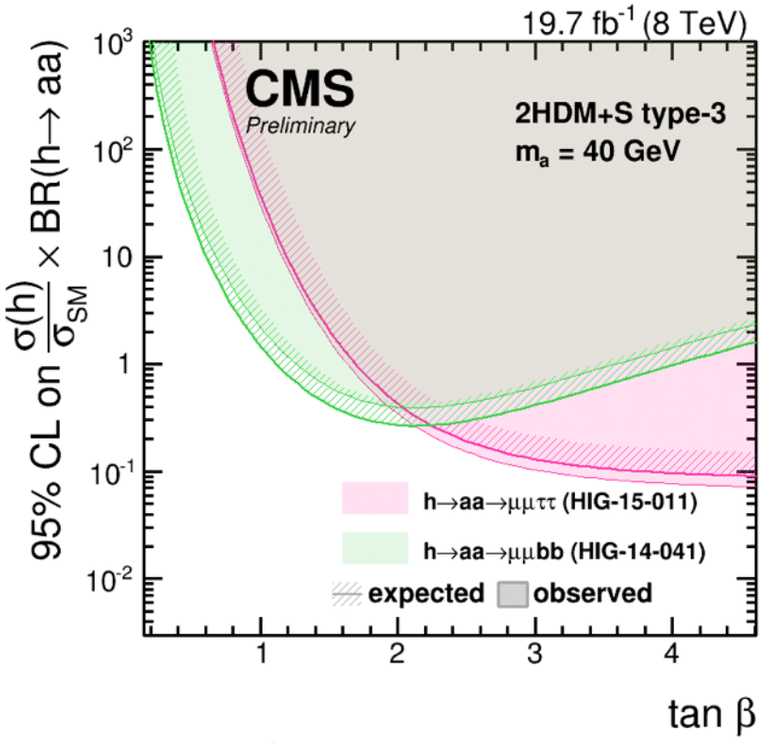
Rare Decays

- Run I also left a large number of searches targeting rare/bsm decays of the h(125) Higgs
  - **With BR(h->BSM)<0.34 allowed, there is plenty of room for new searches targeting exotic decays**
- Examples are the Invisible Higgs and LFV searches (covered yesterday), but also the **h->aa searches,** which can be interpreted in the **2HDM+S model** (with one extra CP even scalar s and one extra CP odd scalar a)

h->aa->2μ2b (CMS-PAS-HIG-14-041, **NEW**)
h->aa->4μ (CMS:Phys. Lett. B 752 (2016) 221)
h->aa->2μ2τ (CMS-PAS-HIG-15-011 (**NEW**), ATLAS:Phys. Rev. D92 (2015) 052002)
h->aa->4τ (CMS-PAS-HIG-14-022, CMS:JHEP 01 (2016) 079)
h>aa->4γ (ATLAS:CERN-PH-EP-2015-187)







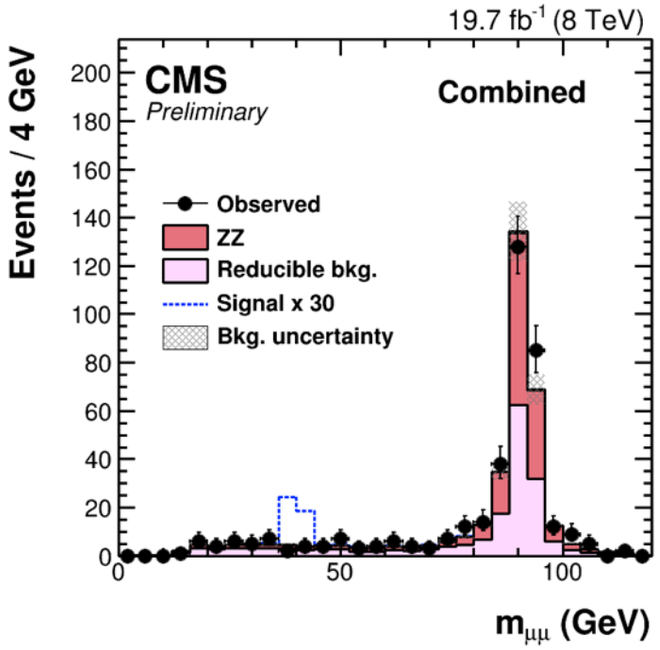
All of these need 2016 statistics to surpass the Run I sensitivity! (2-3 fb^{-1} are not enough)

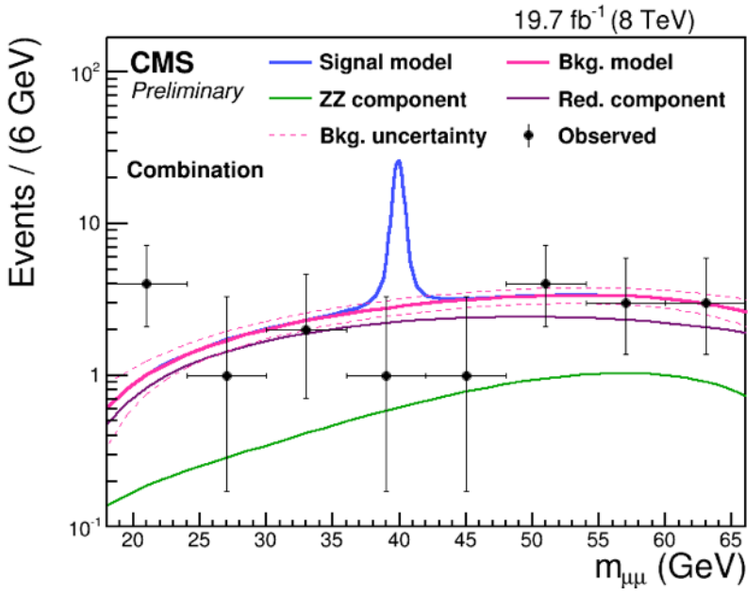
2HDM+S: h→aa→μμττ / h→aa→μμbb

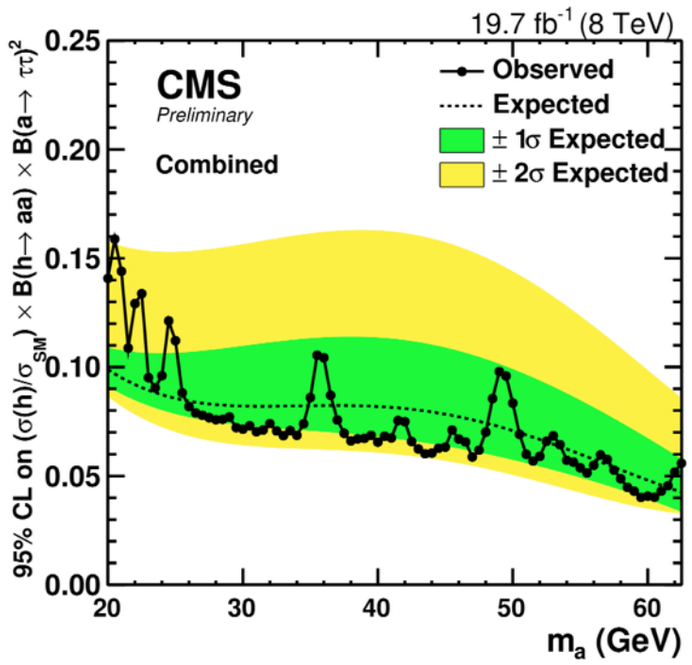
- These are the most recent results of the CMS series of low mass pseudo scalar searches at 8TeV (4μ, 4τ, 2μ2τ, 2μ2b)

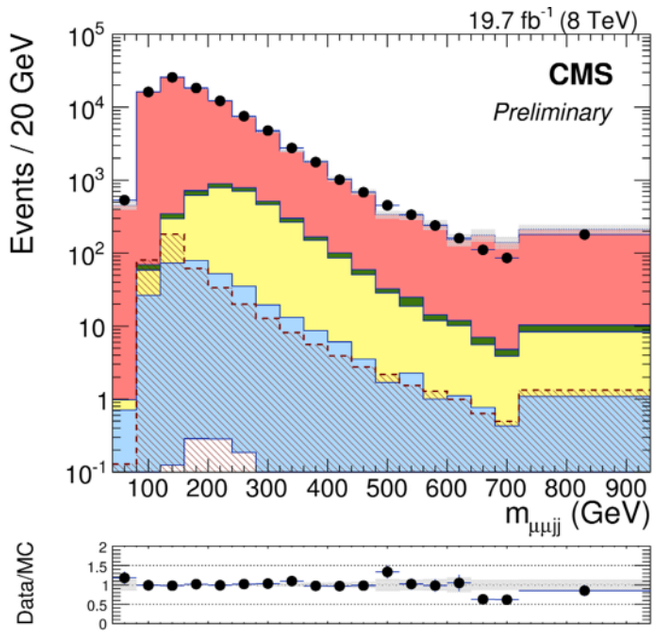
8TeV

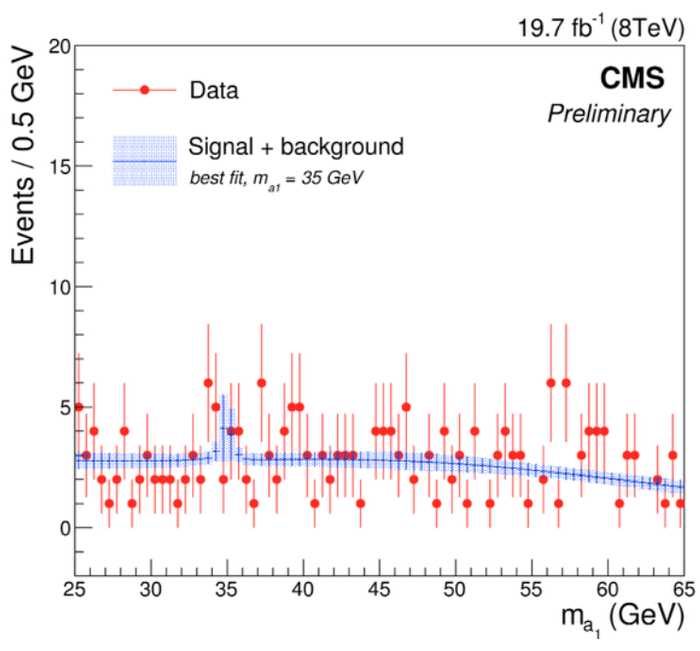
CMS-PAS-HIG-15-011 **CMS-PAS-HIG-14-041**

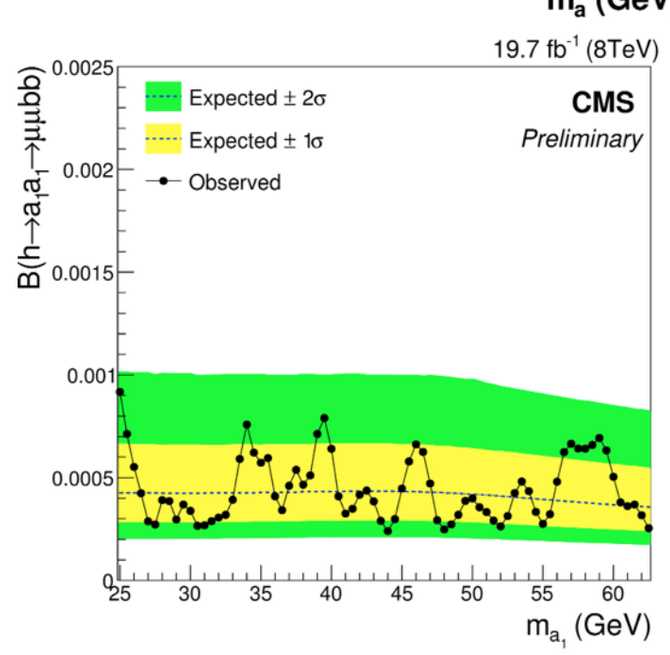








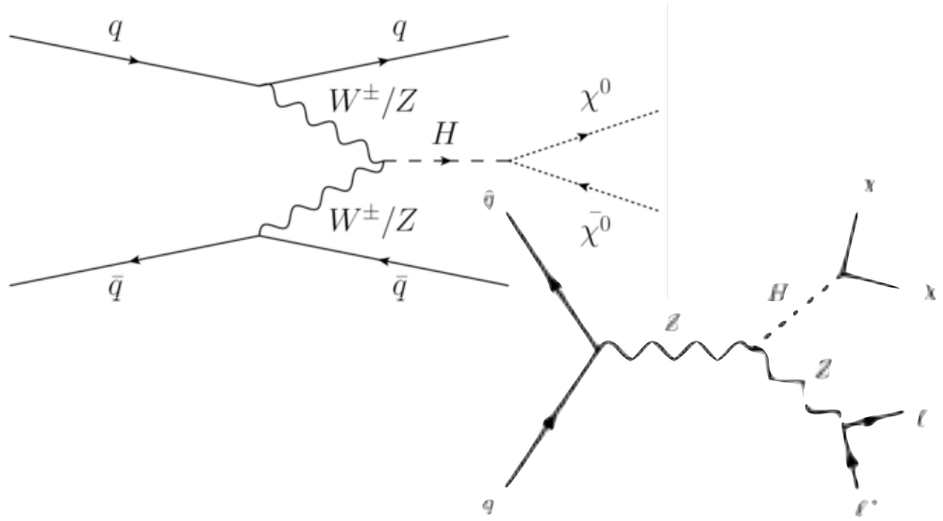




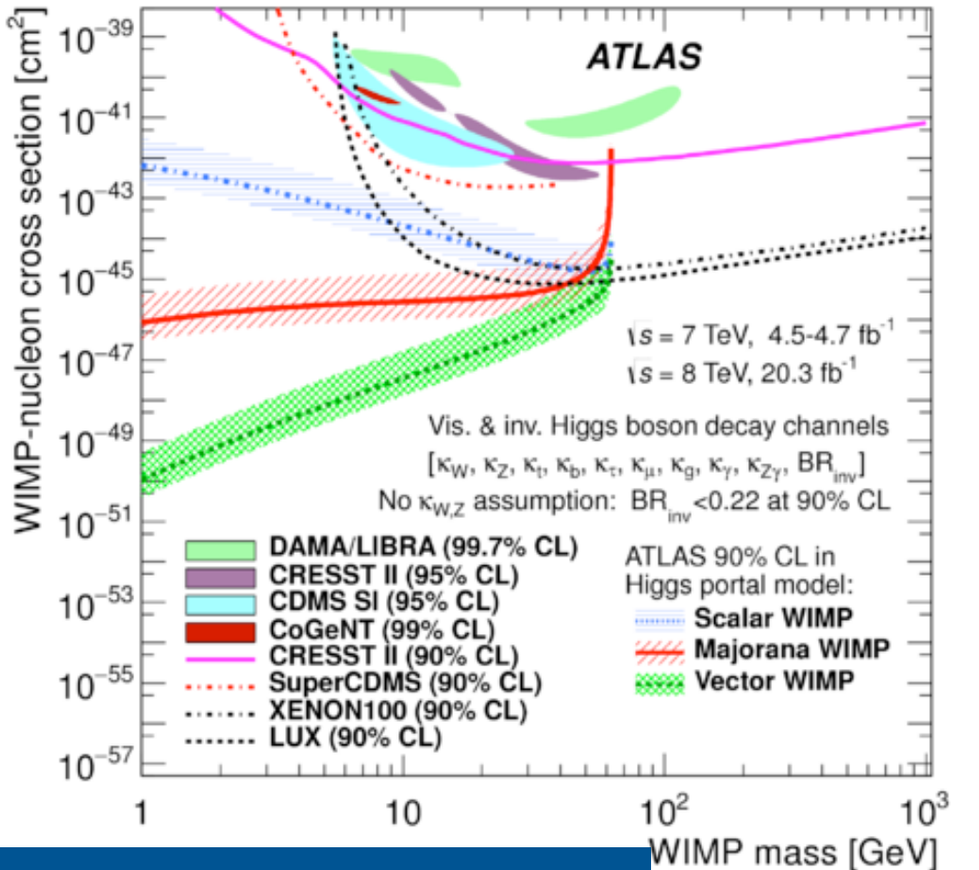
Invisible Higgs Decays

Higgs decays to undetected particles → **connection to Dark Matter Searches**

- Challenging signature: E_T^{miss}
  - Use associated production (WH and ZH) and weak vector boson fusion (VBF) to tag the events
  - **Background modelling** (QCD/WJets/DY) is key



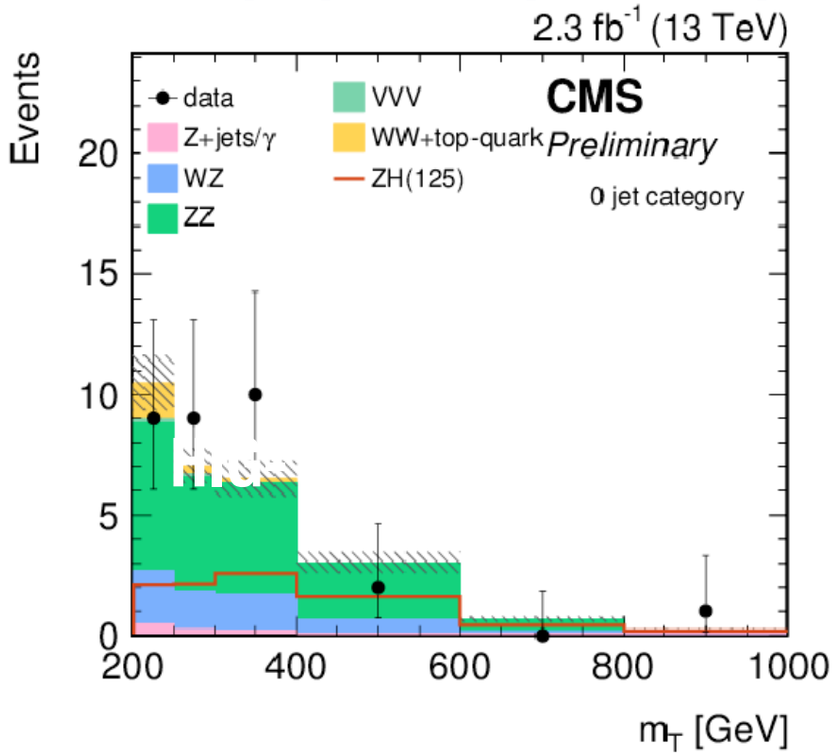
RUN I Summary: 95% CL limit on BR for M	
PRL 112, 201802 (2014): ATLAS Z(ll) H	<75(62)%
arXiv:1504.04324: ATLAS W/Z(had)H	<78(86)%
ATLAS-CONF-2015-004: VBF	<29(35)%
Eur. Phys. J. C 74 (2014) 2980: CMS VBF+ZH	<58(44)%
CMS HIG-14-038: VBF update (including	<47(35) %
CMS HIG-15-012: Run I Combination	<36(30%)

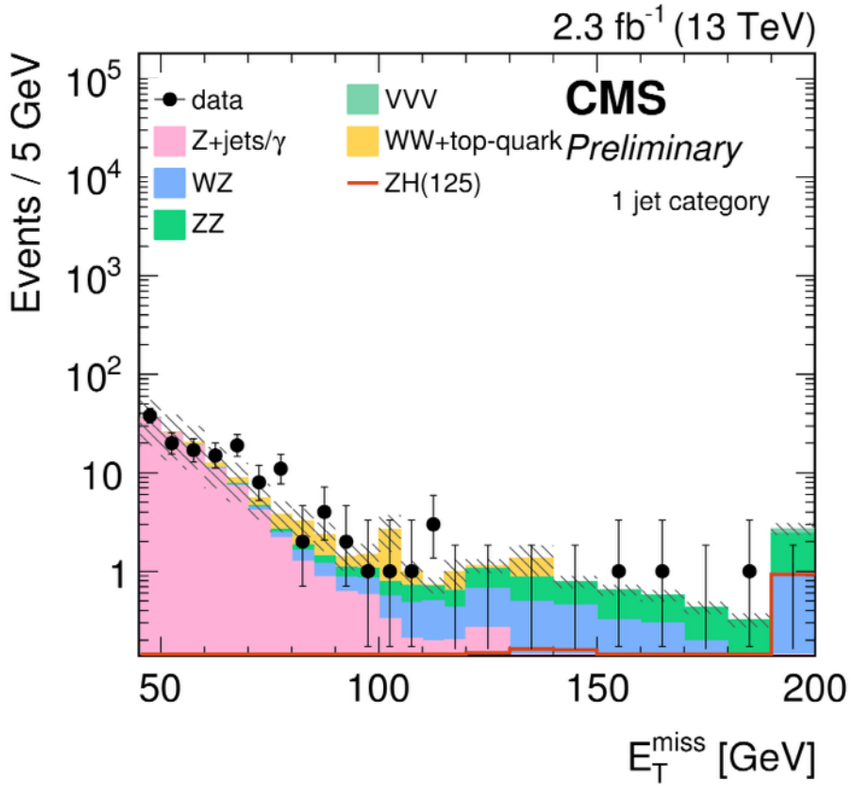


ATLAS: JHEP 11(2015)206

Z(ll)H(Inv)

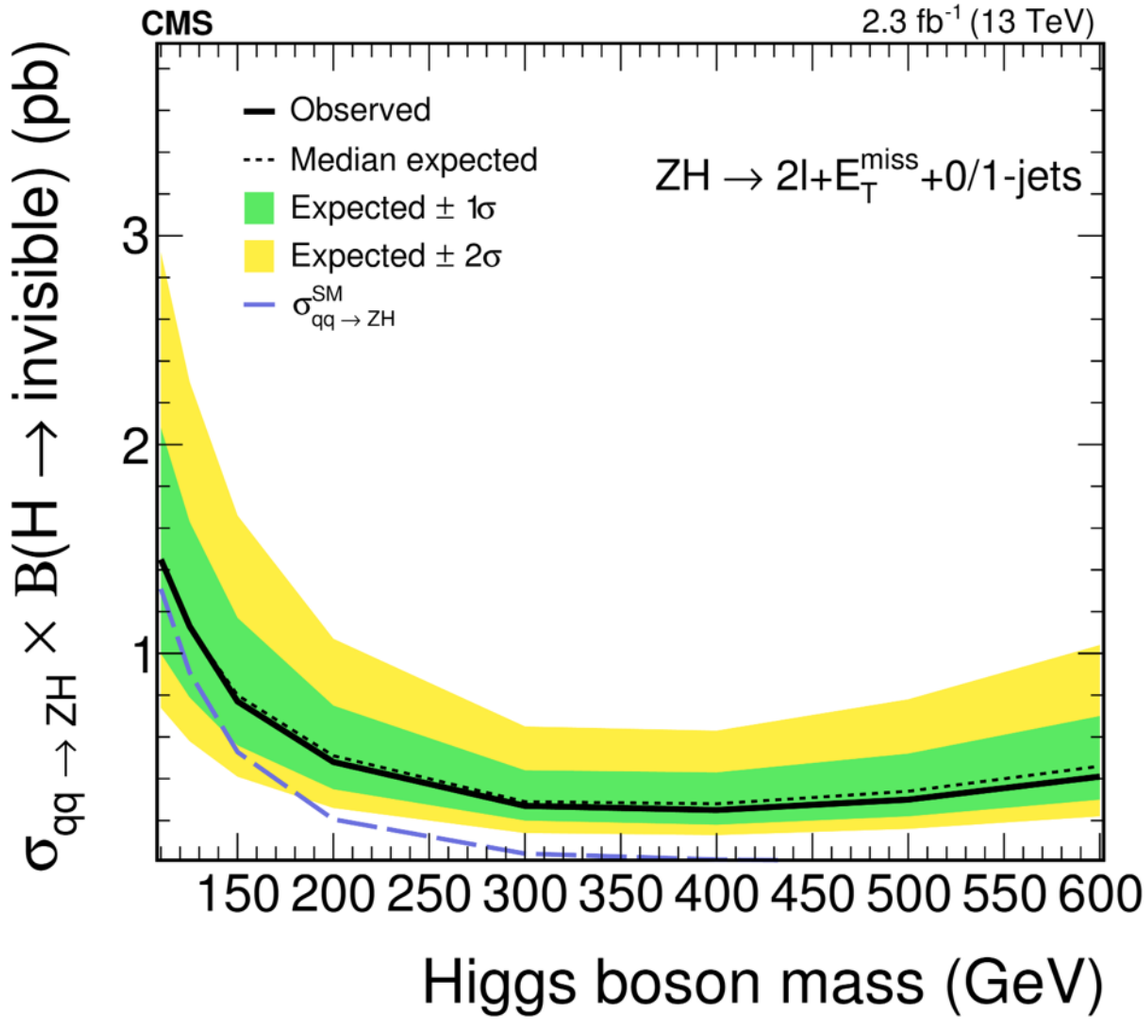
CMS-PAS-HIG-16-008





- DiLepton + Angular Cuts + high E_T^{miss}, MT
- Template fit to M_T distribution
- Four exclusive categorie (ee,μμ) x (0-1 jet)

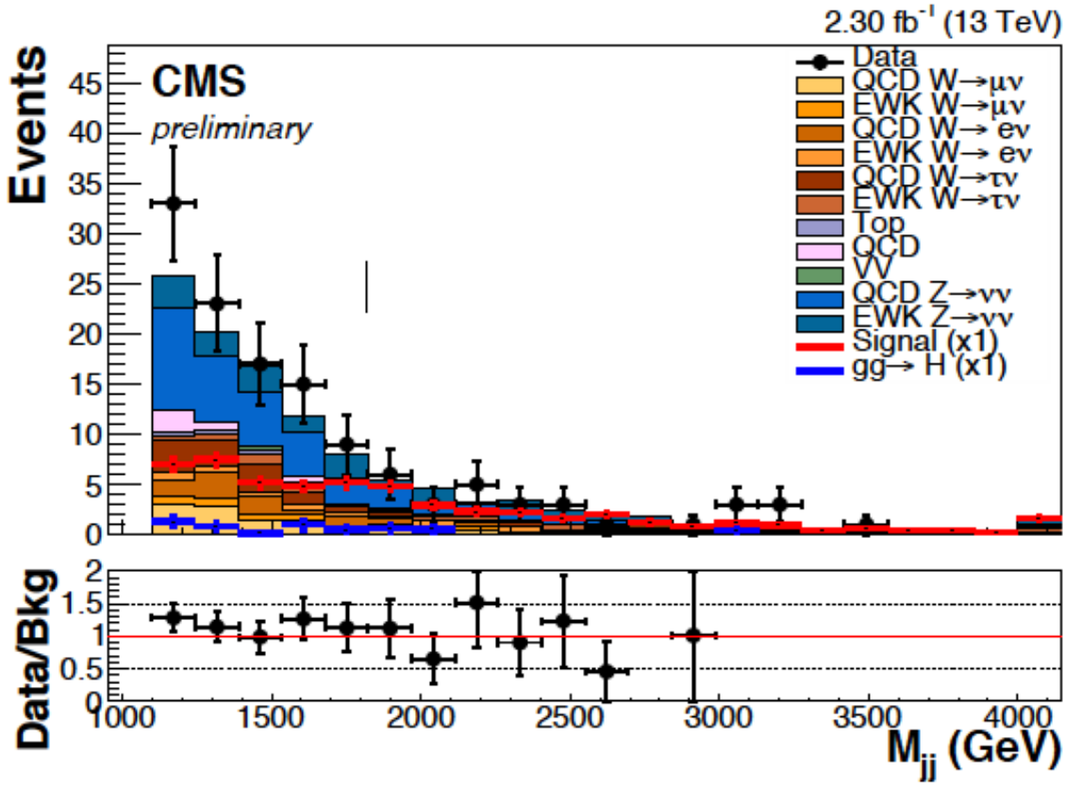
M_H=125GeV —> σ(pp→ZH)xB(H → invisible) <1.1 pb at 95% CL

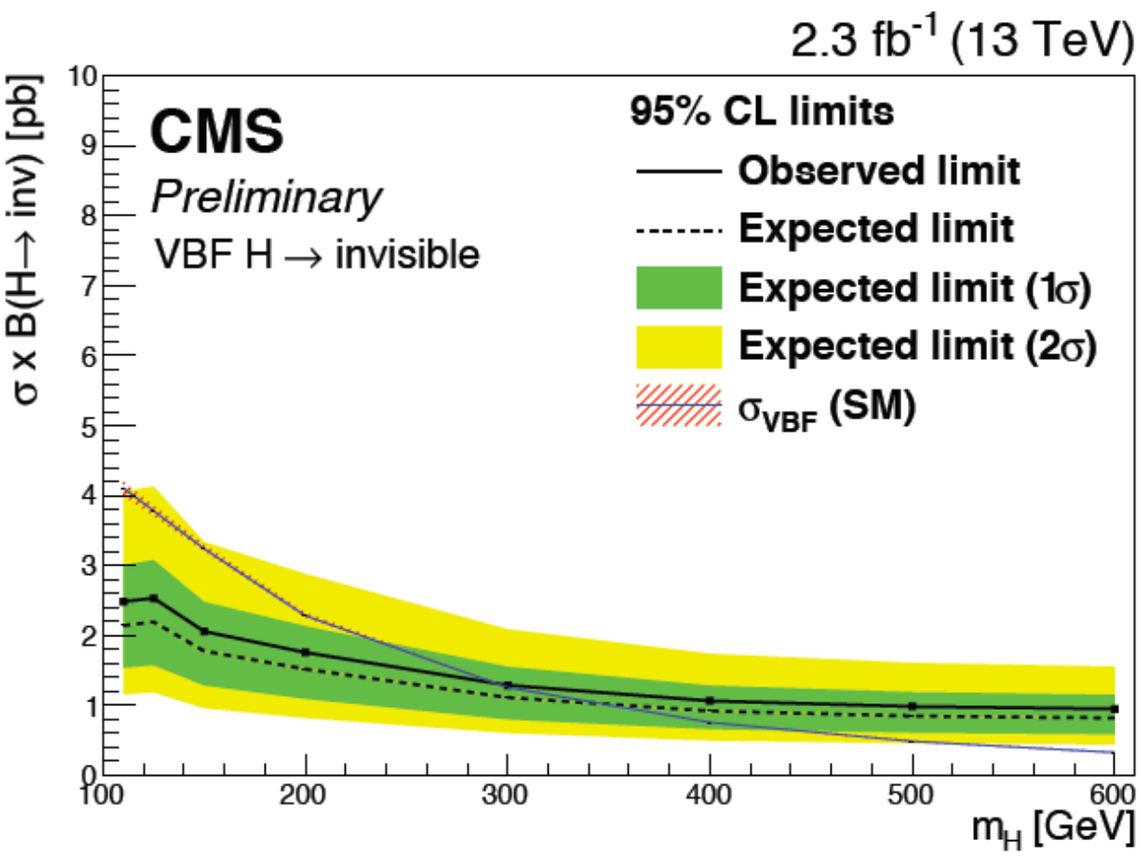


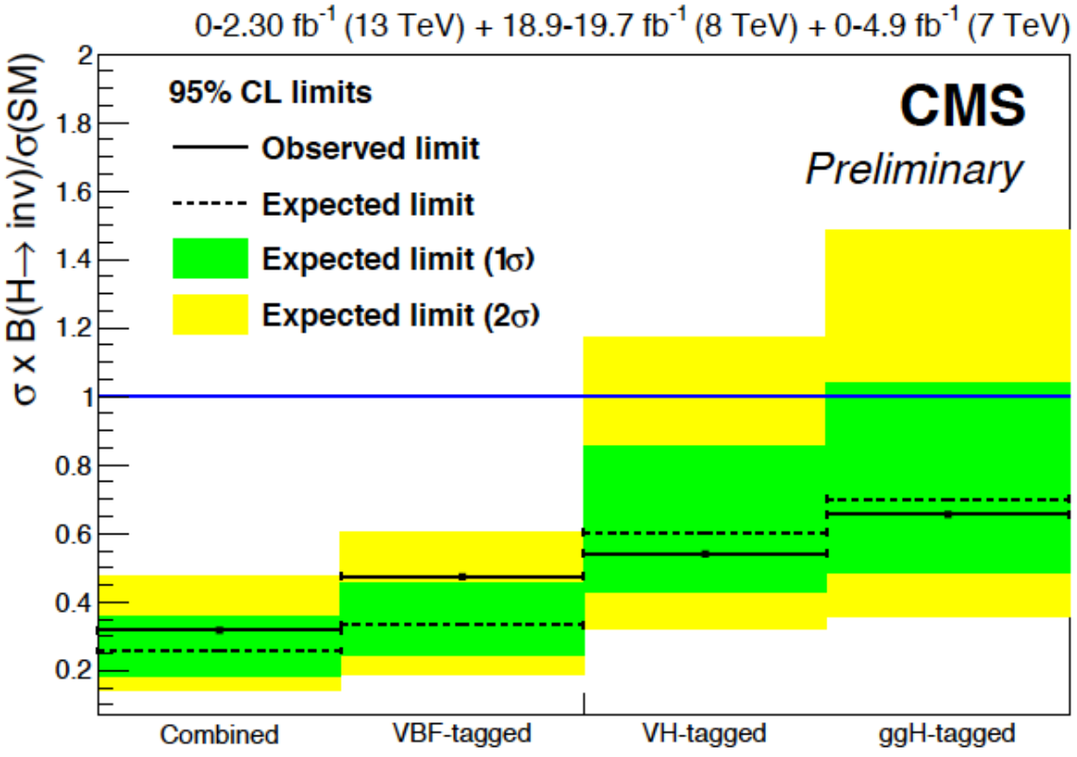
VBF H(Inv)

CMS-PAS-HIG-16-009

- Final state: 2 Forward Jets (high M_{JJ}, high $\Delta\eta$) + E_T^{miss}
- M_H=125 GeV —> σxB(H → invisible)<0.69 (0.62) at 95% CL
- Combining with 13TeV ZH and 8TeV results —> 0.32(0.26)







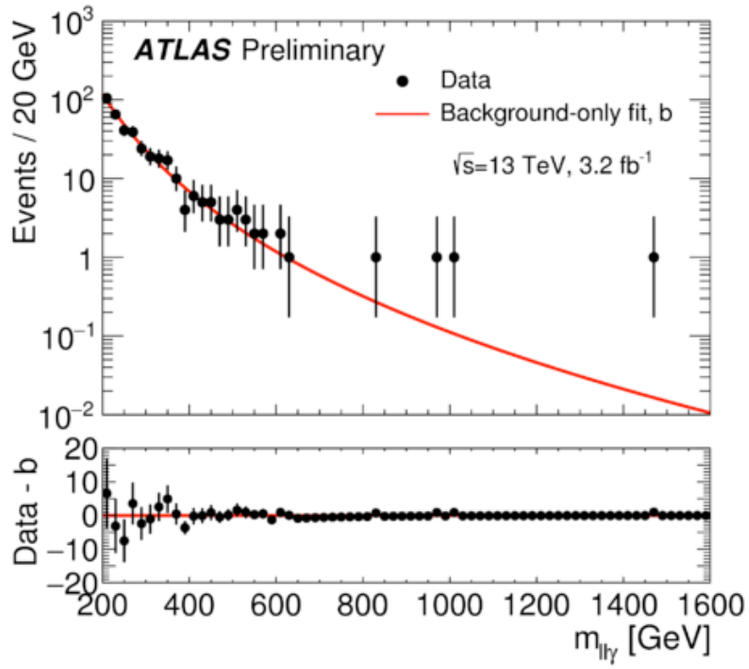
13 TeV: What about DiPhotons?

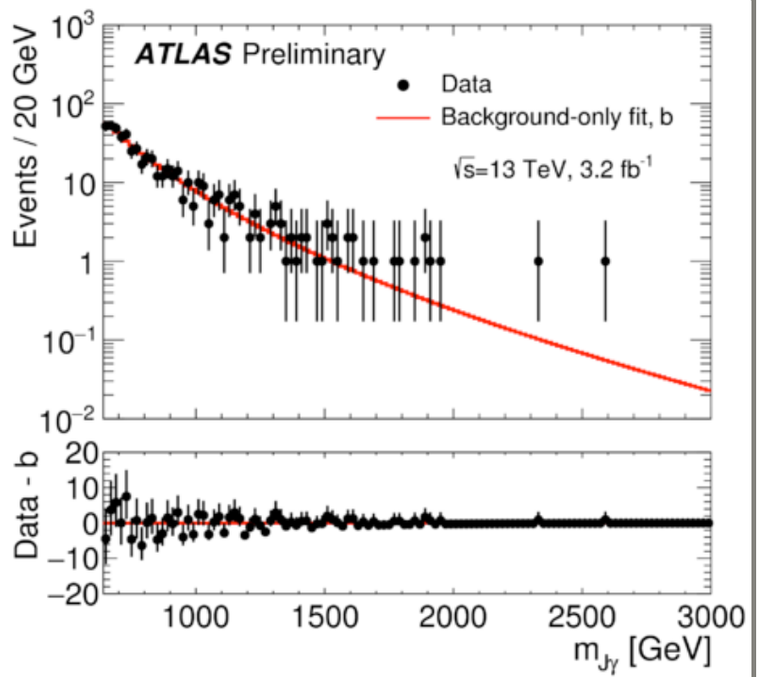
I will not talk here about 750 GeV…
(See tomorrow ;))

H→Zγ

- Search for scalar resonances in the 200-1200 GeV mass range decaying into a Z and a photon in pp collisions

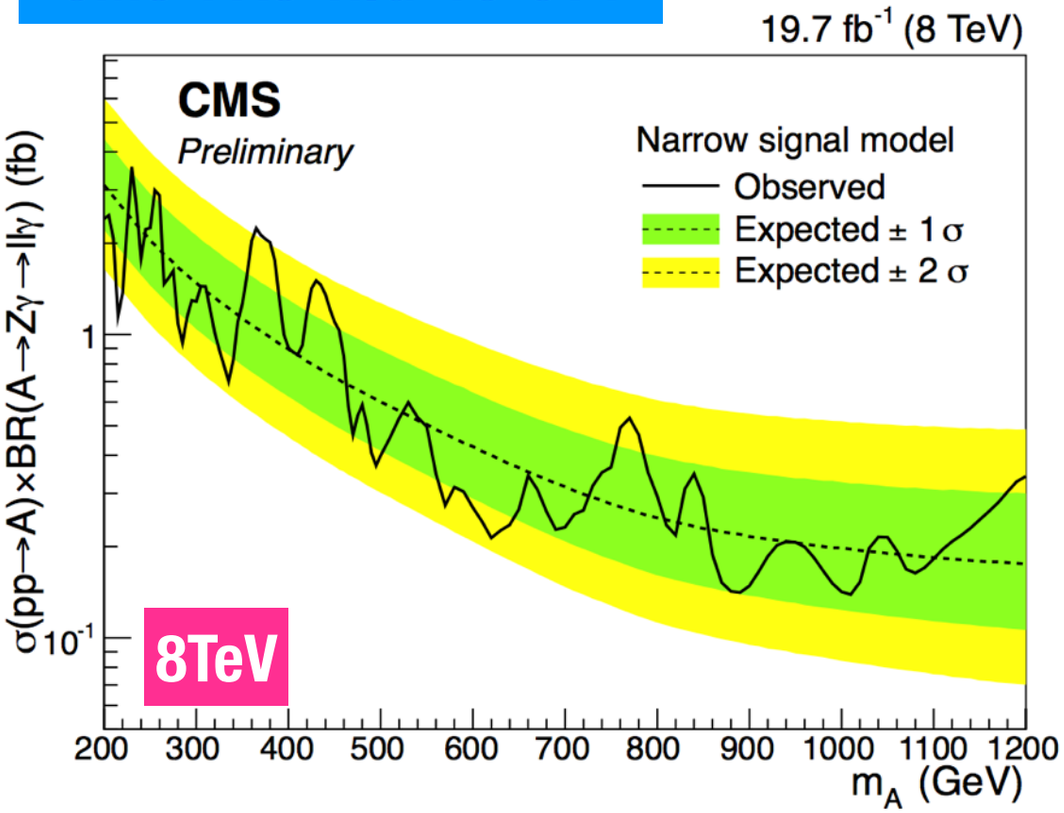
- Z-> ll (CMS, ATLAS) : small BR (6.7%)
- Z->qq (ATLAS): large BR (70%), boosted regime, “fat jet”



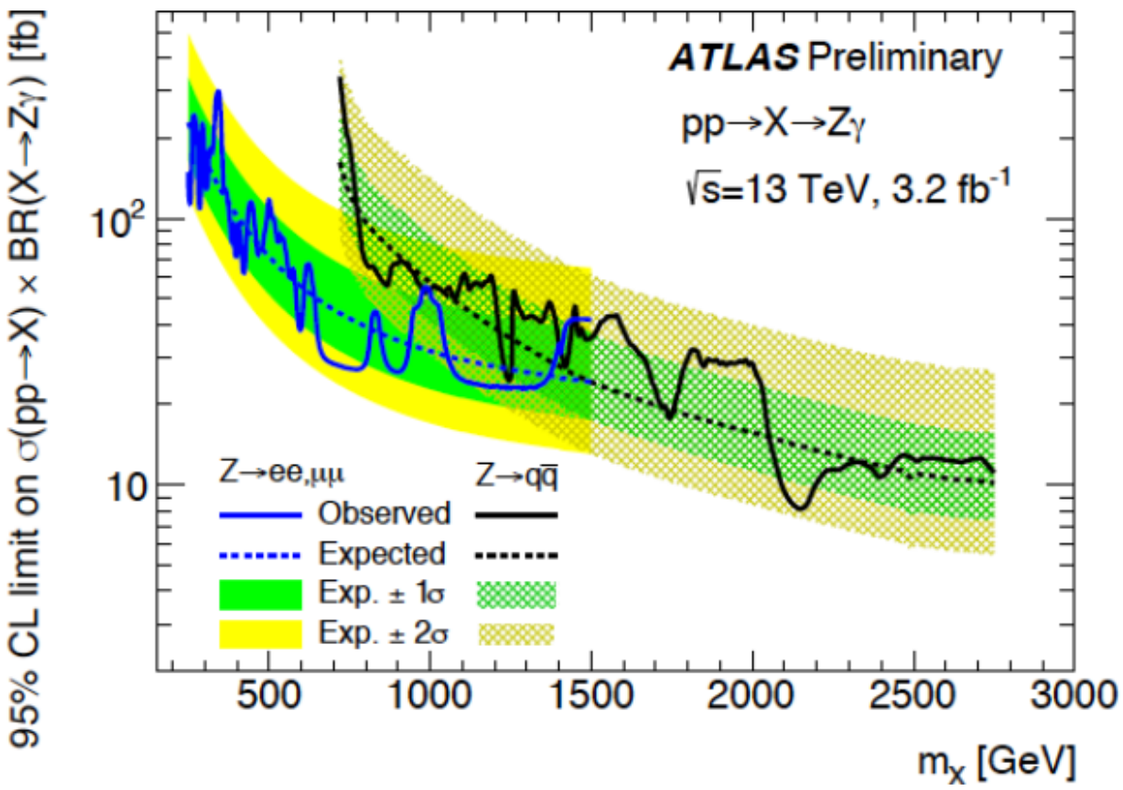


CMS-PAS-EXO-16-019

CMS-PAS-HIG-16-014



ATLAS-CONF-2016-010

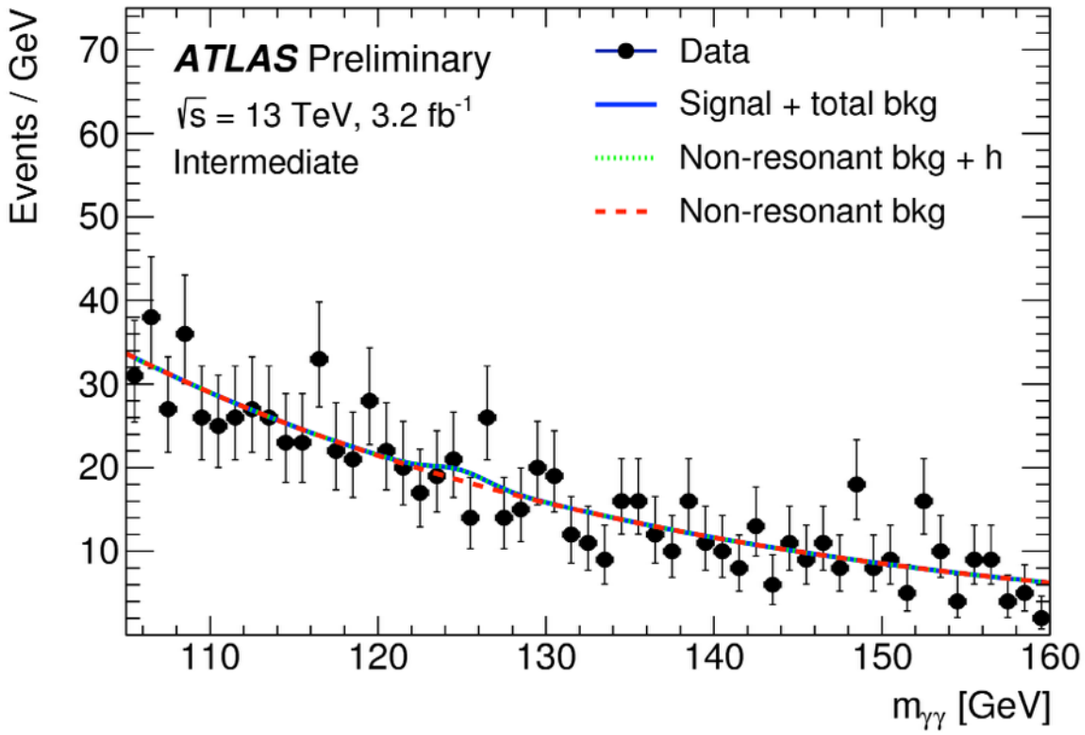


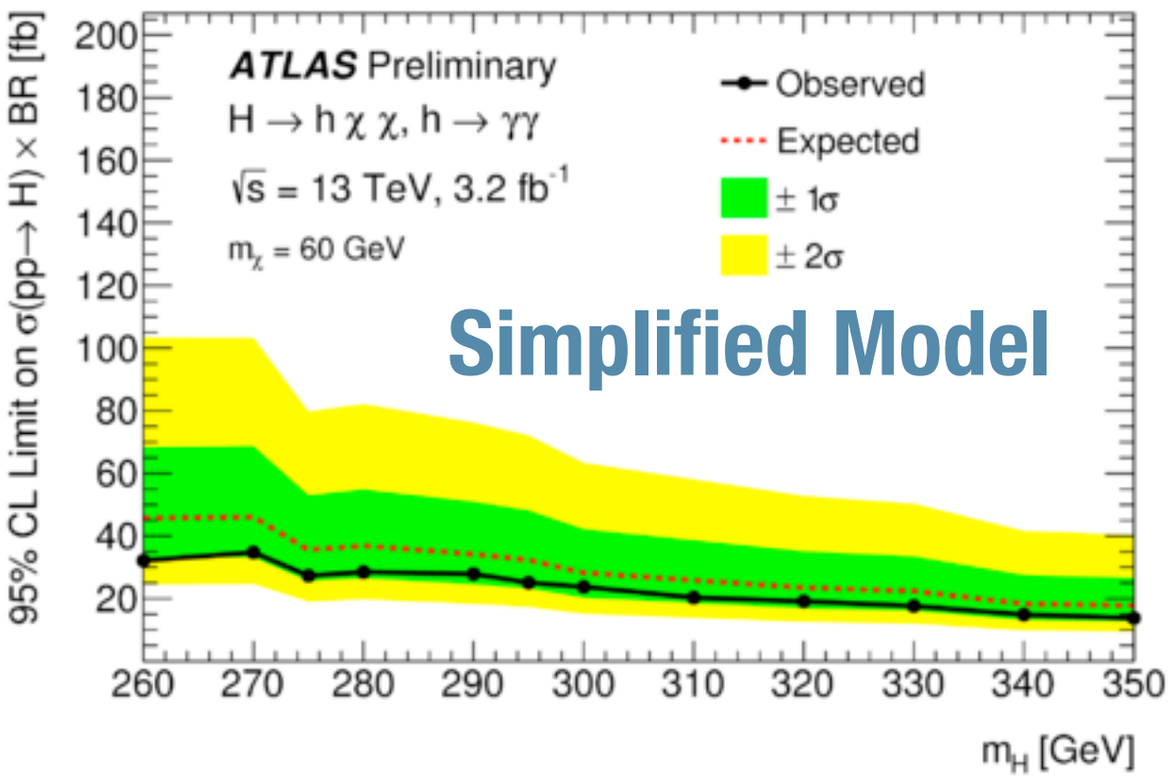
H→γγ+MET

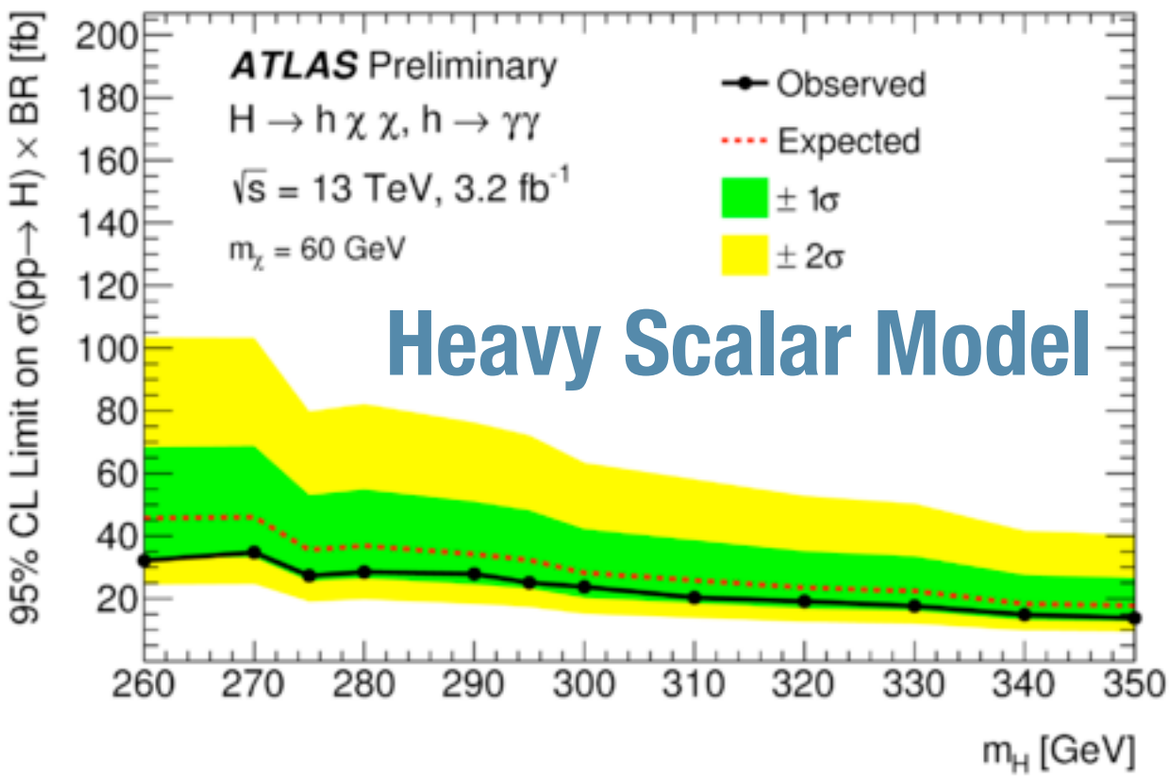
- Two signal models: decays of a heavy scalar into a Higgs boson and a pair of dark matter candidates, and a vector mediator emitting a Higgs boson and decaying into two dark matter candidates

- Four categories based on E_T and $P_T(\gamma\gamma)$ to increase sensitivity to the two signal models
- Analytical fit to $m_{\gamma\gamma}$

ATLAS-CONF-2016-011







Conclusions

- Is the 125GeV Higgs boson *really* the *minimal* SM Higgs?
  - Does it decay unusually?
  - Are there more Higgses?

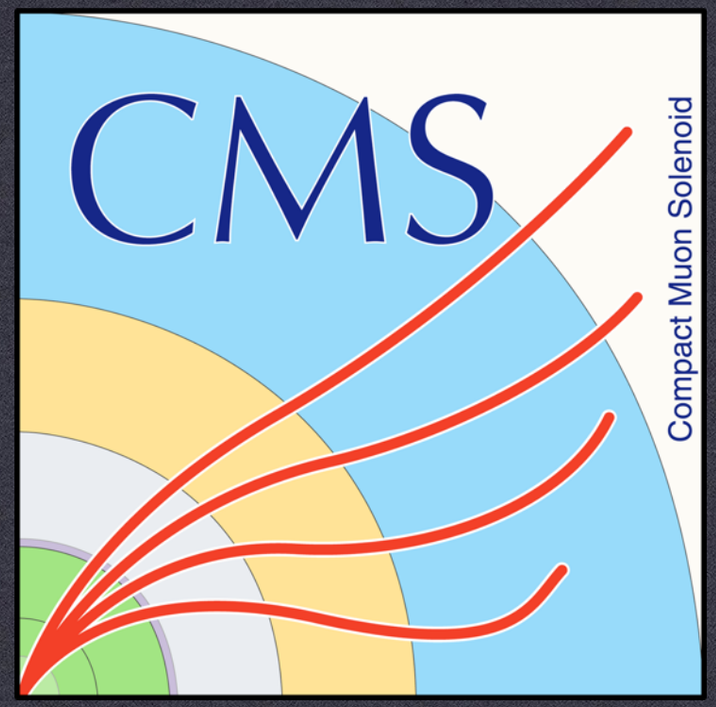
- With the restart of the LHC, the ATLAS and CMS collaborations are working hard to answer these questions
  - Large variety of models under the experimental lens : EWS, MSSM, hMSSM, 2HDM, 2HDM+S, RSG, Higgs Triplets,…

- **The LHC program for BSM Higgs studies has re-started with force**
  - New 2-3 fb^{-1} @13 TeV results arriving to compete and in some cases already surpass our 20 fb^{-1} @8 TeV ones
  - We are ready to attack the analysis of this year's data

- 2016 might be the year! Stay tuned!

For the full picture of Higgs@LHC:

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



GRACIAS!