Some recent BSM Higgs searches in ATLAS and CMS

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Menu of the day

- Review of some standard BSM Higgs searches:
  - ~~MSSM ττ searches~~ → See talk by Roger
  - 2HDM-inspired signatures
  - Heavy H → ZZ
  - NMSSM: h → aa
  - Higgs couplings re-intrepretation

More exotic menu in the talk by Erez and Mario this afternoon!

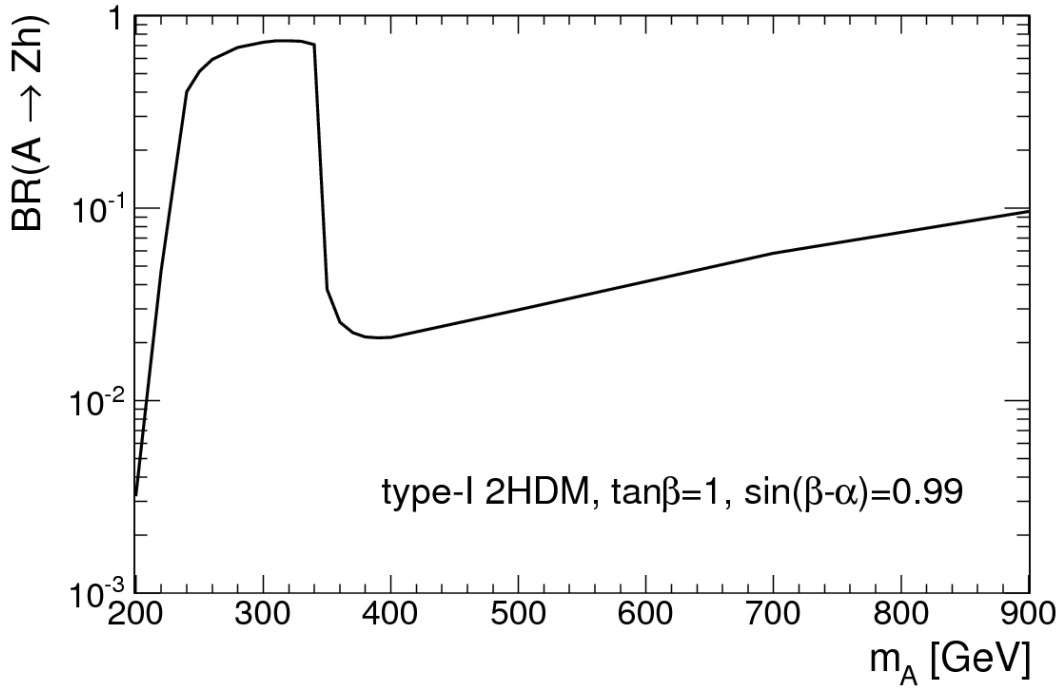
ATLAS A->Zh

arXiv:1502.04478

- Signature that dominates in many models below the tt kinematic threshold

The search is optimized for a gluon-fusion produced Higgs boson.

Effort to make a robust analysis, based on simple cuts.



Channels included:

- ◊ $A \to Zh \to \ell\,\ell\,bb$
- ◊ $A \to Zh \to \ell\,\ell\,\tau\tau \to \ell\ell$ lephad, $\ell\ell$ hadhad, $\ell\ell$ leplep
- ◊ $A \to Zh \to \nu\nu\,bb$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-06/

ATLAS A->Zh

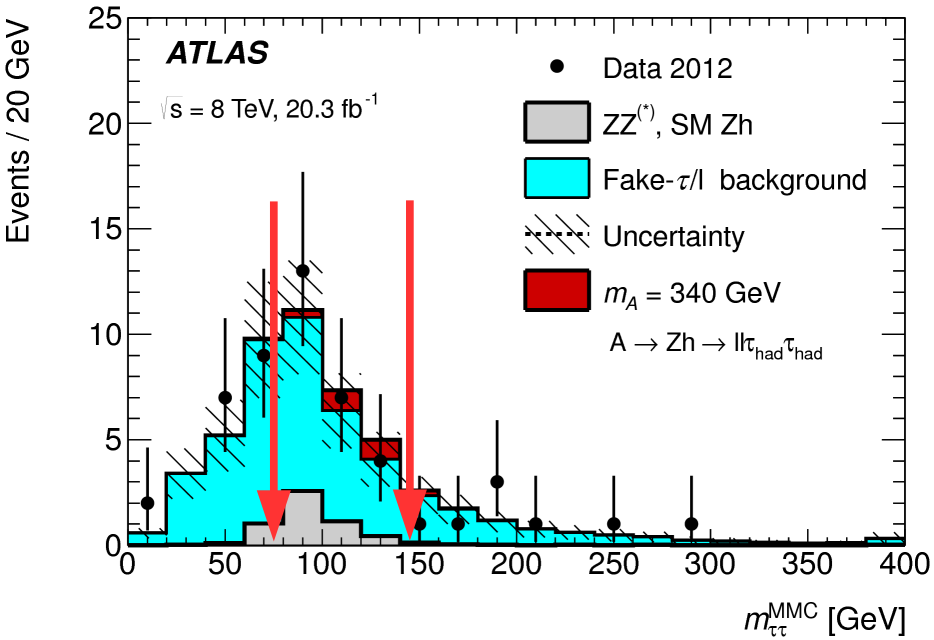
arXiv:1502.04478

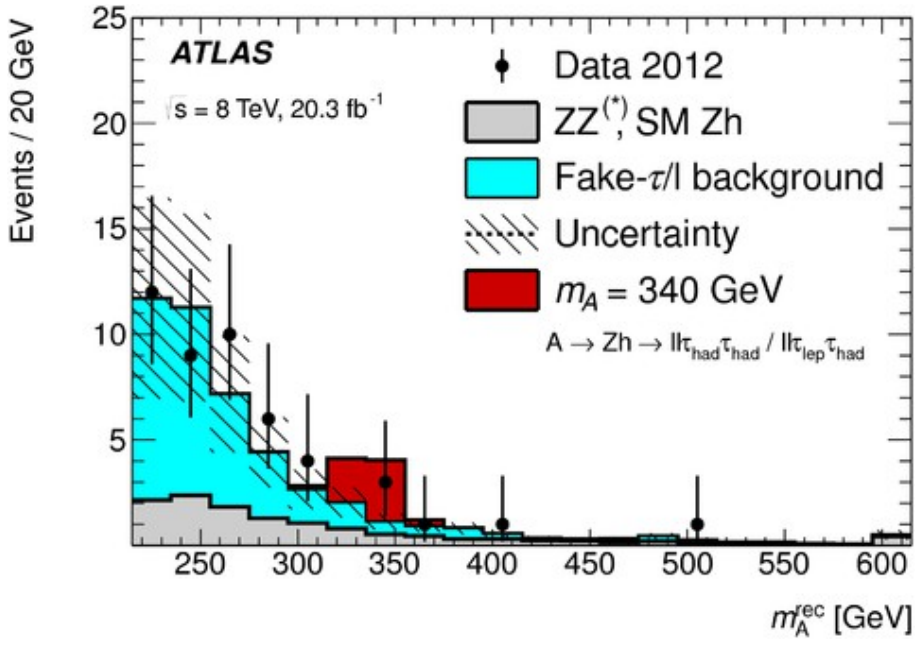
- Some highlights from the $\ell\ell\tau_{lep}\tau_{had}$ and $\ell\ell\tau_{had}\tau_{had}$ analysis

◊ m($\ell\ell$): 80 – 100 GeV, m($\tau\tau$): 75 – 175 GeV, p_T^Z cut in the hadhad channel

◊ Fake tau background (mostly Z+jets) is dominant: data-driven estimation

Shape from control region (fail opposite-sign and tau identification) and normalized in the m($\tau\tau$) sidebands

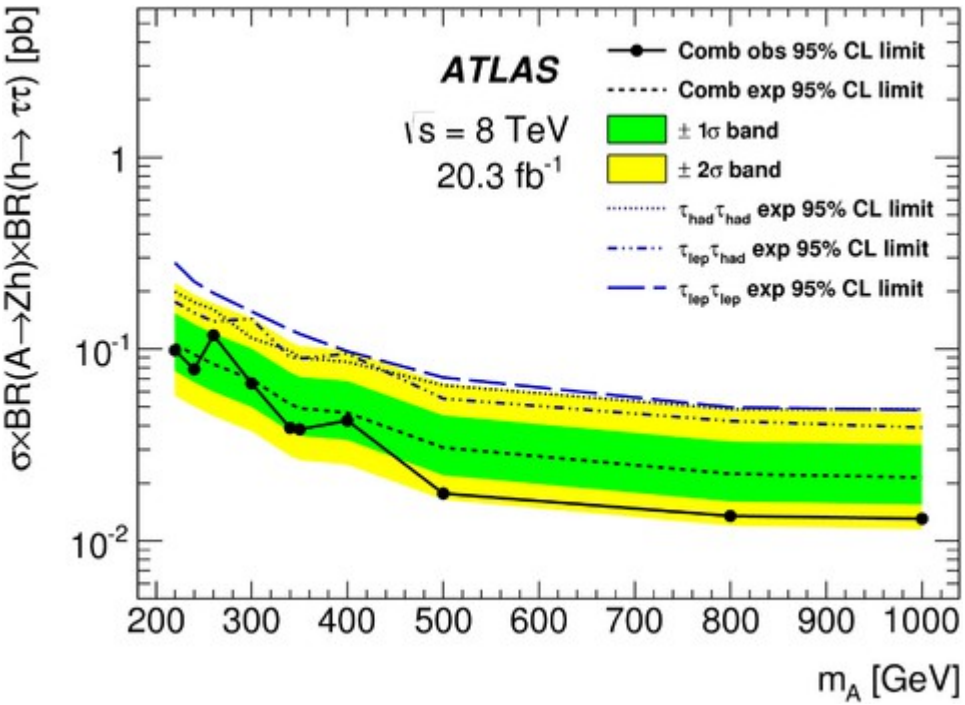


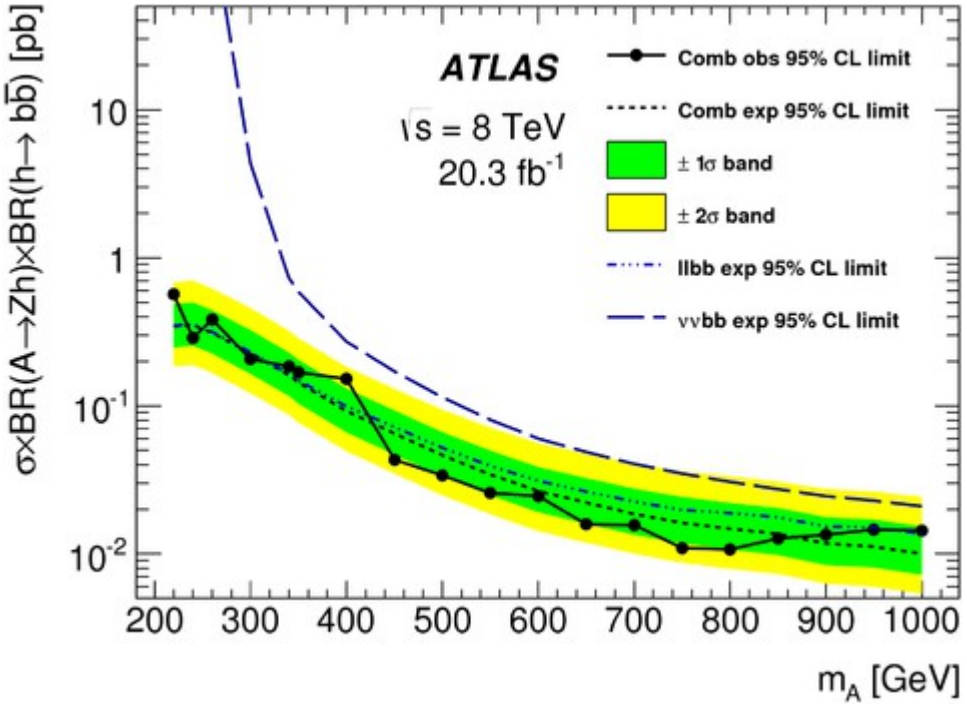


ATLAS A->Zh

arXiv:1502.04478

Cross sections limits for a narrow-width Higgs boson produced via gluon-fusion





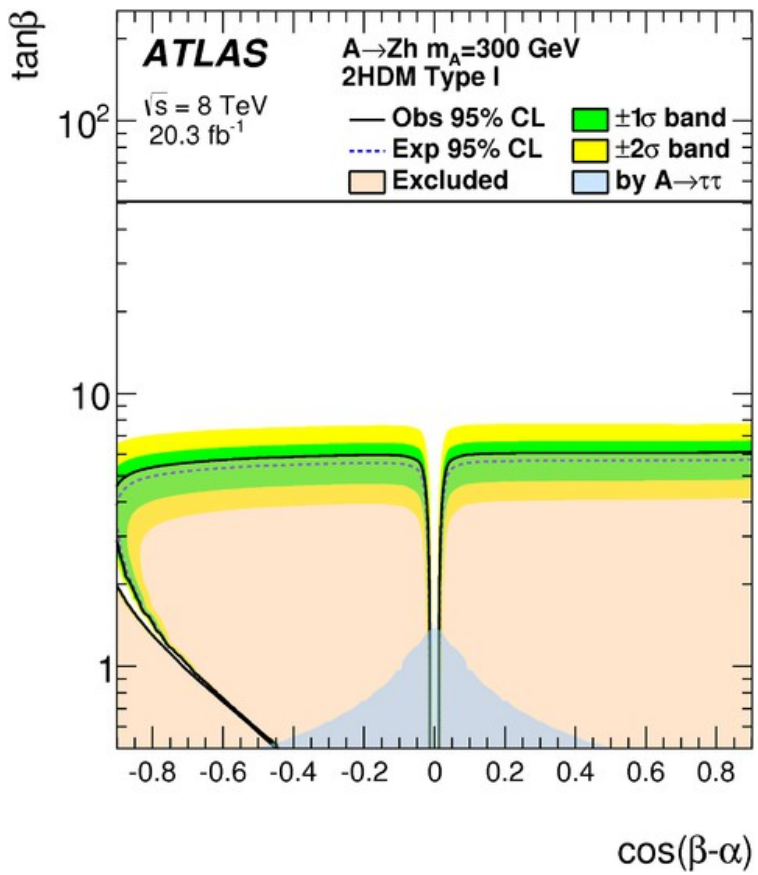
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-06/

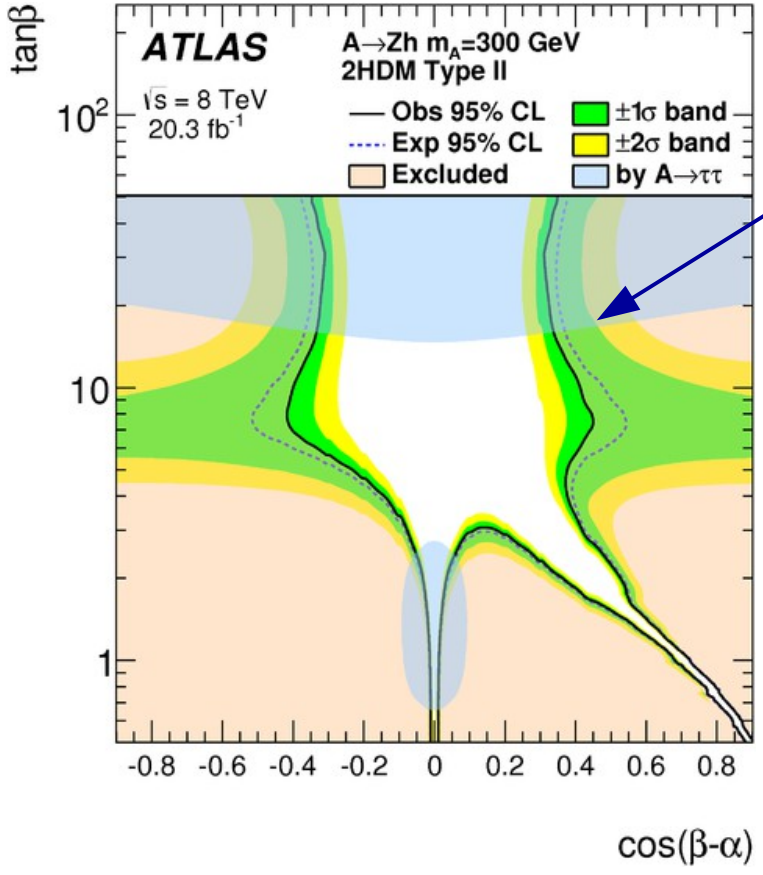
ATLAS A->Zh

arXiv:1502.04478

Interpretation in the CP-conserving 2HDM

→ overlay on the plots the constraints from A→ττ, which is complementary in this channel





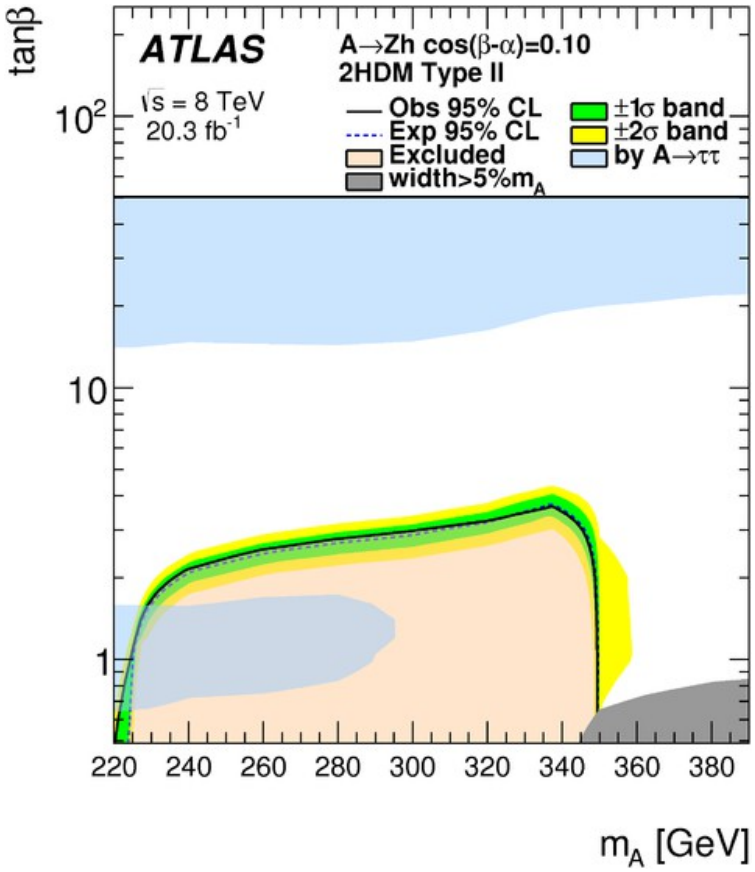
For type-II 2HDM at the high tanβ region the acceptance of the b-associated production is estimated and included in the interpretation.

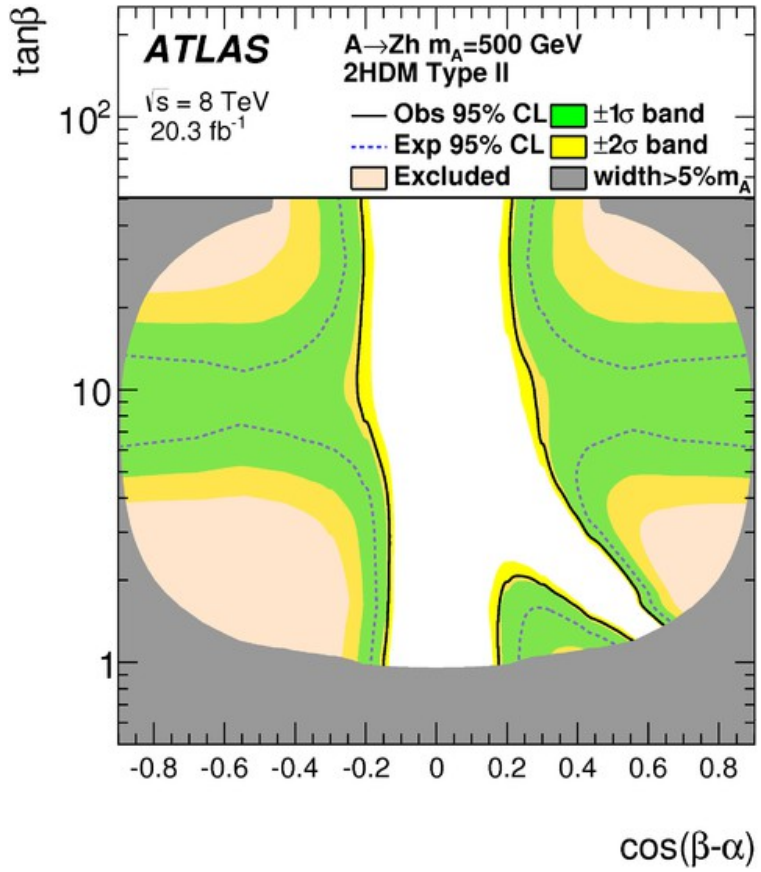
ATLAS A->Zh

arXiv:1502.04478

Interpretation in the CP-conserving 2HDM

More plots for your visual pleasure!





CMS A->Zh

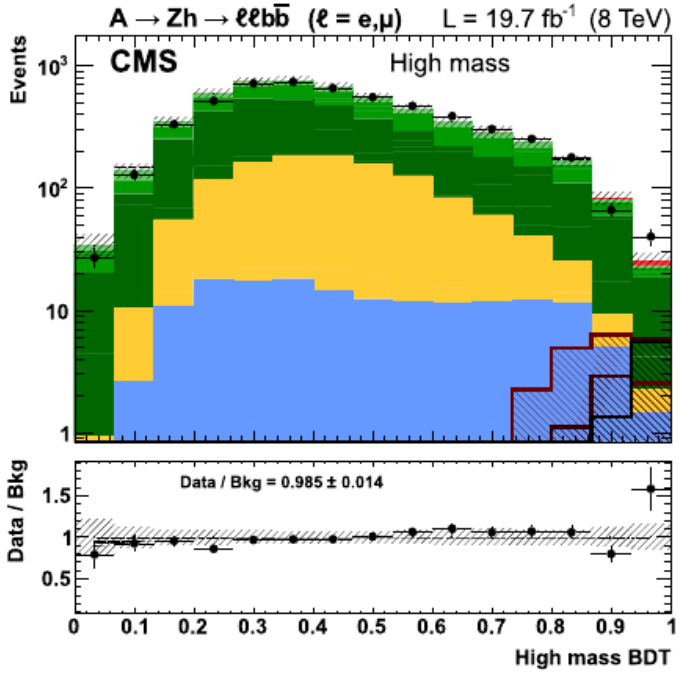
arXiv:1504.04710

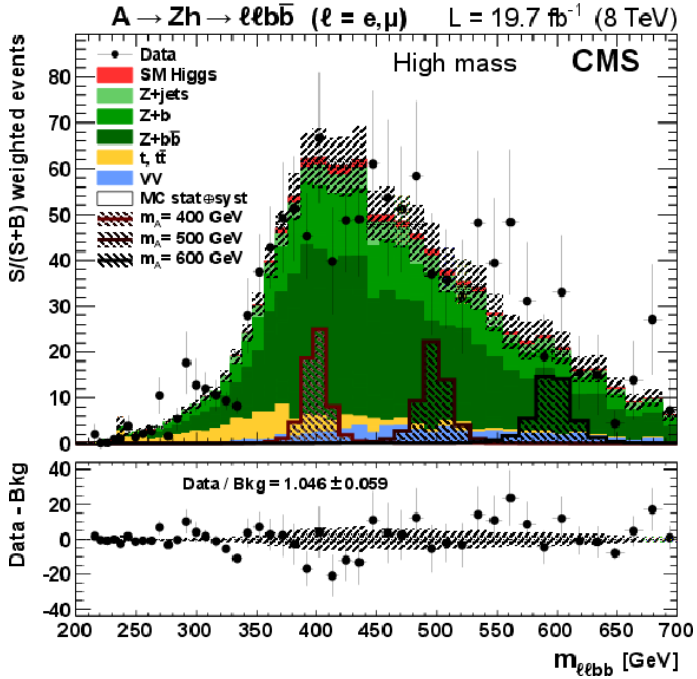
- Similar result from CMS: uses only A->Zh->llbb final state

◊ boosted decision tree with 16 variables (mostly kinematics) in 3 different mass category regions.

◊ The final result is extracted with the 2D likelihood fit in the (BDT > 0.6) versus m(ℓℓbb) plane.

Example from the high mass category region (mA >400 GeV)



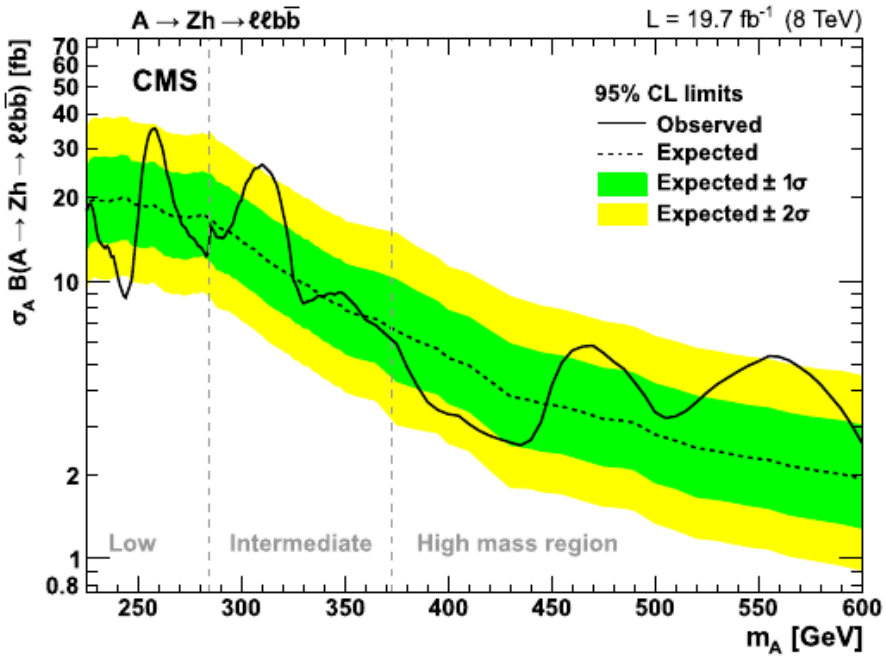


CMS A->Zh

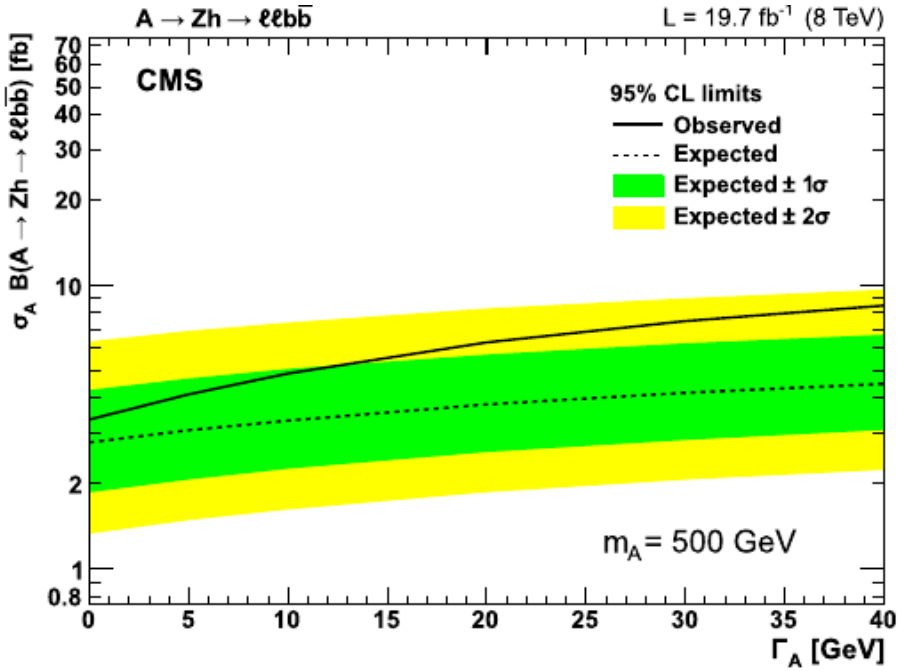
arXiv:1504.04710

- Constraints

Gluon-fusion produced, narrow-width signal limit in the 3 BDT mass categories



Dedicated study of the effect of larger signal widths in the limit

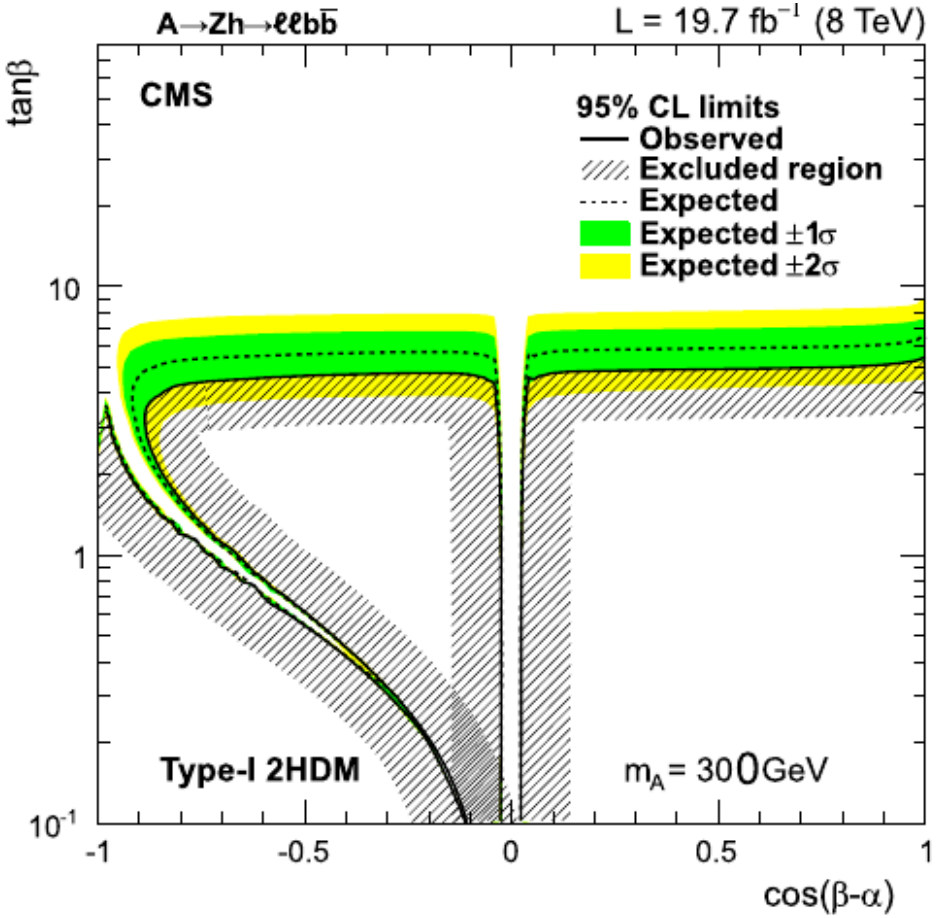


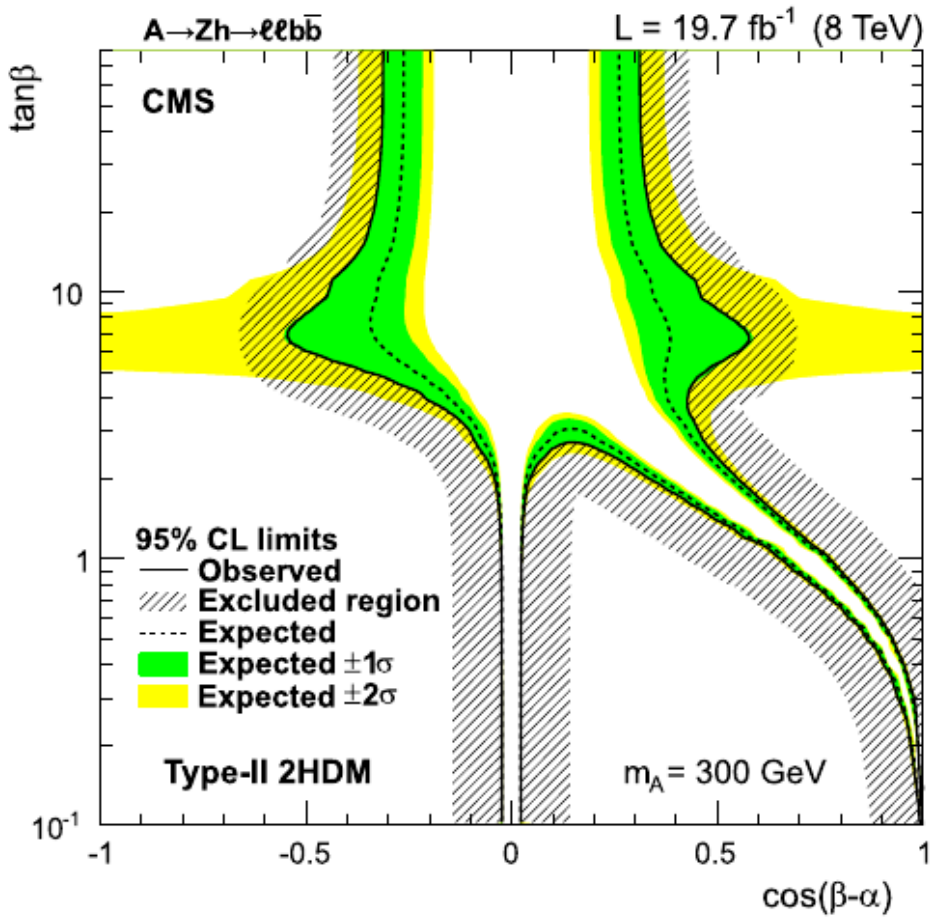
Compared to the simple cut-based analysis in ATLAS you can gain 10 – 15% in sensitivity for masses up to 500 GeV, though for high masses (~600 GeV) the results are the same

CMS A->Zh

arXiv:1504.04710

- Same strategy with ATLAS in the 2HDM interpretation





CMS A->ZH

HIG-15-001

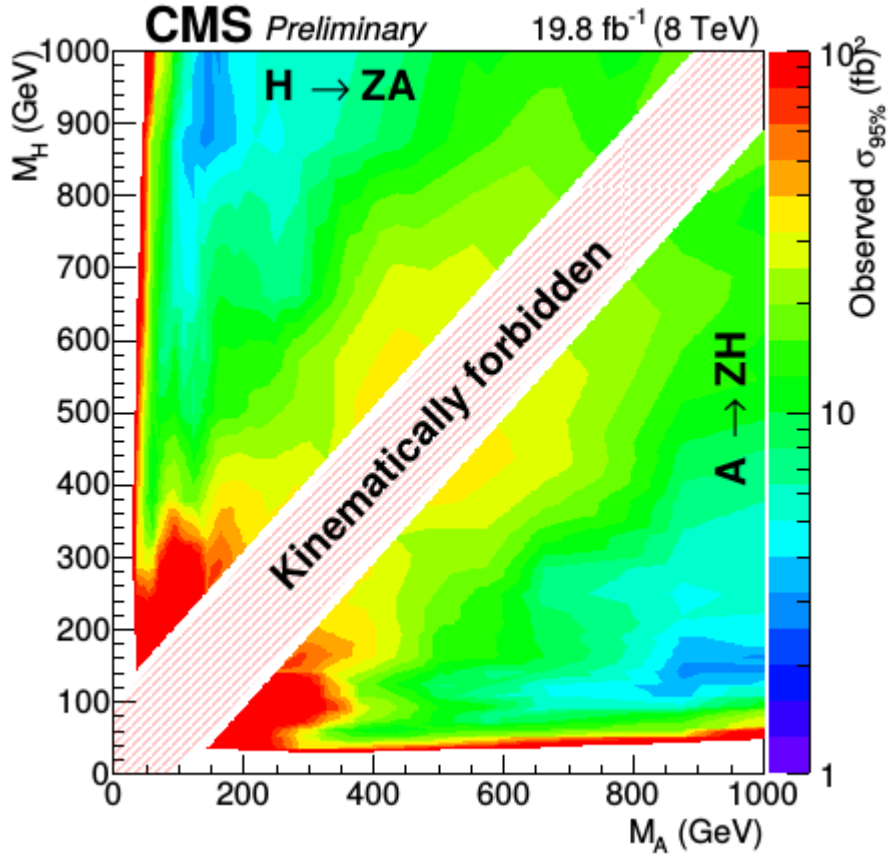
- CMS proceeds one step further and examines Heavy Higgs to Heavy Higgs decays

Cut-based analysis using:

◊ A → ZH → ℓ ℓ bb

◊ A → ZH → ℓ ℓ τ τ → ℓ ℓ τ(lep) τ(lep), ℓ ℓ τ(lep) τ(had), ℓ ℓ τ(had) τ(had)

Example of 2D observed limit plot from the ℓ ℓ bb final state



CMS A->ZH

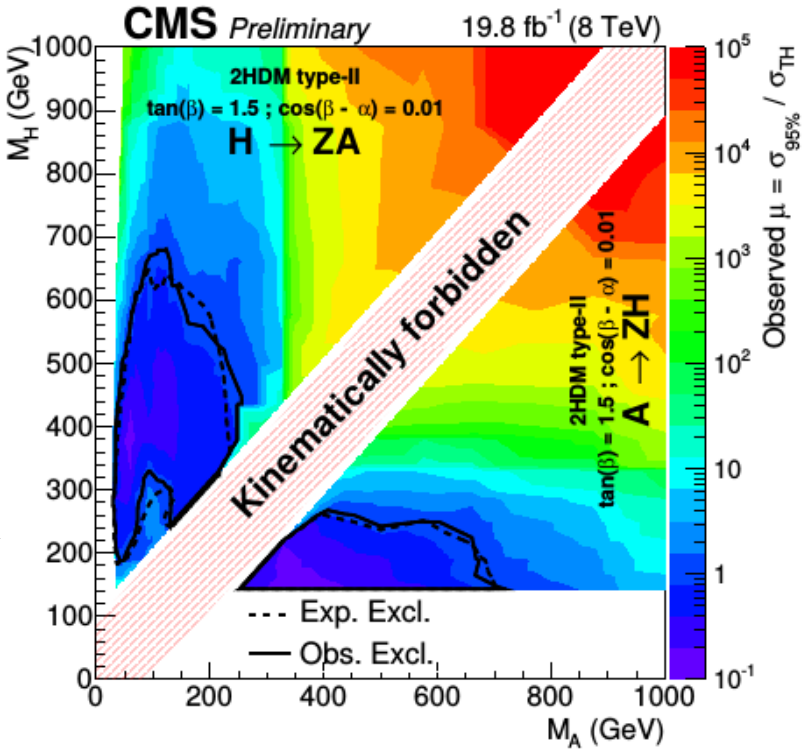
HIG-15-001

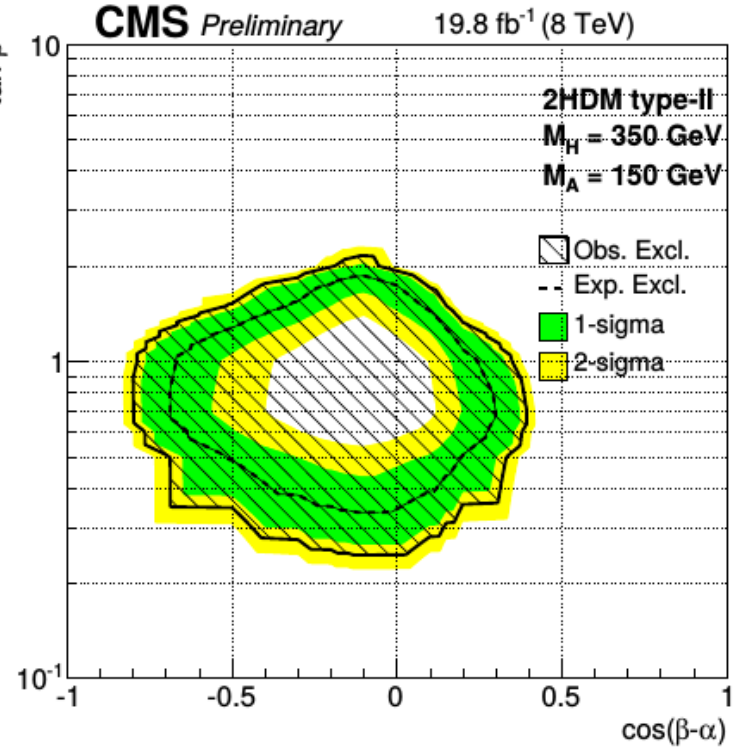
- Interpretation of the search in the CP-conserving 2HDM with softly broken Z_2

◊ Separate results for τ τ and b b final states, no combination is attempted

◊ ($m_A - m_H$) plane for given tanβ, cos(β-α) or on the (tanβ – cos(β-α)) plane for given m_H and m_A

Examples from the bb final state constraints





H->hh->bbbb

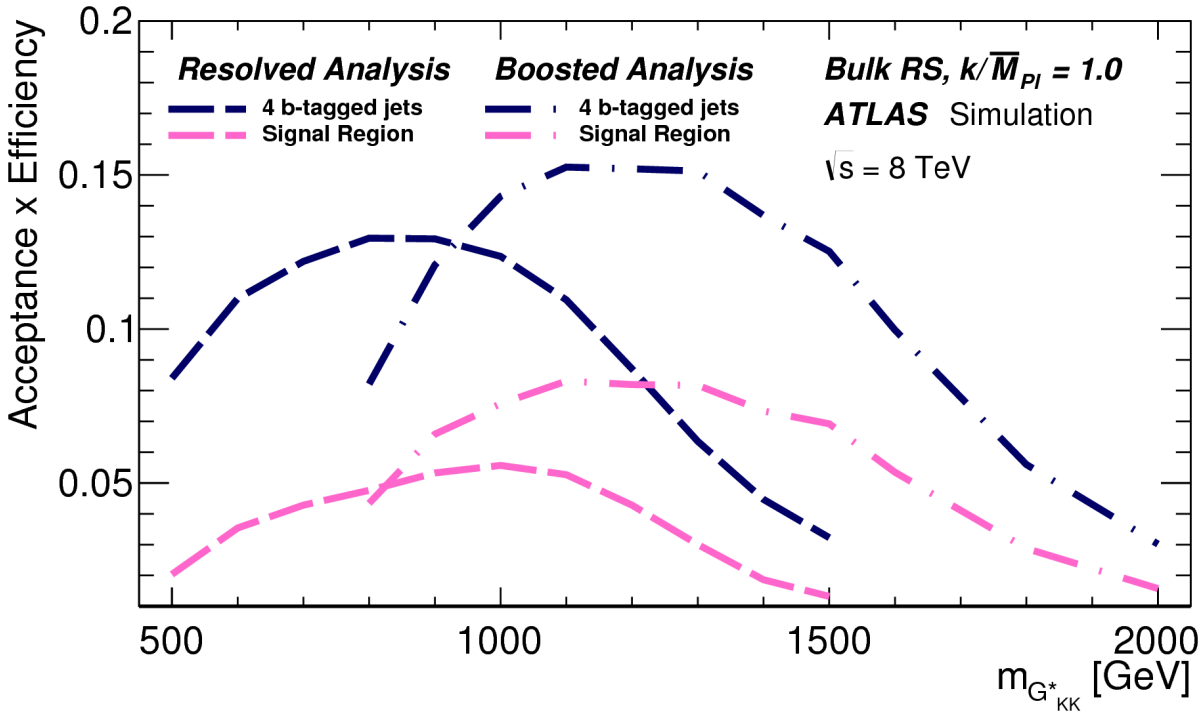
arXiv:1506.00285

- Looking for both resonant and non-resonant hh production

In order to improve performance the analysis is split in two categories:

◇ **"Resolved" analysis**
– uses 4 b-tagged jets

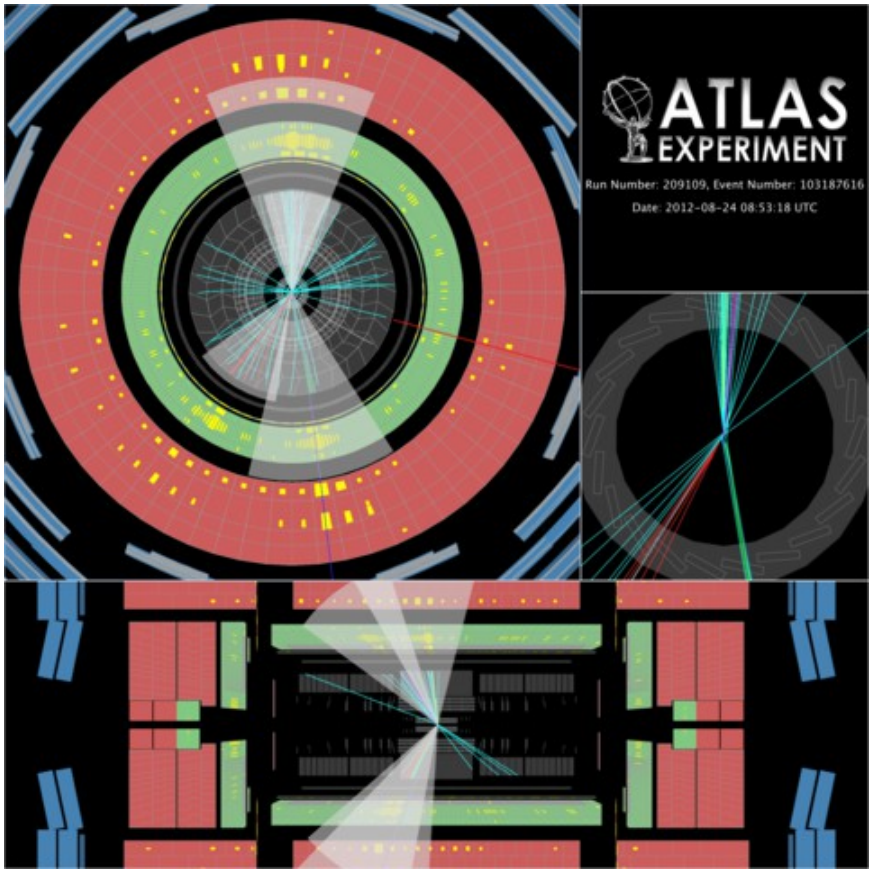
◇ **"Boosted" analysis**
– uses special techniques to reconstruct the boosted bb pair at high masses



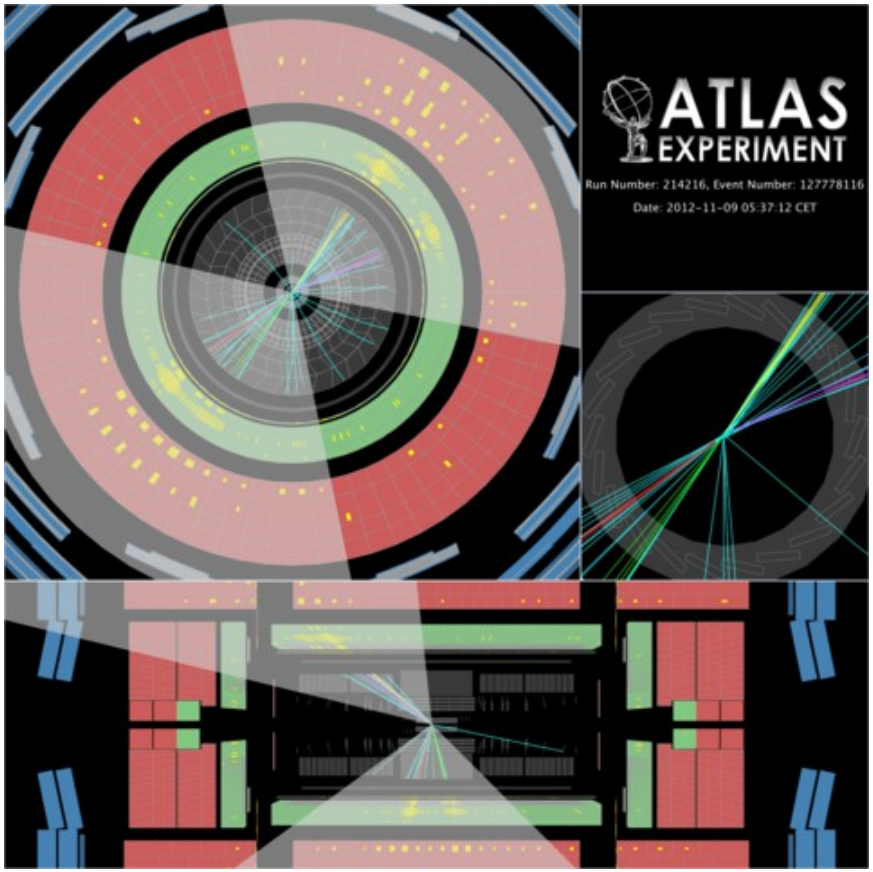
H->hh->bbbb

arXiv:1506.00285

Event examples: “resolved” and “boosted”



m(4j)= 809 GeV
dijet pT = 394 GeV and 333 GeV



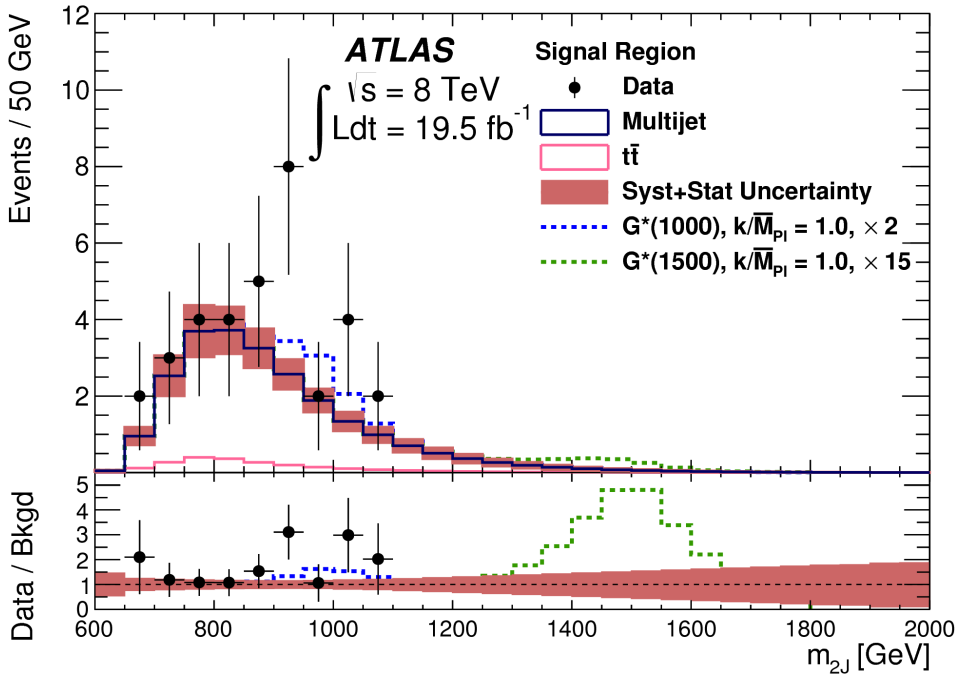
m(2j) = 1030 GeV
jet pT = 447 GeV and 441 GeV

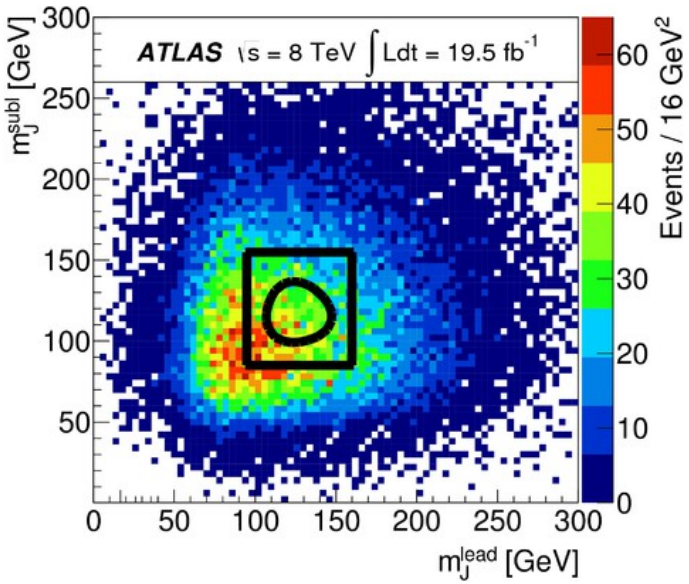
H->hh->bbbb

arXiv:1506.00285

- "Boosted" analysis highlights
  - ◇ two "large jets" anti-kt R=1.0
  - ◇ pT > 350 GeV, 250 GeV
  - ◇ $|\Delta\eta(\text{jet1,jet2})| < 1.7$ (vs multi-jet)
  - ◇ 4 b-tagged jets
  - ◇ Backgrounds: multi-jet ~90%, top ~10%

Mass distribution for the full selection



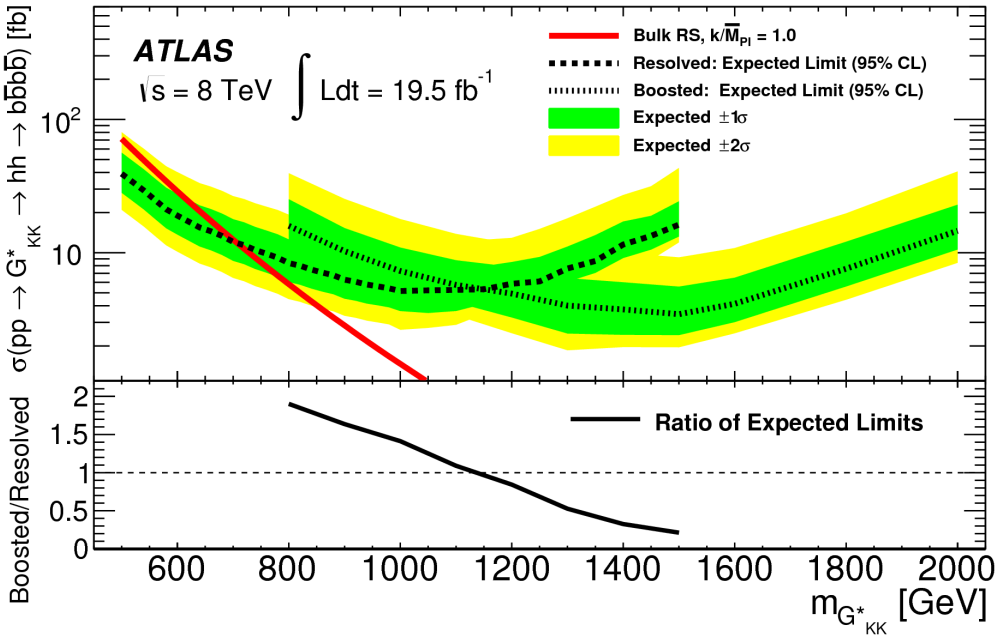


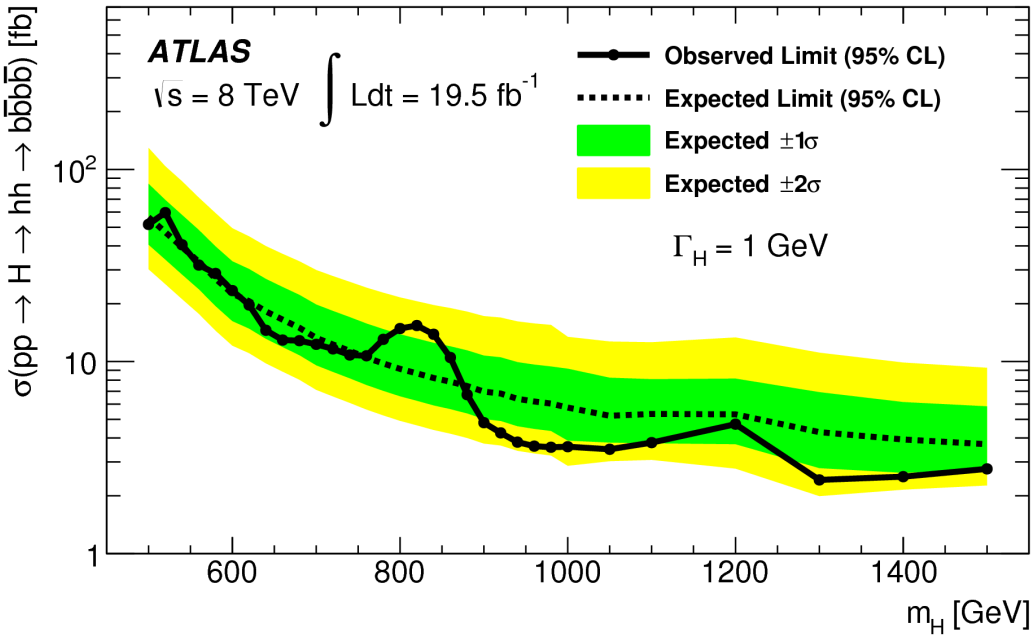
Backgrounds are estimated in a data driven way using the side-bands and the number of b-tagged jets

H->hh->bbbb

arXiv:1506.00285

- Sensitivity comparison: “resolved” vs “boosted” and combined cross section limit





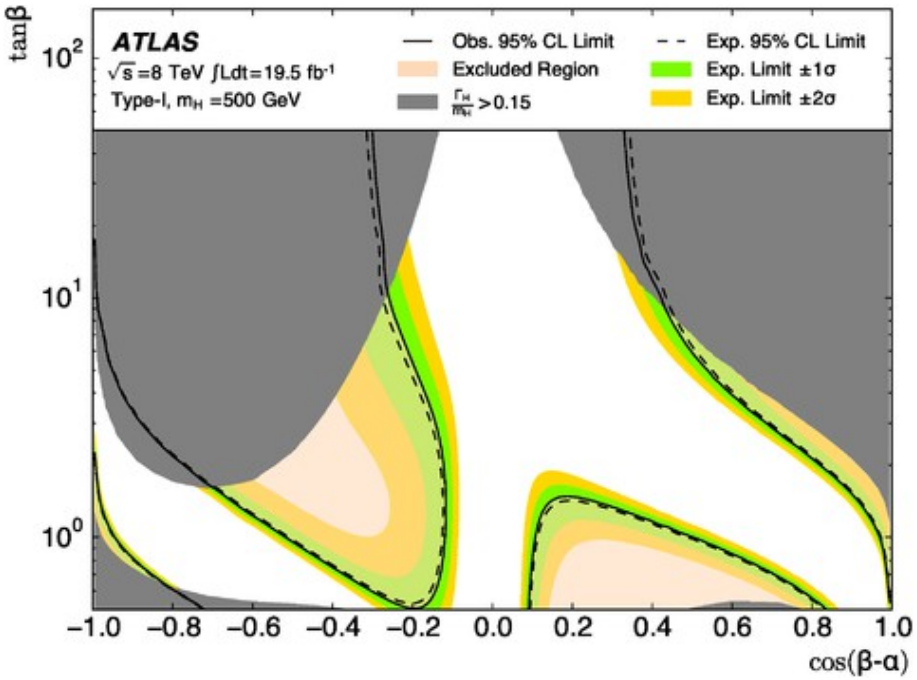
- Search for anomalous non resonant hh->bbbb production uses the resolved analysis only

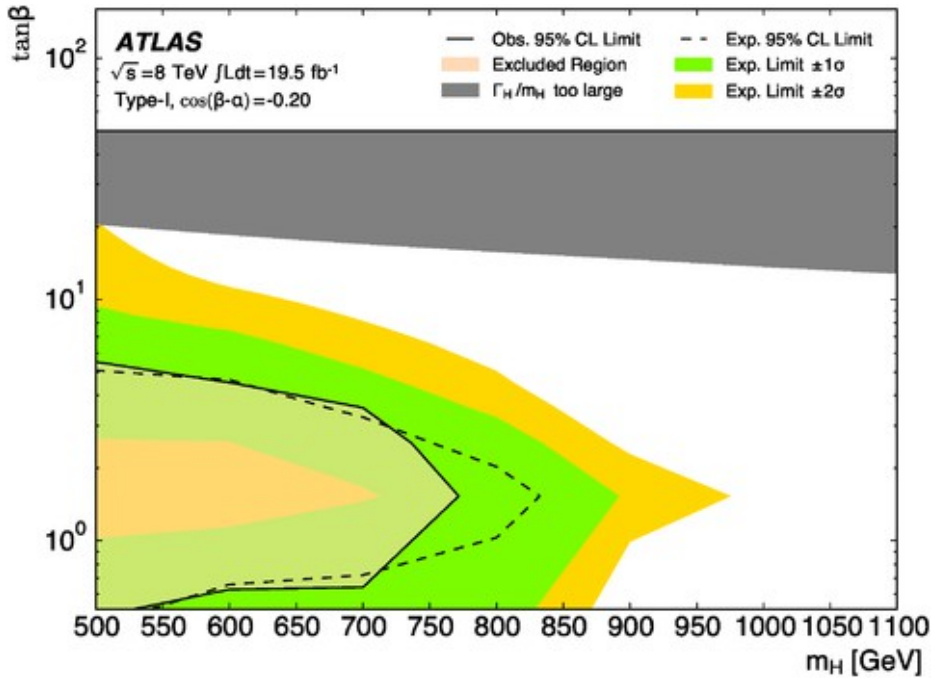
ATLAS Limit σ(pp → hh → bbbb) < 202 fb (c.f. SM production ~4 fb)

H->hh->bbbb

arXiv:1506.00285

- Interpretation of the resonance search in the CP-conserving 2HDM





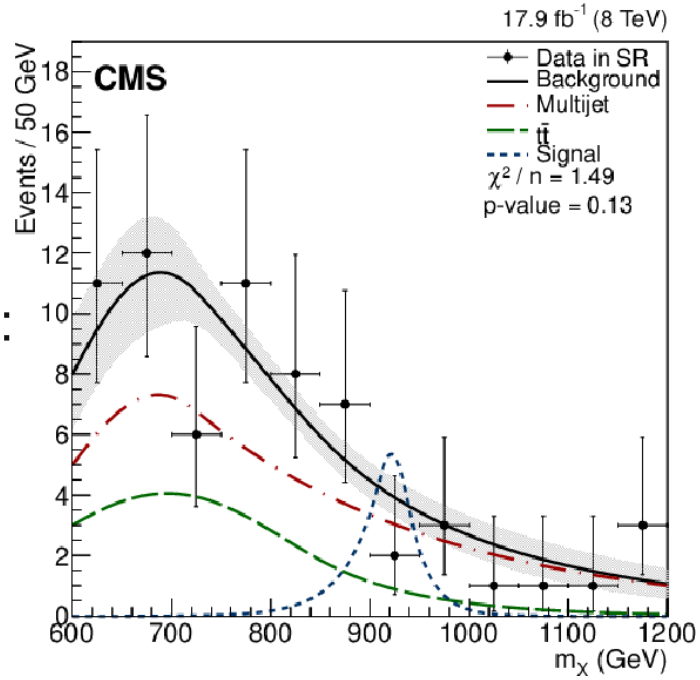
CMS H->hh->bbbb

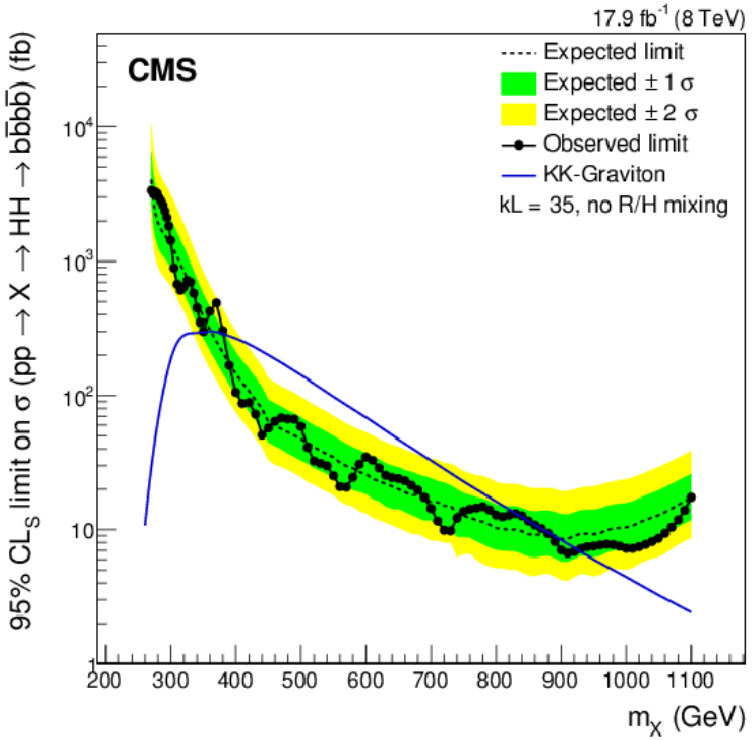
arXiv:1503.04114

- Similar to the ATLAS analysis
  - Cut-based, no use of boosting techniques, but separate optimization for low and high mass
  - Similar control regions as in ATLAS for the background estimation

Cross section limit for resonant hh production

Example distribution: mH: 600 – 1200 GeV and pT(Higgs)> 300 GeV



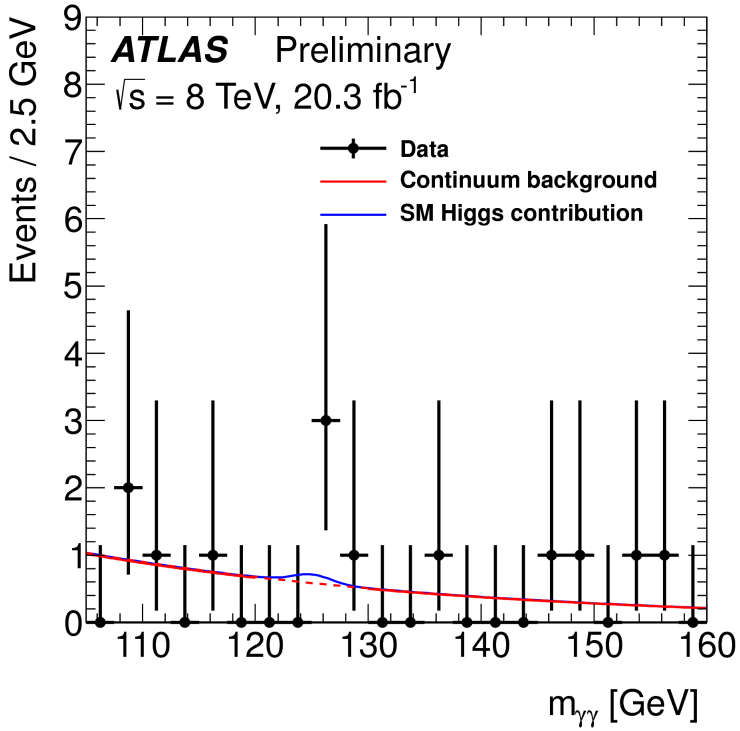


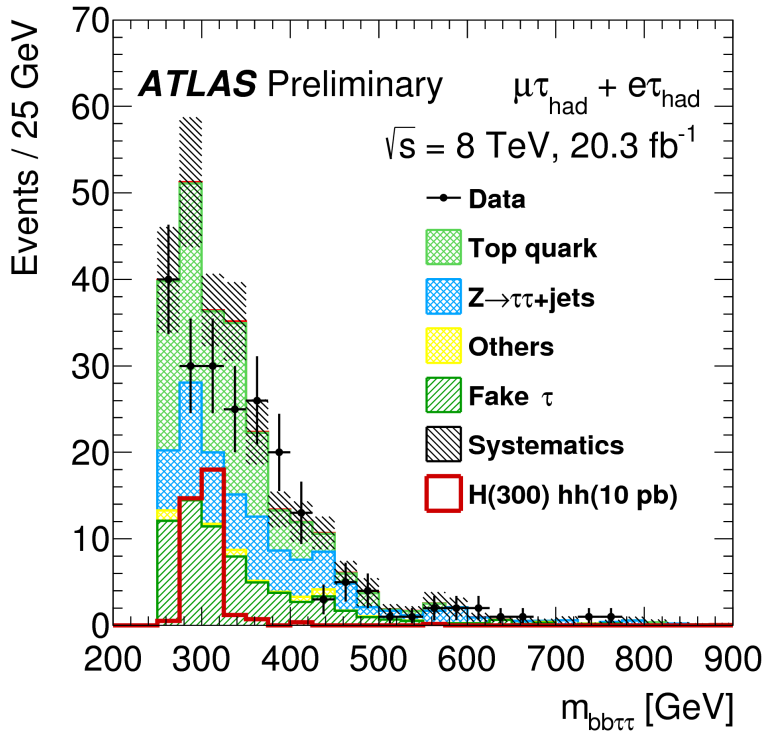
H->hh combination

- ATLAS has also a combination paper for hh production that includes: **bbττ, γγWW***, γγbb, bbbb

◊ 2 new channels *New!*

◊ bbbb: only resolved analysis, since the focus is on masses below 1 TeV

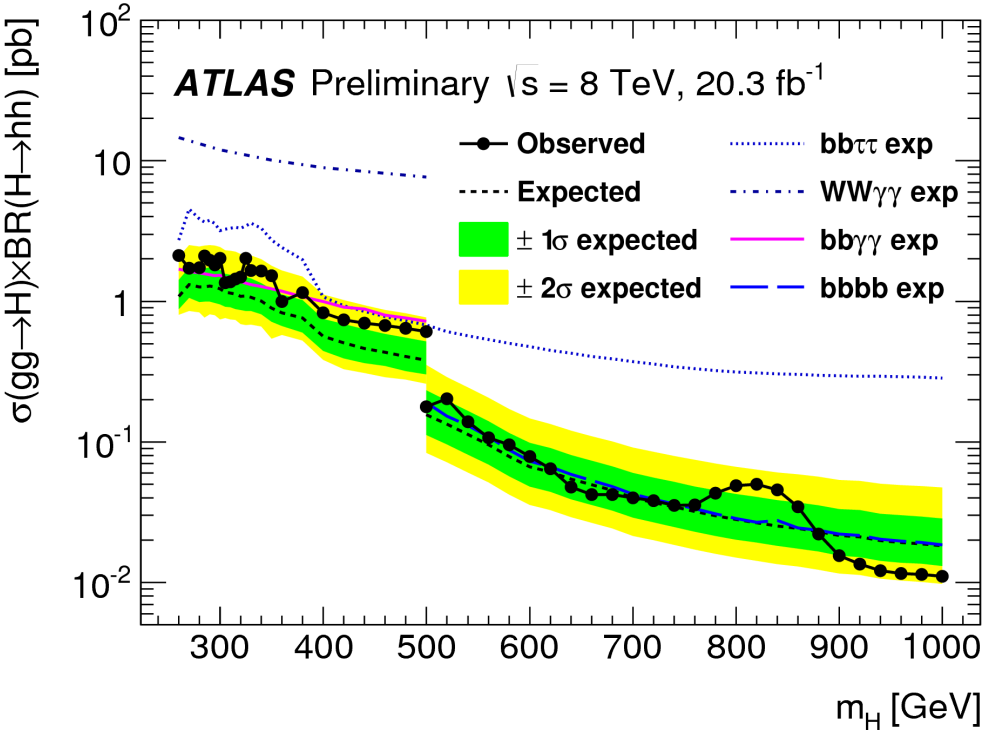




H->hh combination

- Results

Limit on resonant hh production

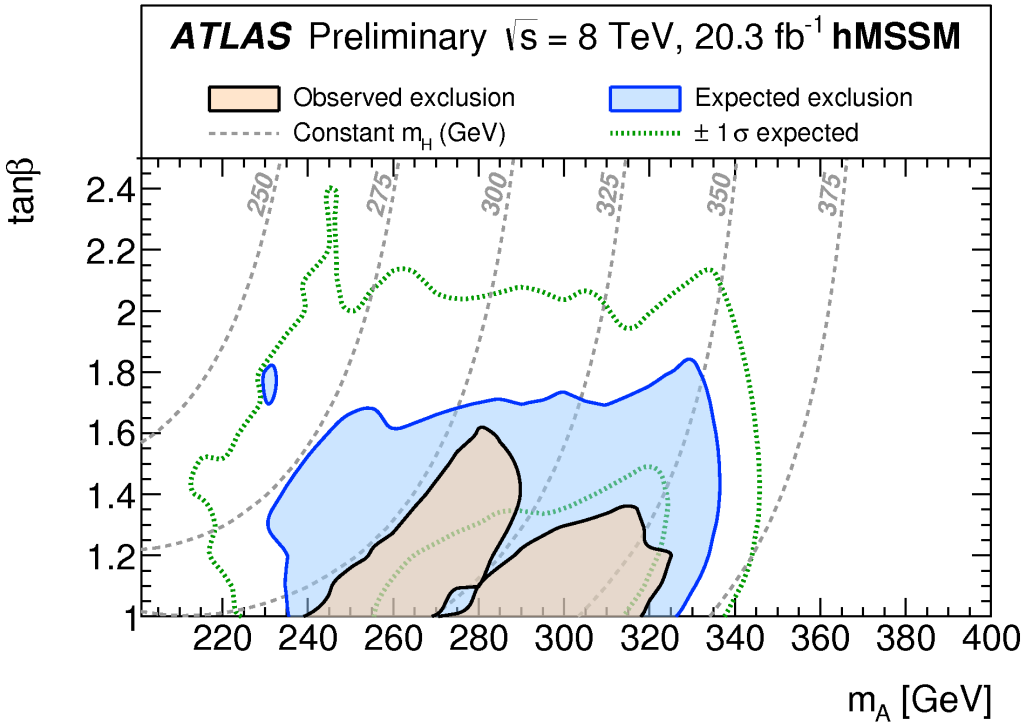


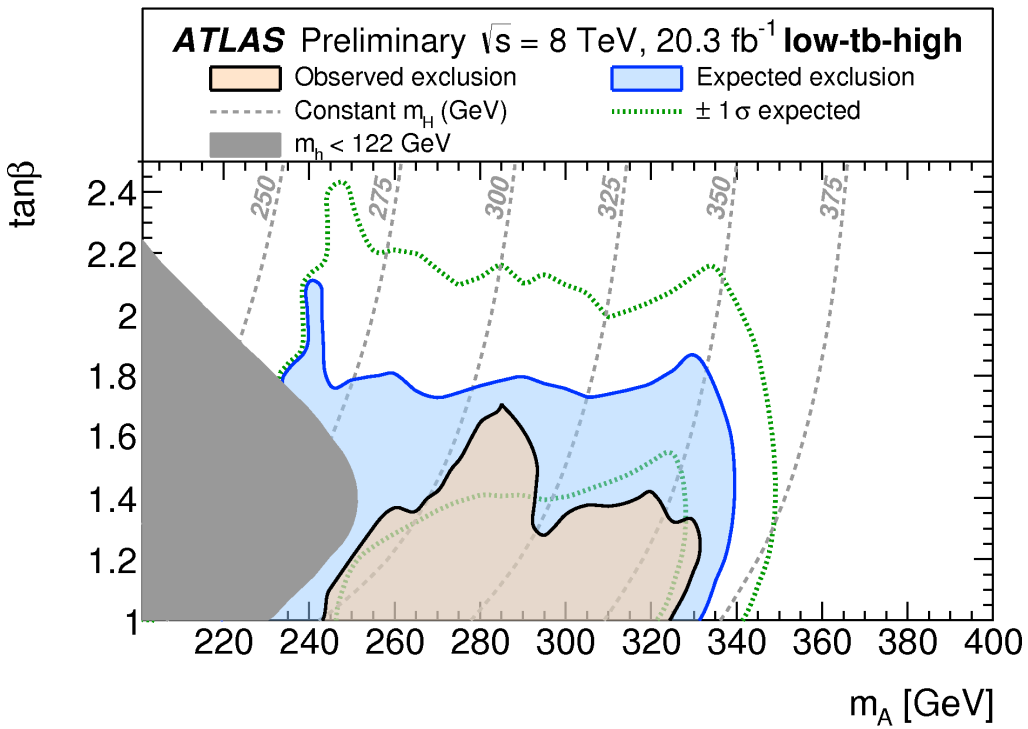
Limit on anomalous non-resonant hh production

Analysis	$\gamma\gamma b\bar{b}$	$\gamma\gamma WW^*$	$b\bar{b}\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

H->hh combination

- Interpretation: hMSSM and low-tb-high

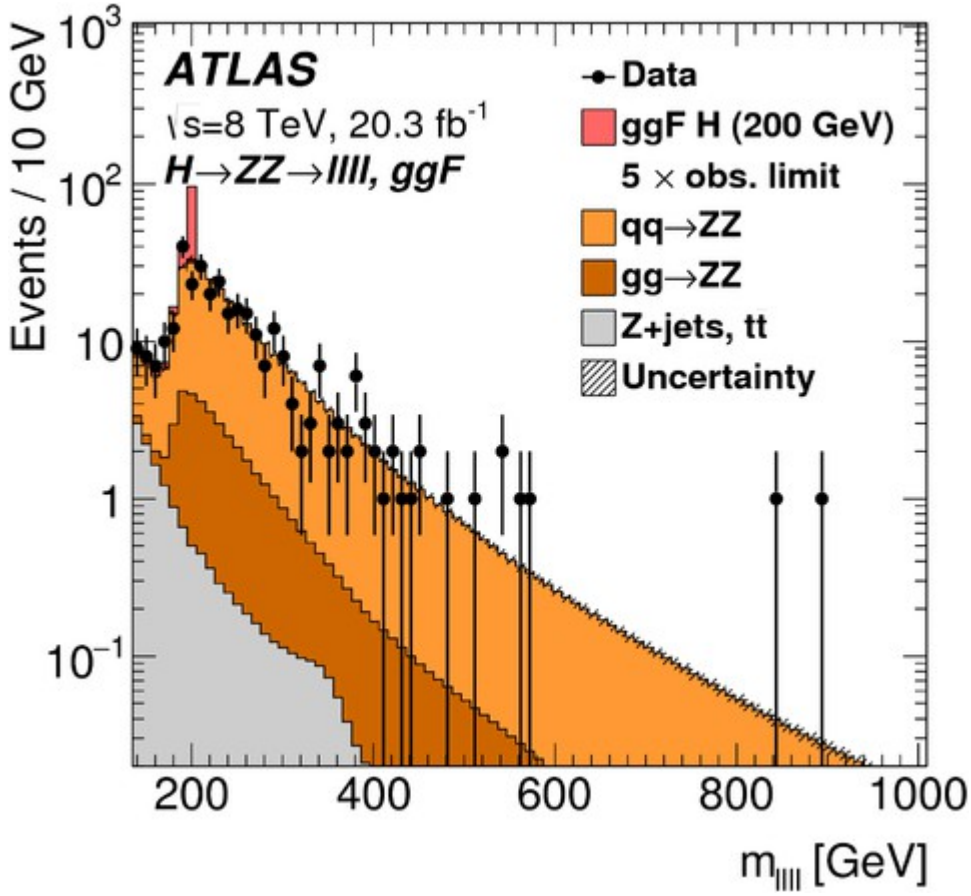




H->ZZ

- Search for a Heavy Higgs decaying to ZZ and WW

◊ 140 GeV – 1 TeV
◊ narrow width Higgs
◊ VBF, [VH], gluon-fusion
◊ Channels used:
  – ZZ → 4l
  – ZZ → ll νν
  – ZZ → ll qq
  – ZZ → νν qq



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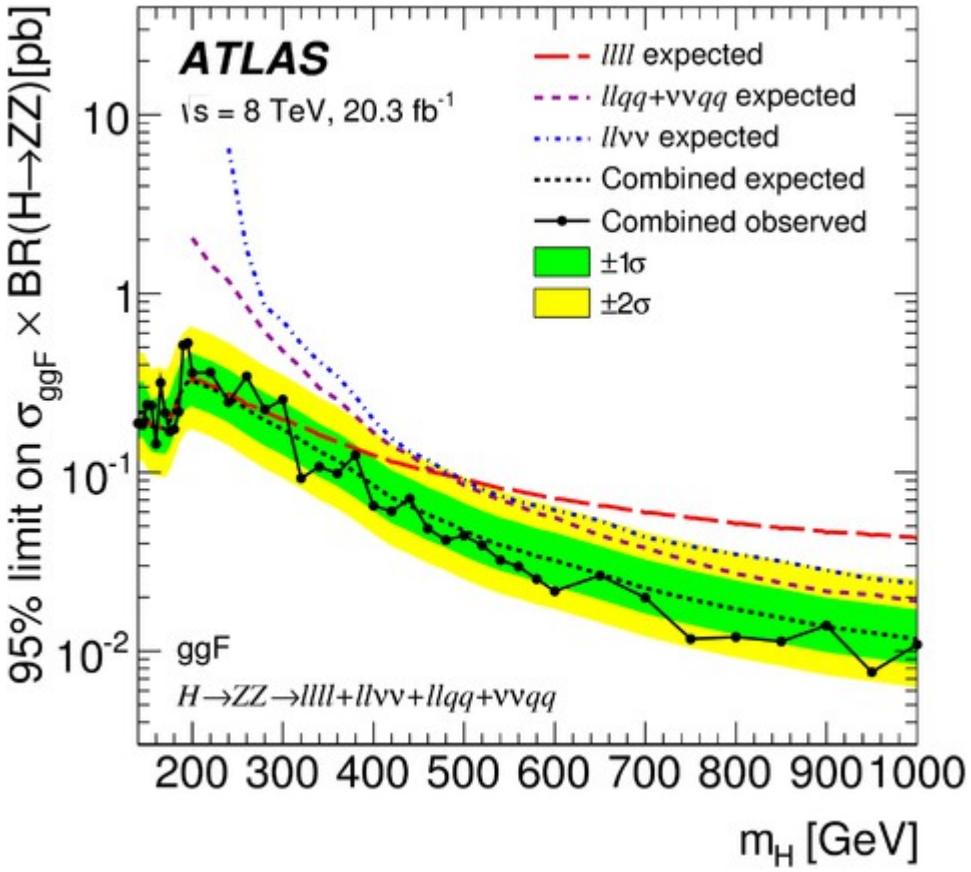
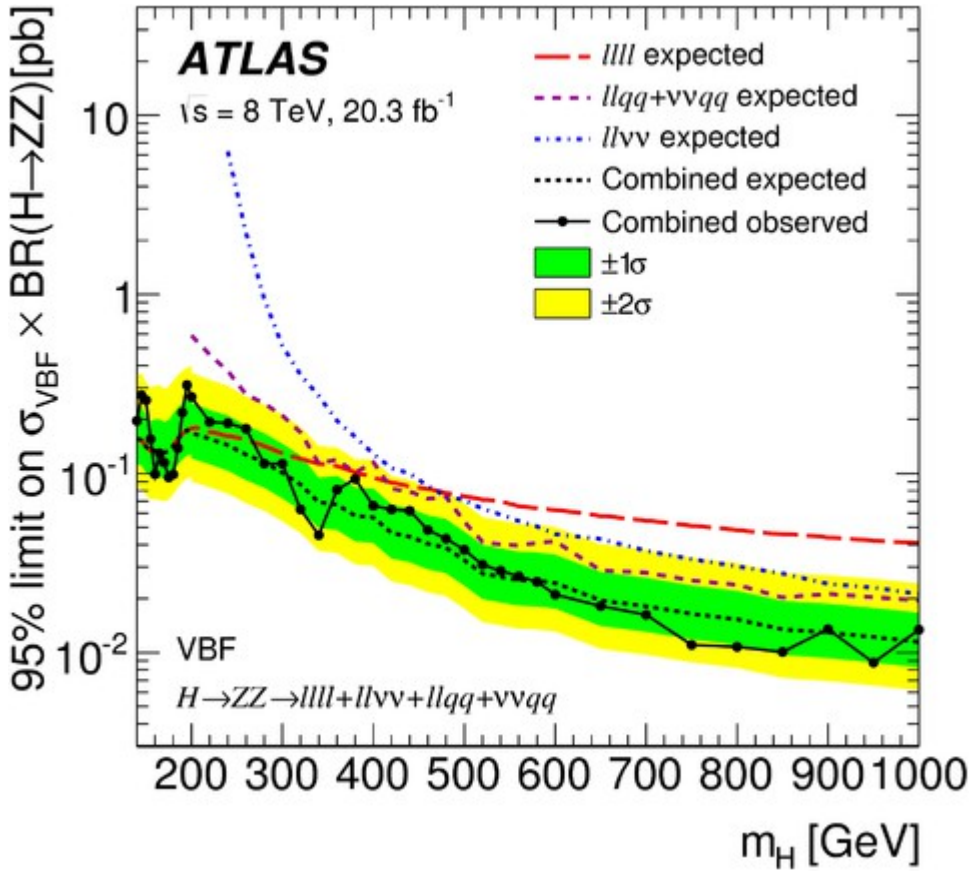
Cross section limits

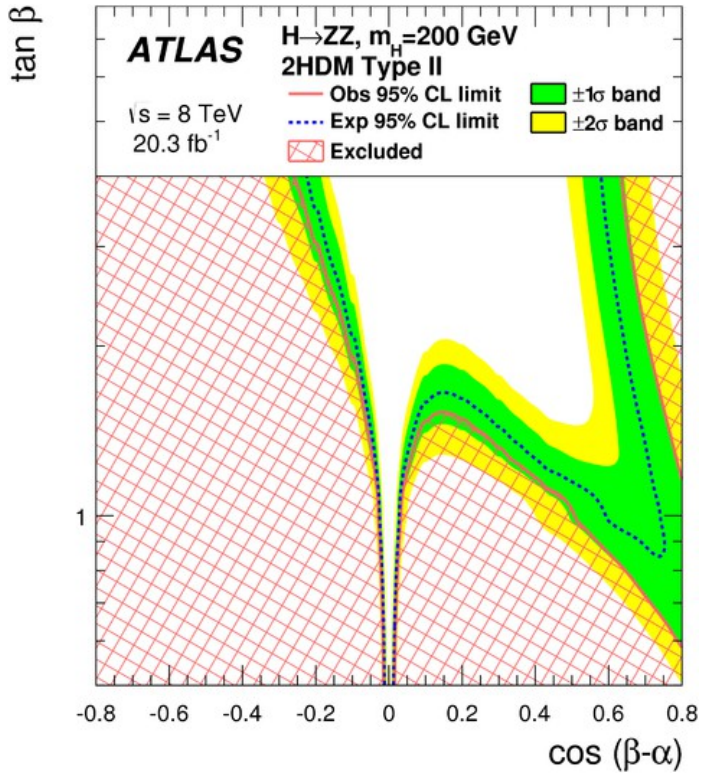
- Assuming single production mechanism

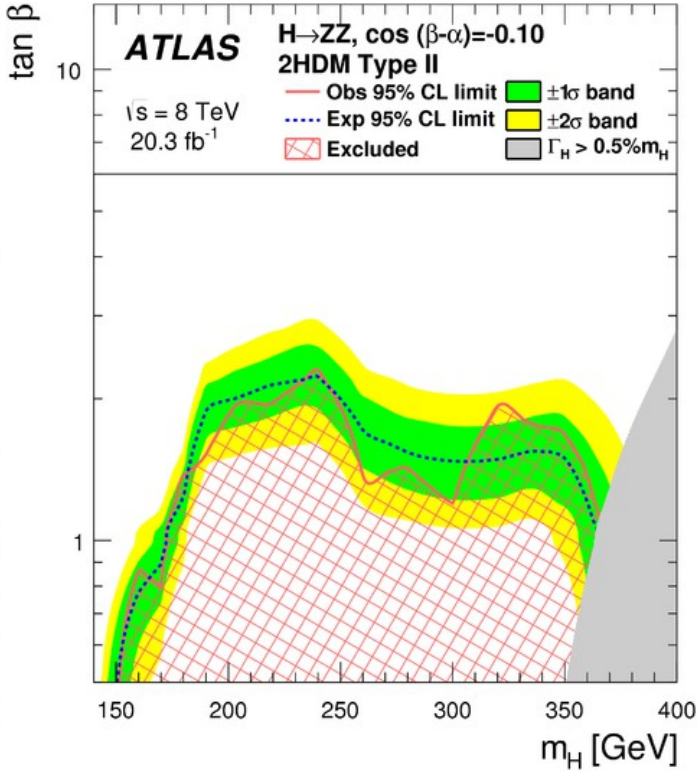


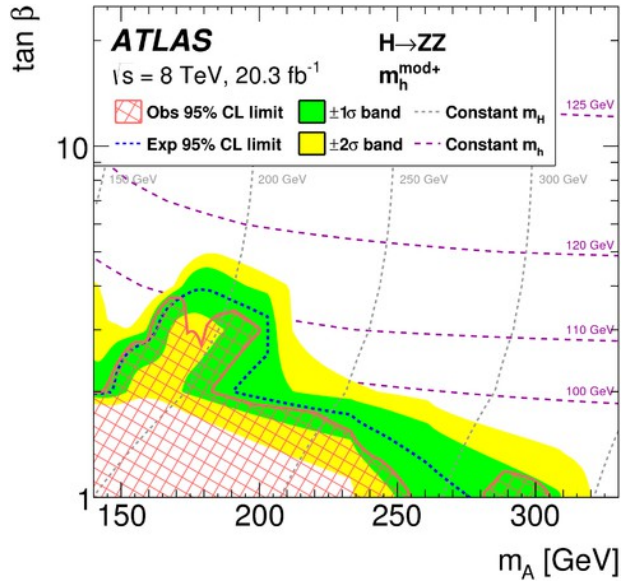


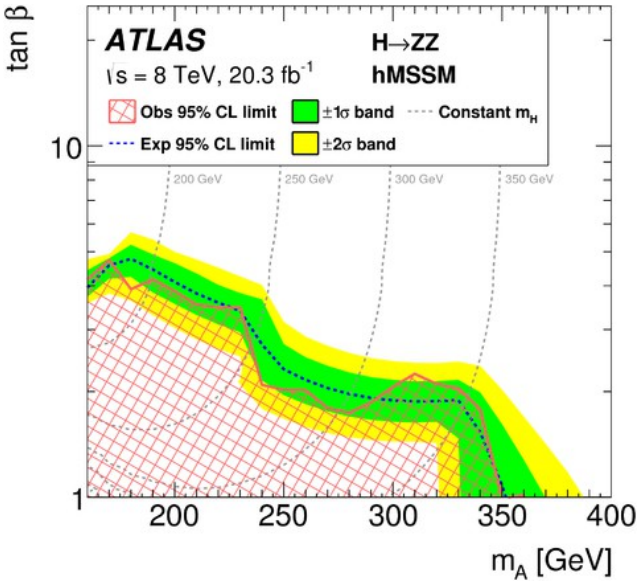
Search interpretation

Interpretation in 2HDM and various MSSM scenarios



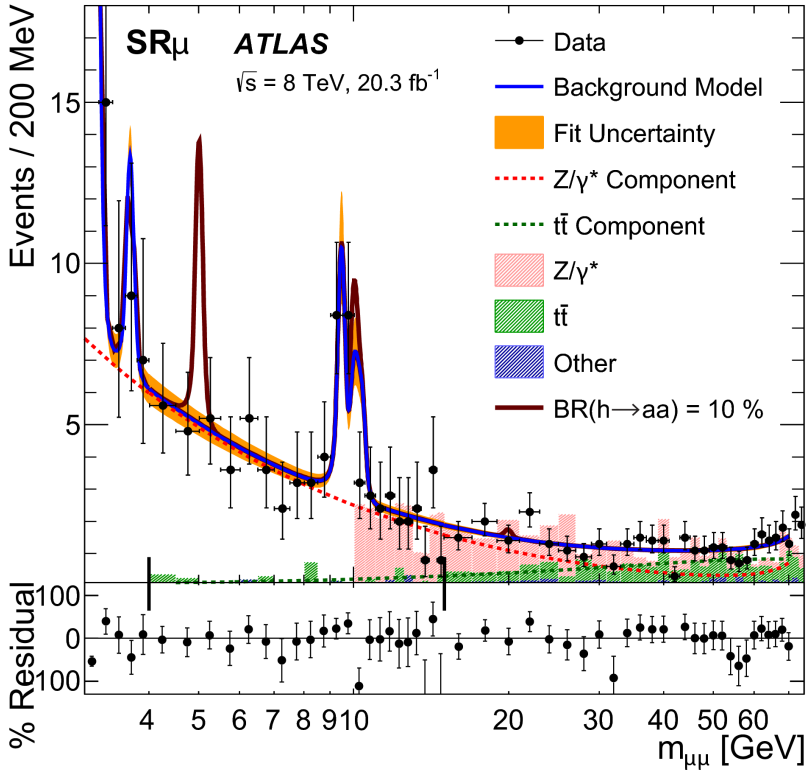


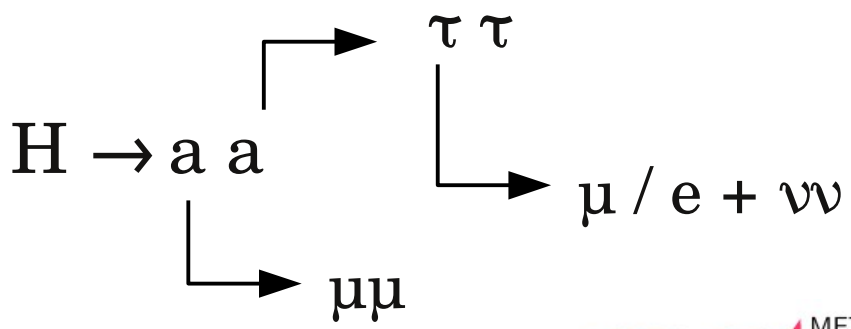




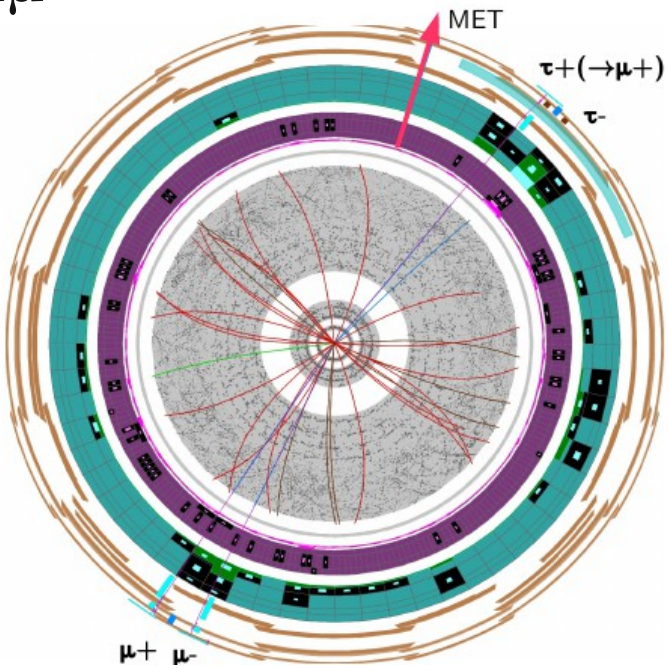
NMSSM-inspired H->aa

- Various NMSSM inspired results mostly for H->aa
- Example: **arXiv:1505.01609**



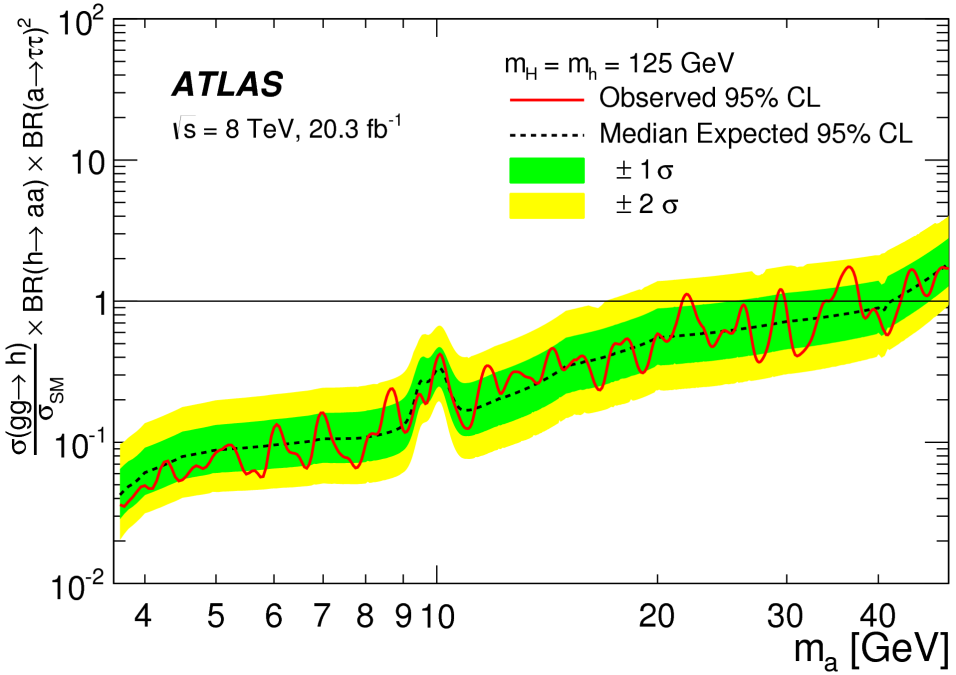


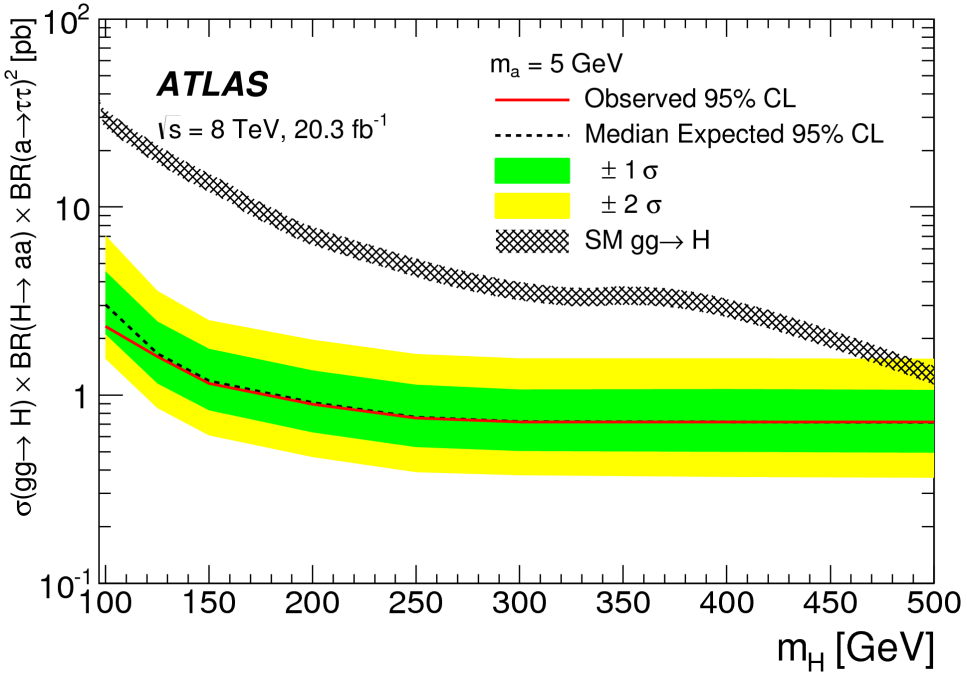
Searching for a bump in the μμ spectrum



NMSSM-inspired H->aa

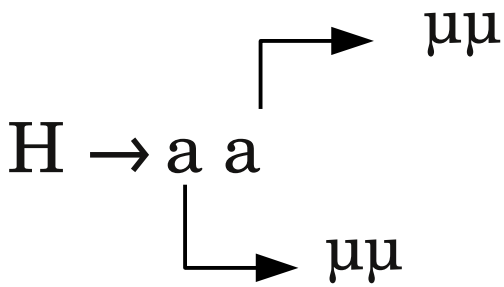
Look for m_a in the mass range: 3.7 – 50 GeV and for a heavy Higgs decaying to aa in the range 100 – 500 GeV



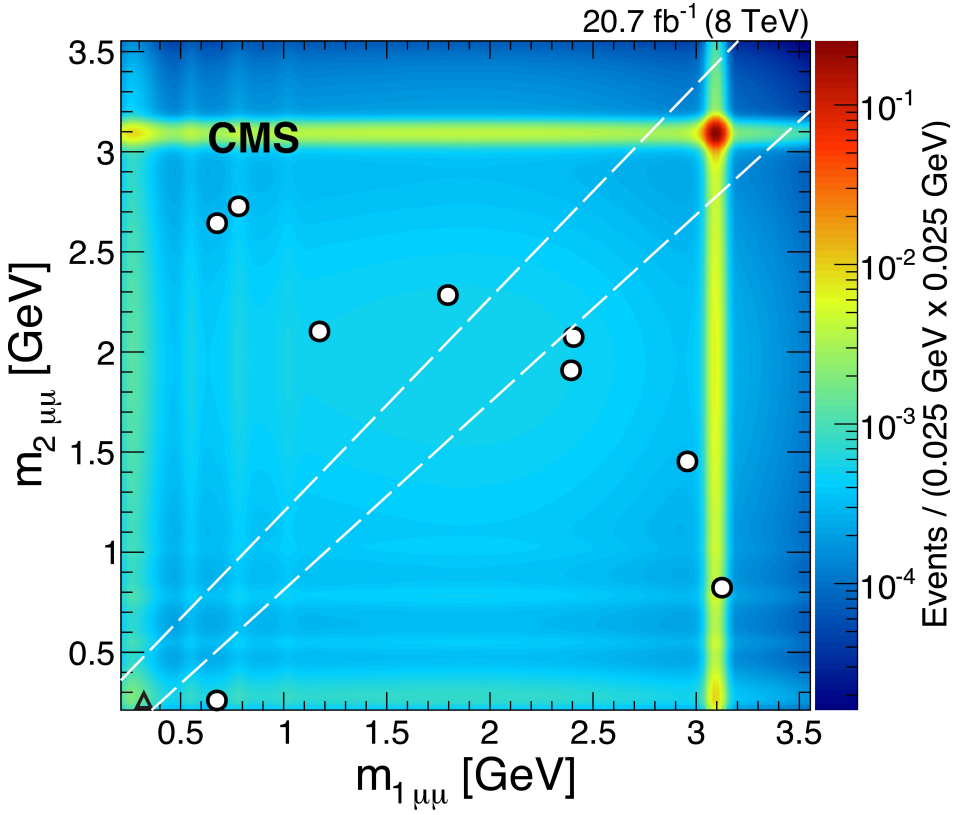


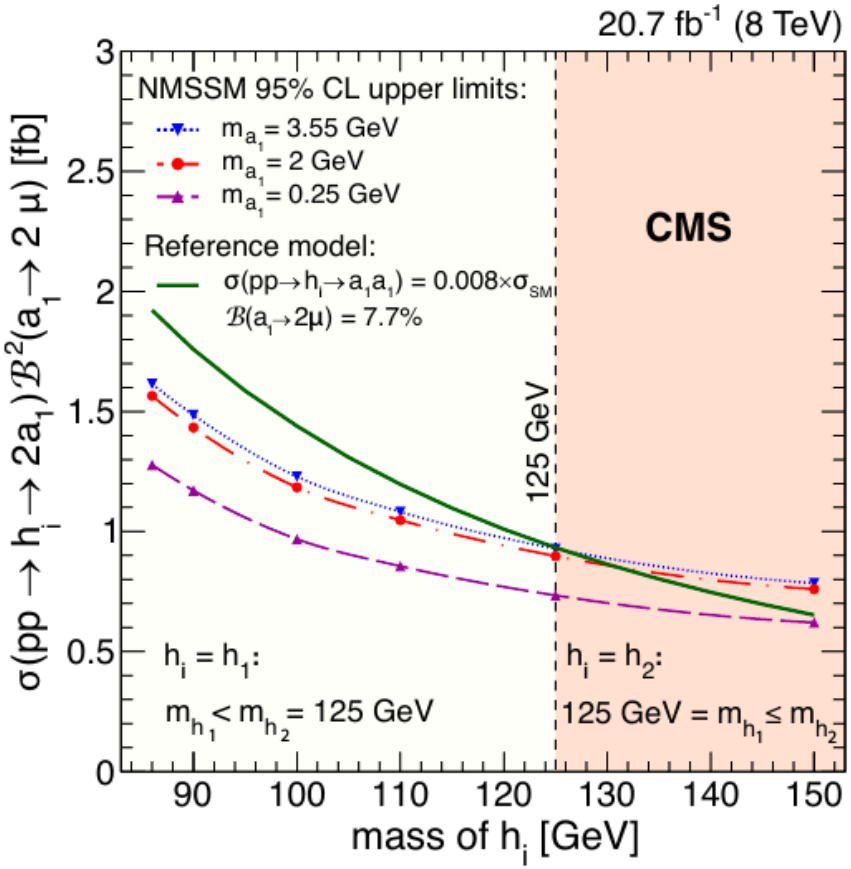
CMS NMSSM searches

- Some recent searches



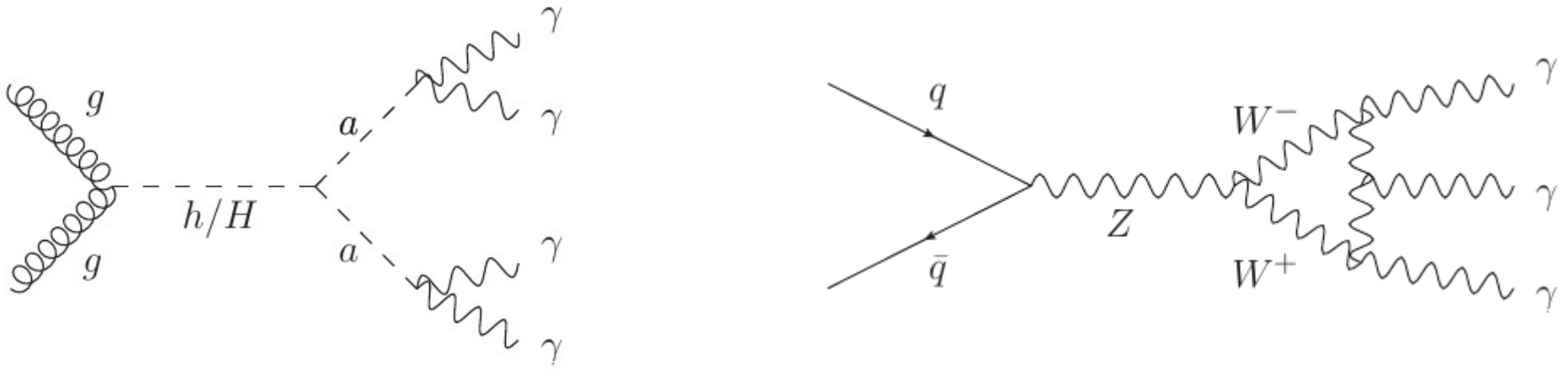
arXiv:1506.00424





NMSSM-inspired H->aa

- Looking for events with 3 photons: sensitive to H->aa->4γ and to more exotic signatures like Z->3γ



◊ Search is based on a trigger with 3 γs with some shower shape requirements

◊ Event candidates have isolated 3 γs with p_T >22, >22, >17 GeV

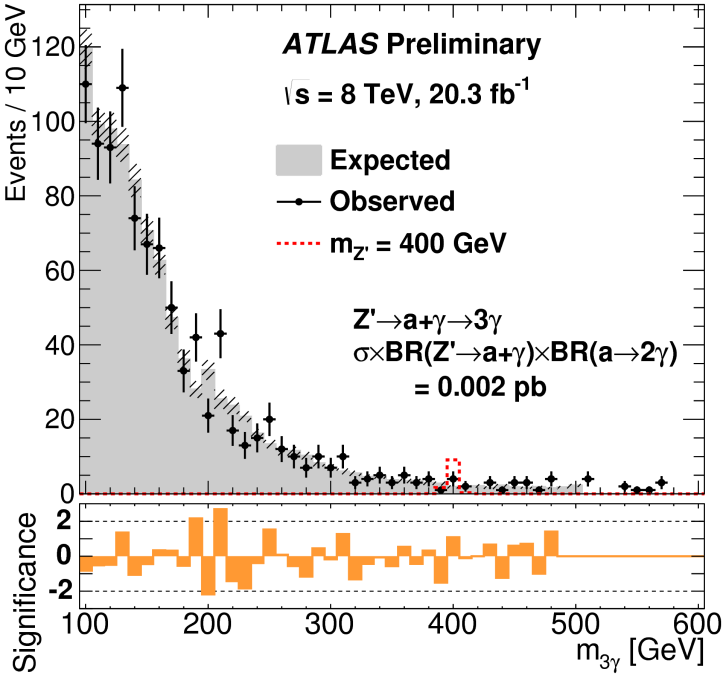
◊ Data-driven estimation of the events with jet(s) faking γ(s) based on the isolation shape

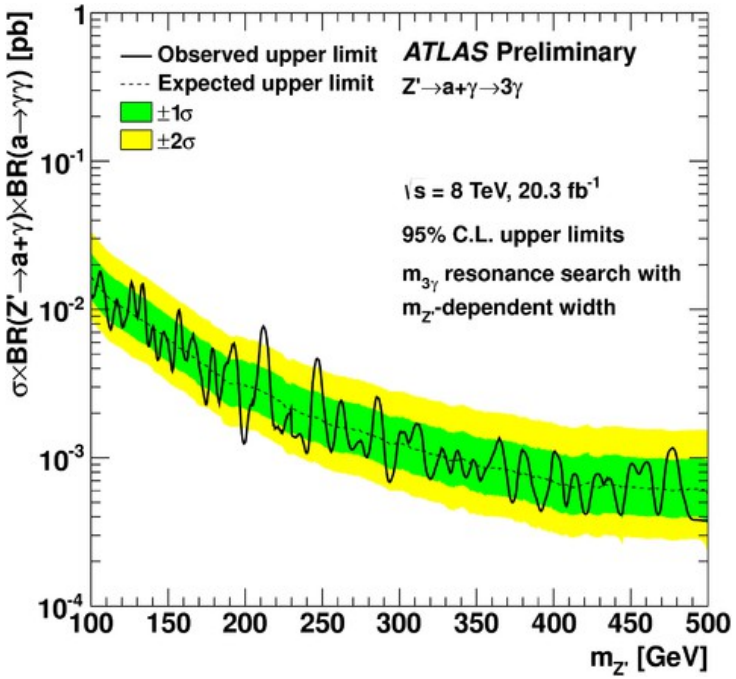
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-24/

3 photon search

- Inclusive search in the 80 – 100 GeV m(3γ) region gives a constraint BR(Z->3γ) < 2.2 x 10^{-6} (c.f. LEP result< 10^{-5})
- Resonance search in the m(2γ) and m(3γ) distributions from a fit to the sideband region

The 3 γ search starts from 100 GeV;
The background shown in gray is just for illustration

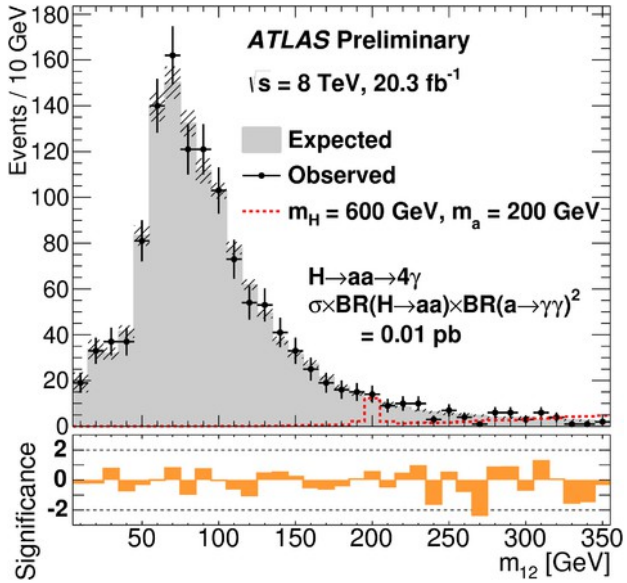


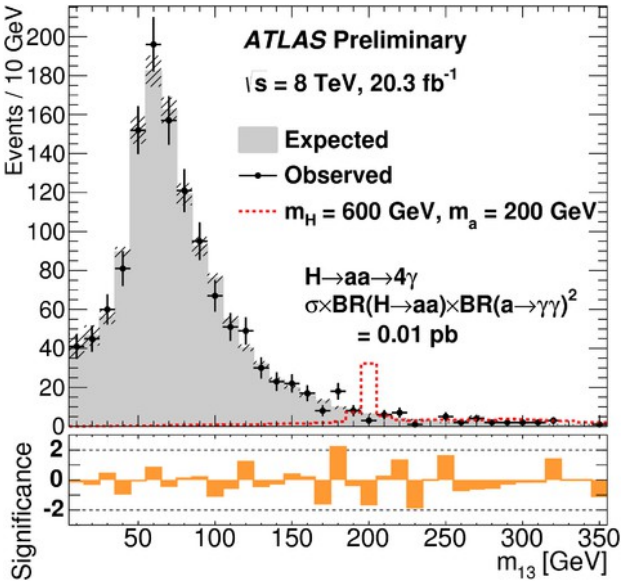


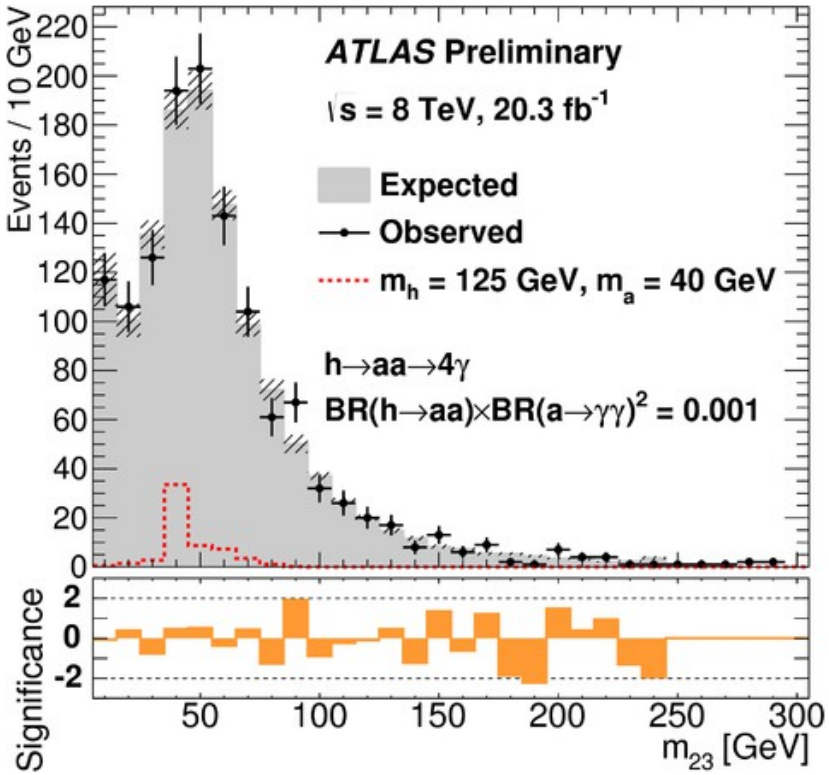
3 photon search

The 2γ search starts from 10 GeV and examines all the photon pairs (photonss are p_T ordered)

The background shown in gray is just for illustration.

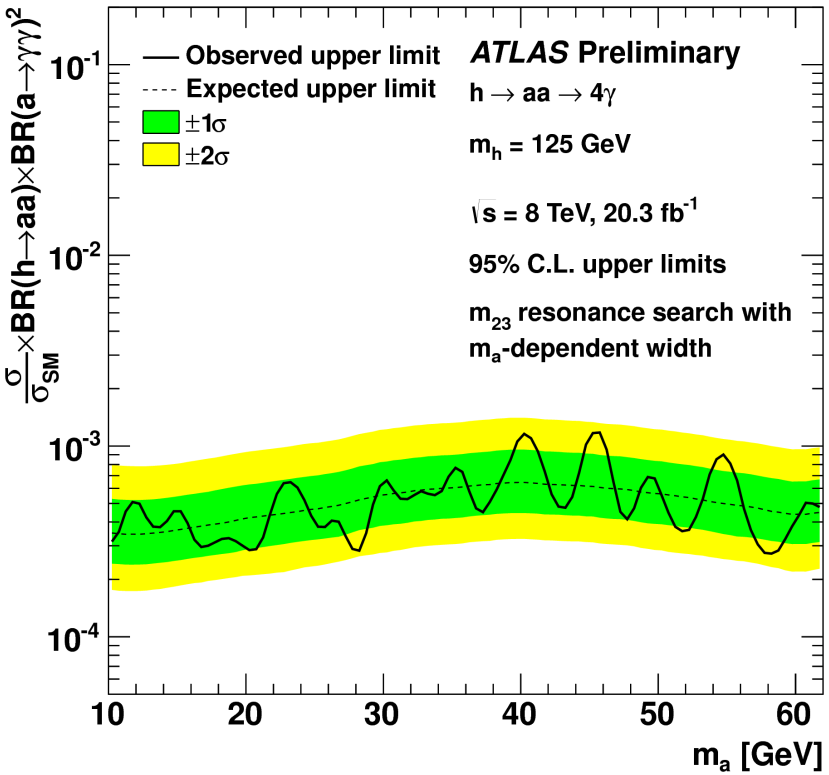


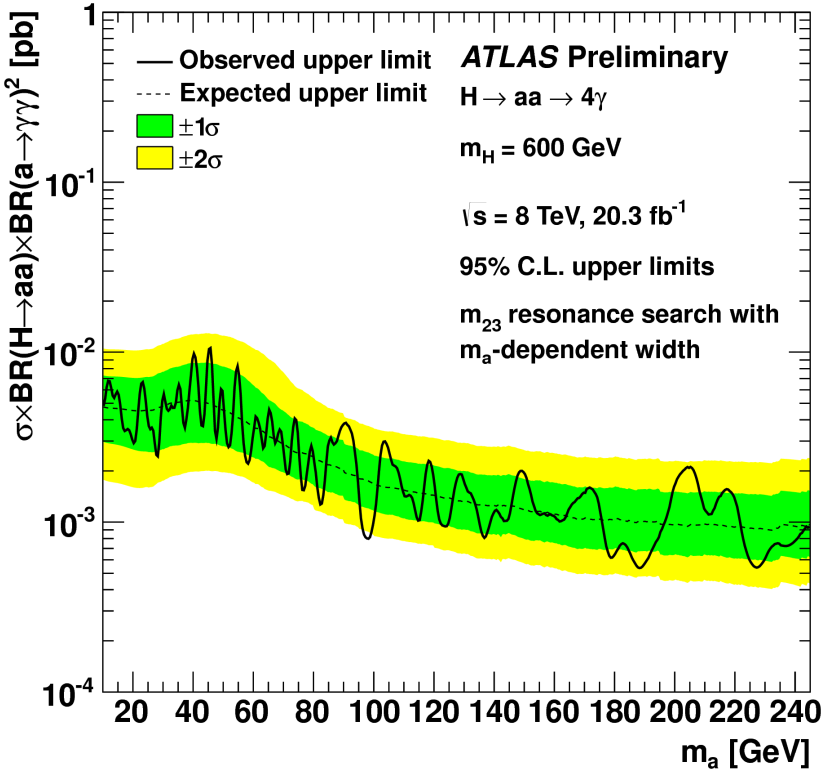




3 photon search

- Limits for the production of the 125-GeV Higgs and for a heavy BSM Higgs decaying to 4γ

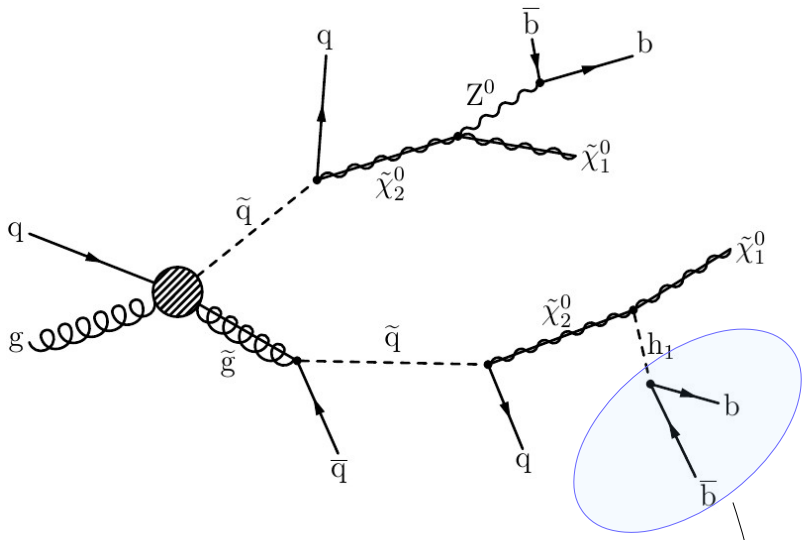


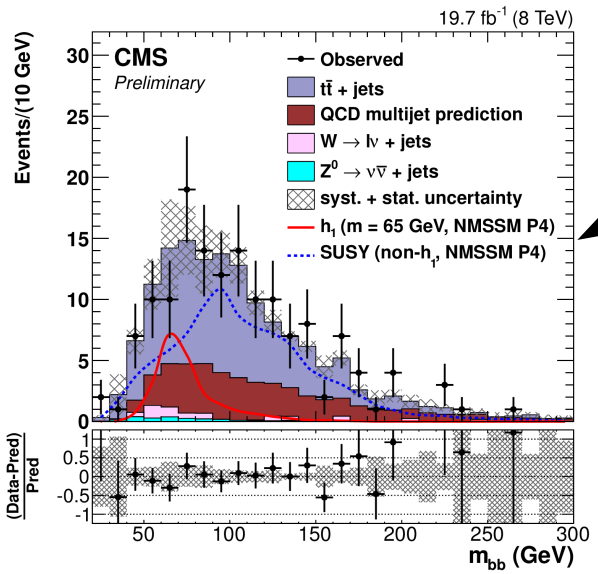


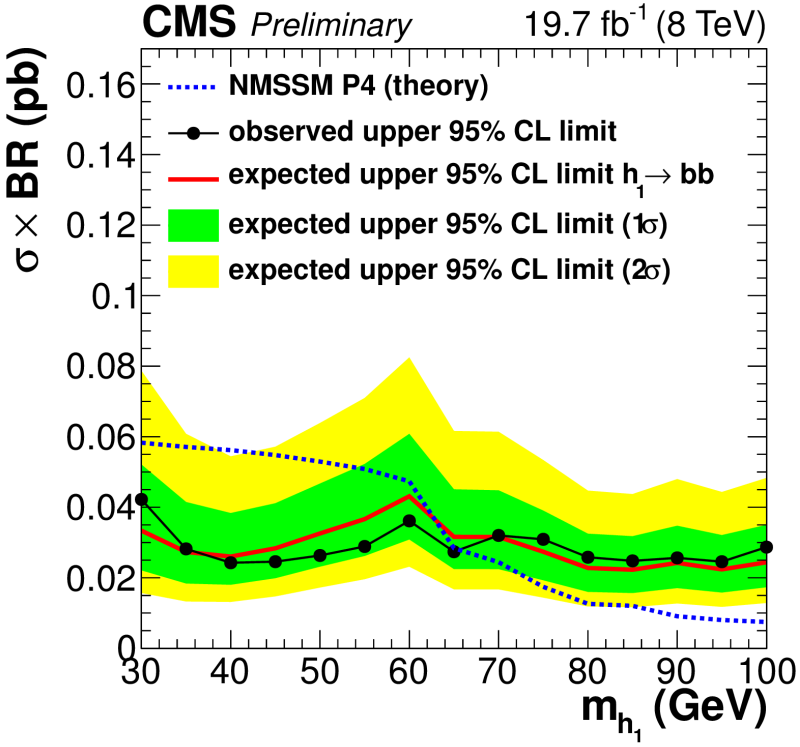
h_1->bb in cascades

CMS-PAS-HIG-14-030

A light higgs boson produced in a SUSY-inspired cascade: hard jets, MET and b-jets from Higgs decay





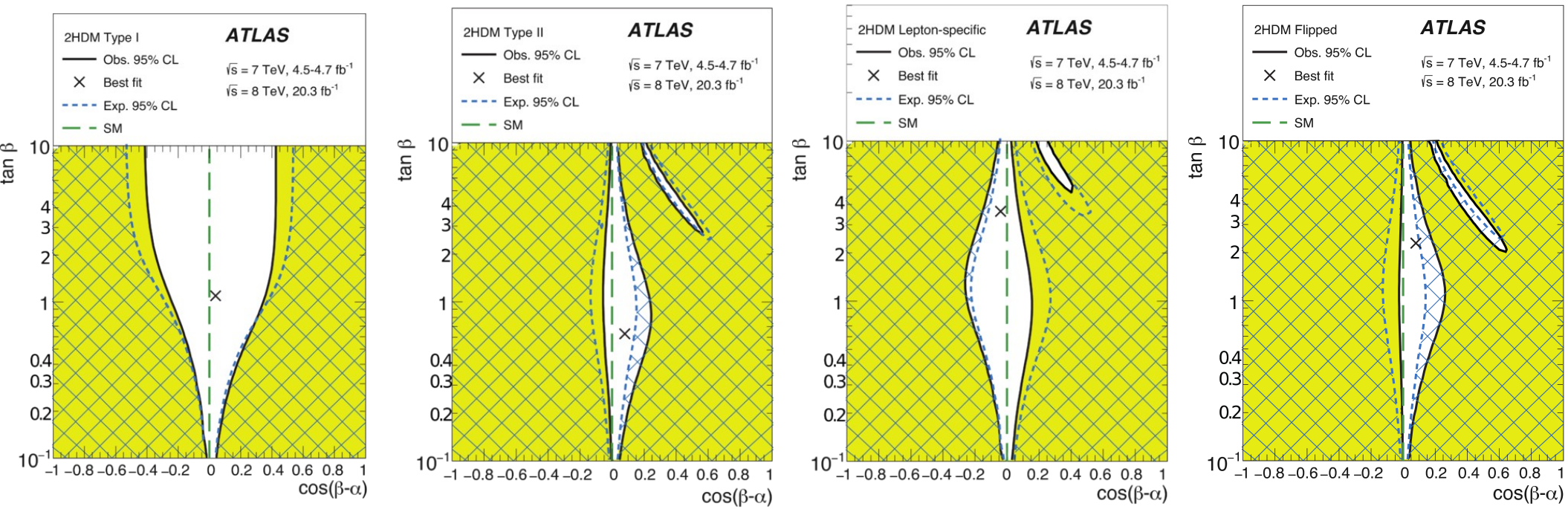


Shown prediction from an NMSSM benchmark taken from arXiv:0801.4321

Higgs couplings re-interpretation

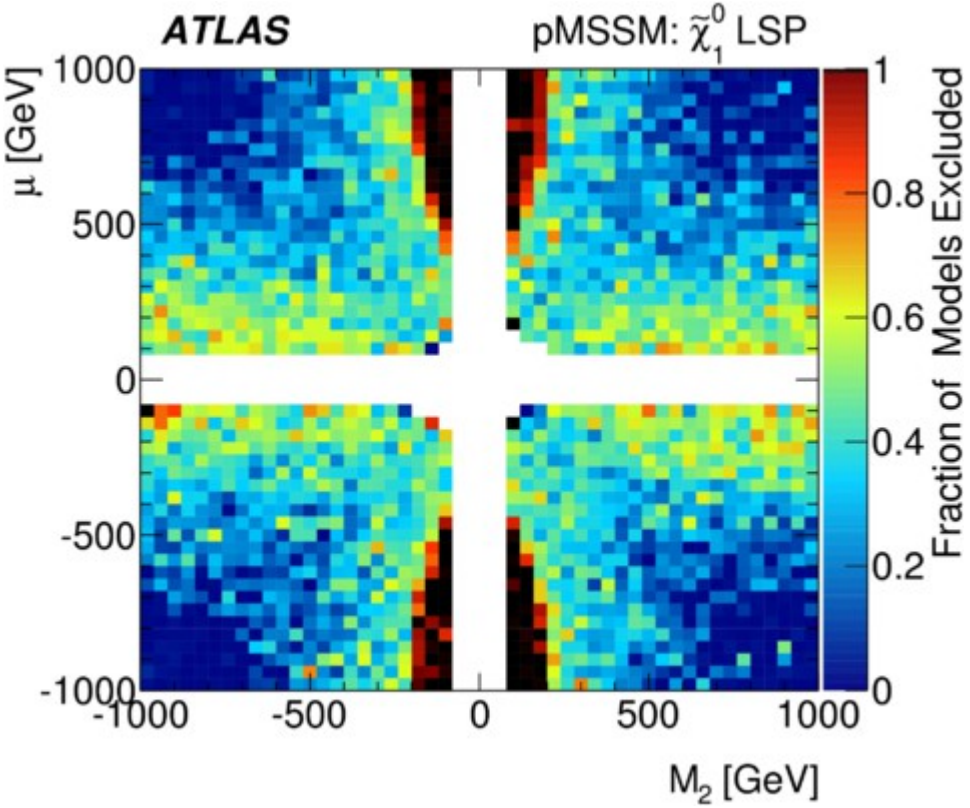
- ATLAS has finalized the Run-I Higgs coupling re-interpretation in arXiv:1509.00672, which was presented also in Higgs Days 2014 as ATLAS-CONF-2014-010

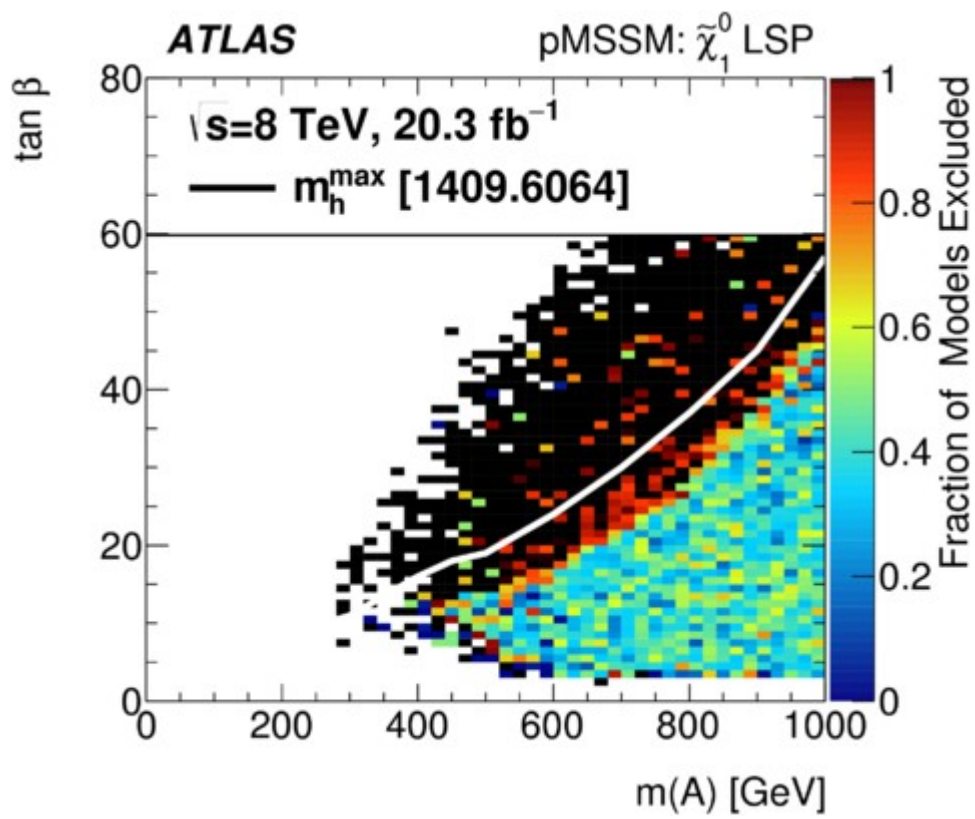
Example: CP-conserving 2HDM coupling measurement interpretation



A/H->tautau impact on pMSSM NEW!

arXiv:1508.06608

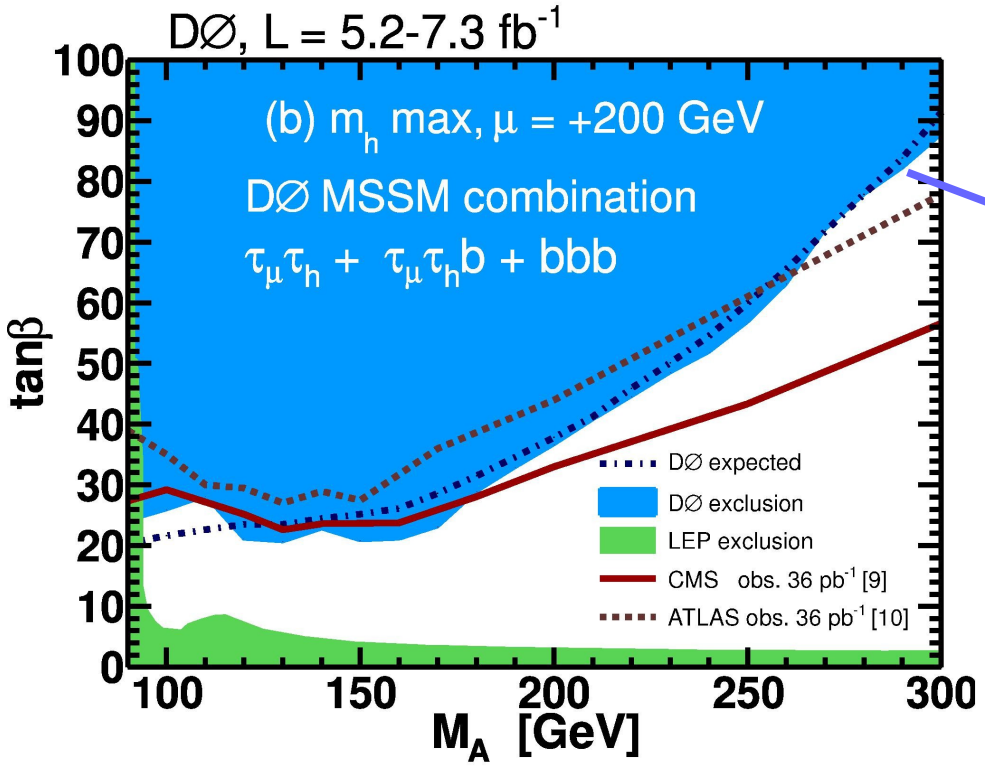


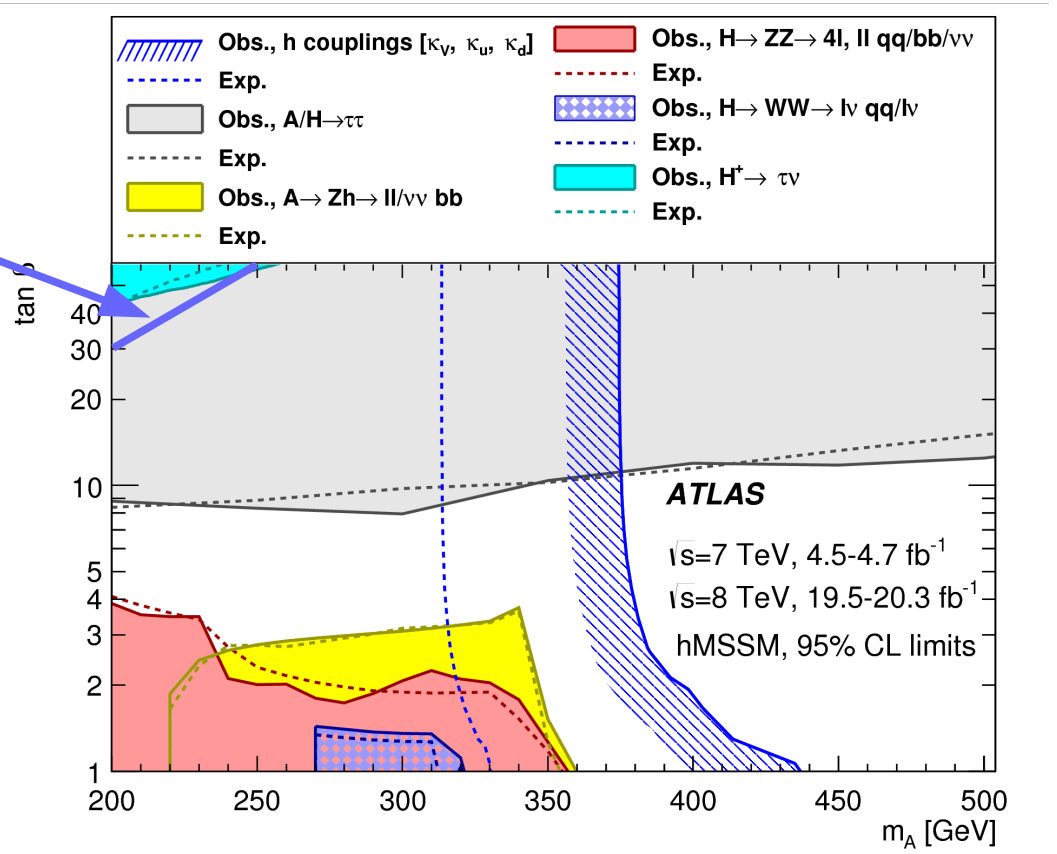


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2014-08/

Final Remarks

- In LHC Run-I we went a very long way
  - Lots of channels improved a lot the sensitivity
- Let's see what Run-II has now in stock for us





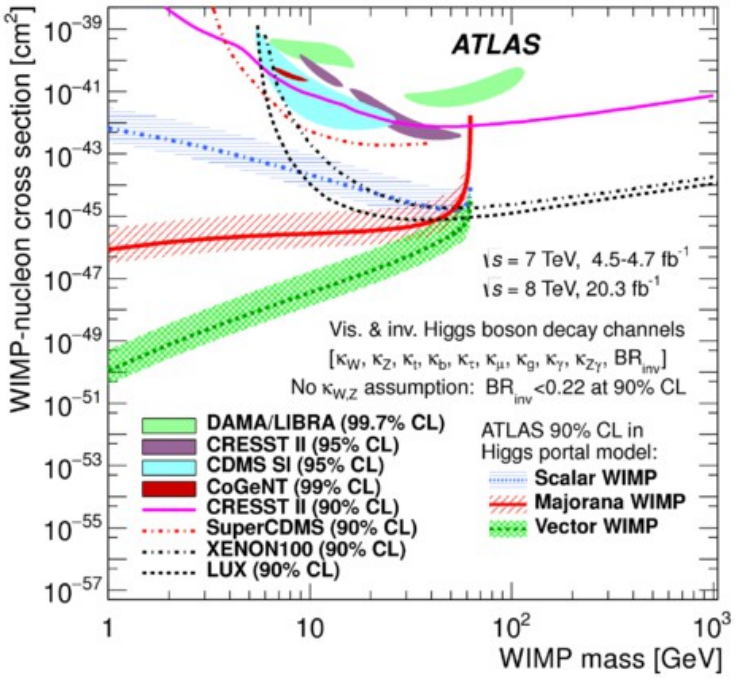
Additional slides

Higgs couplings re-interpretation

Combination of the Higgs to invisible channels in ATLAS:

Direct searches: VBF and Z(→ℓℓ)h

Channels	Obs.	Exp.
VBF h	0.28	0.31
$Z(\rightarrow \ell\ell)h$	0.75	0.62
$V(\rightarrow jj)h$	0.78	0.86
Combined Results	0.25	0.27



Indirect constraints: channels included for the couplings:

h → γγ, ZZ→4ℓ, WW→ℓνℓν, Zγ, ττ, μμ, bb

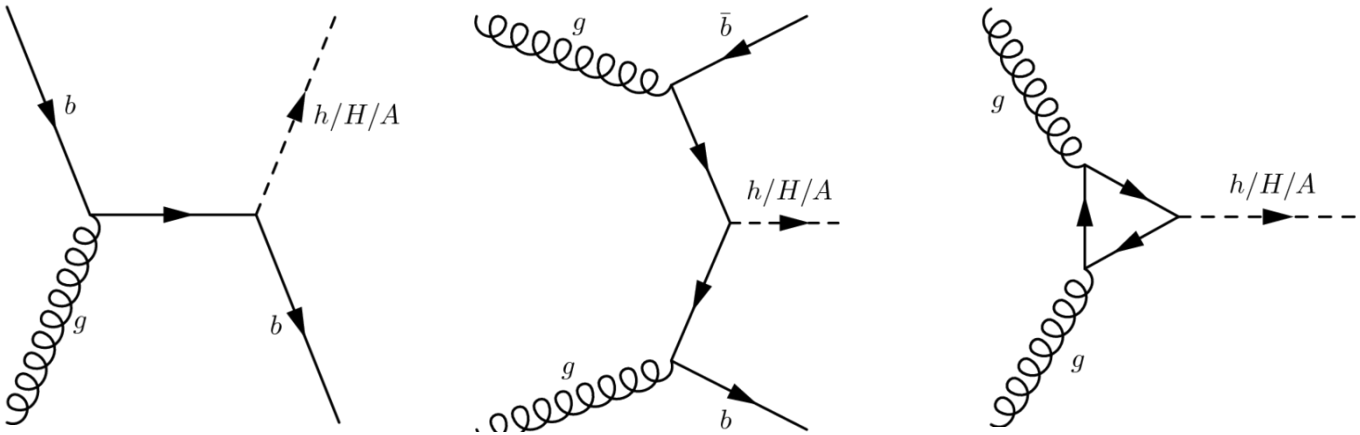
$$\kappa_h^2 = \Gamma_h/\Gamma_{h,\mathrm{SM}} = \sum_j \kappa_j^2 \mathrm{BR}_j/(1-\mathrm{BR}_{\mathrm{inv}})$$

Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on $\mathrm{BR}_{\mathrm{inv}}$ Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR}_{\mathrm{inv}}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR}_{\mathrm{inv}}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR}_{\mathrm{inv}}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR}_{\mathrm{inv}}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23

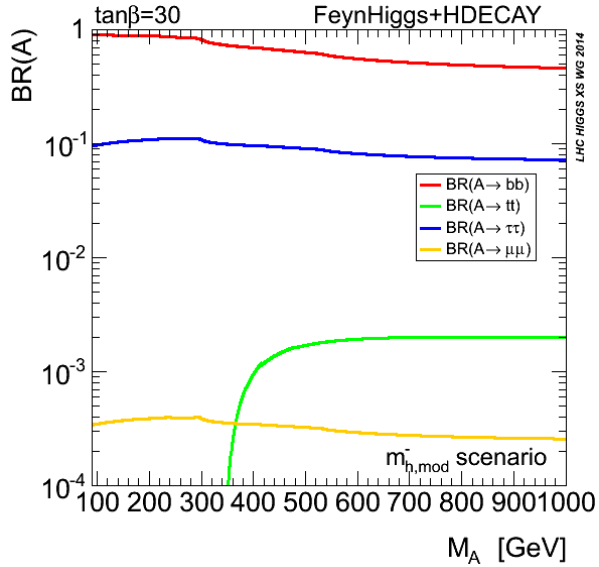
MSSM ττ search

- The most standard BSM Higgs search

The standard MSSM mixture:
gluon-fusion + b-associated production



"b-associated" production dominates at high-tanβ

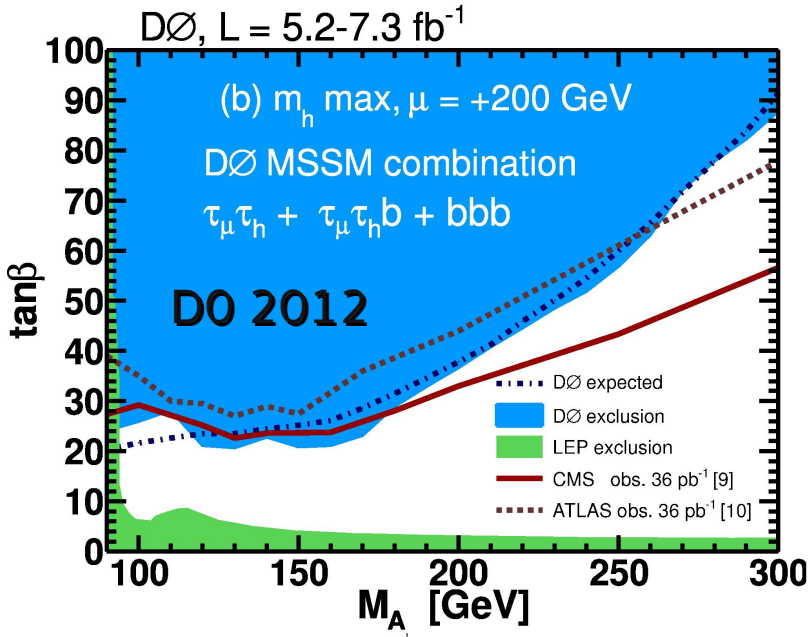


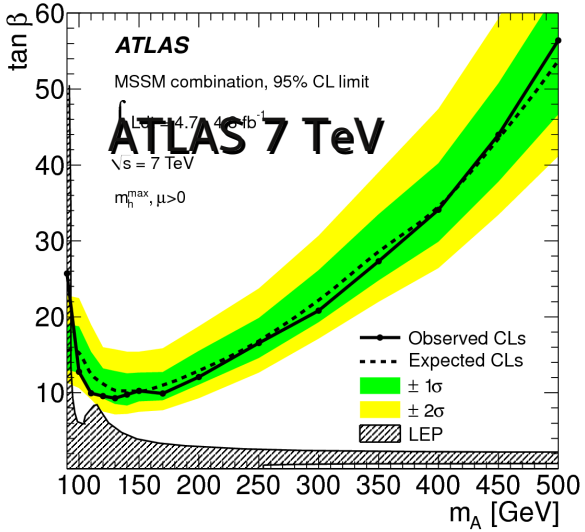
Branching ratio at moderate and high tanβ is dominated by h/H/A → ττ (~10%) and bb (~90%)

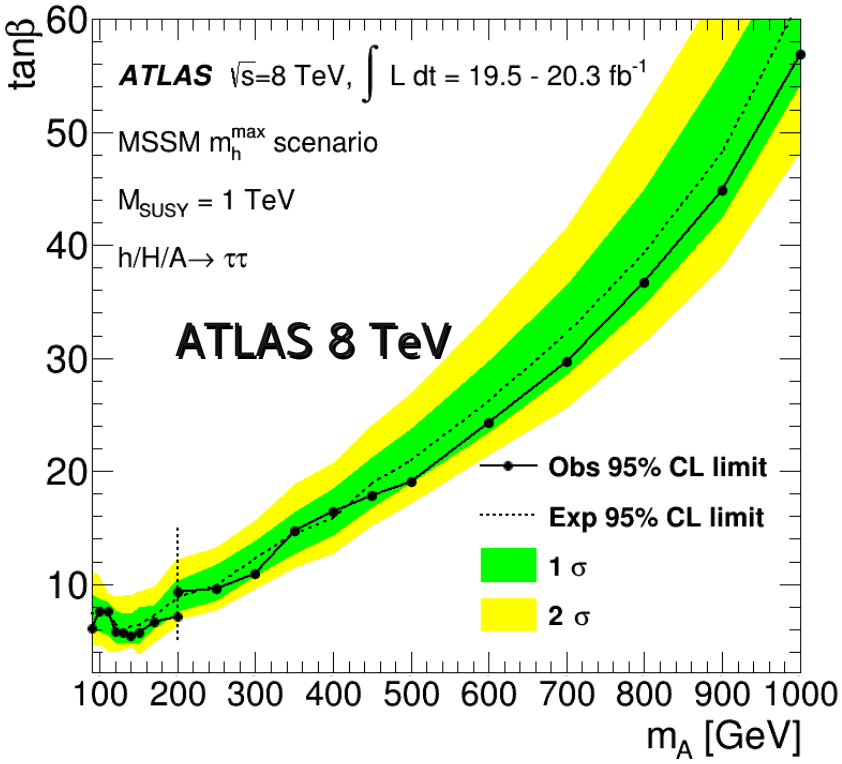
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-31/

MSSM ττ search

A brief history of the constraints



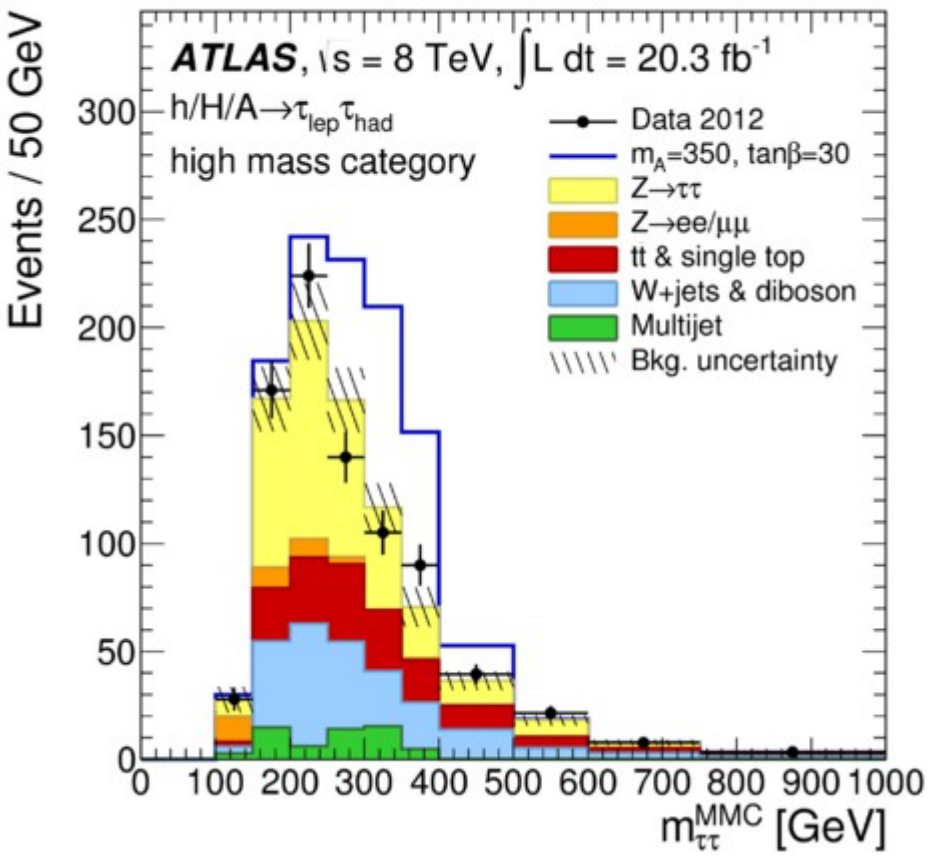




MSSM ττ search

- Elements of the ATLAS 8 TeV search

◊ Low and high mass categories
◊ Low mass category:
  ◊ τ(lep)τ(had) and τ(lep)τ(lep) final states
  ◊ in each final state b-tag and b-veto channels
◊ High mass category:
  ◊ τ(lep)τ(had) and τ(had)τ(had) final states, inclusively, i.e. no b-tag/b-veto categorization



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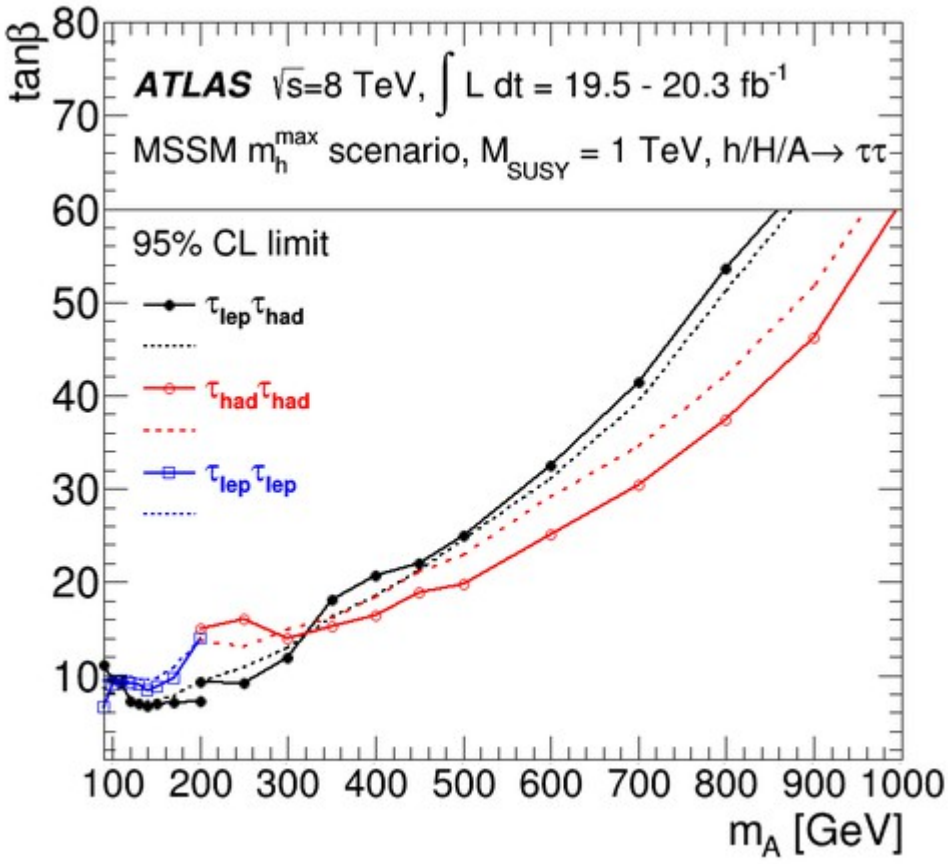

MSSM ττ search

Interpretation:

◊ standard cross section limits for a singly produced Higgs boson via either ggH or bbH

◊ on the mA – tanβ plane of the various MSSM scenarios