25th International workshop on weak interactions and Neutrinos (WIN2015), June 8 – 13, 2015, MPIK, Heidelberg, Germany


# Searches for supersymmetric Higgs signatures at the LHC

Nikolaos Rompotis (University of Washington)
on behalf of ATLAS and CMS collaborations

# Introduction

- Supersymmetric Higgs signatures may be a diverse topic
  - Here I will focus mostly on “standard” SUSY Higgs

**MSSM Higgs searches:**

◊ h/H/A → ττ
◊ H+ → τν and tb
◊ A → Zh

**NMSSM motivated searches for a light Higgs:**

◊ a → μμ
◊ H → aa
◊ NMSSM inspired cascades

- For more exotic signatures, e.g. $H \rightarrow \chi^0\chi^0$, see other experimental talks and in particular the talk by James Beacham tomorrow

# The MSSM

- MSSM: minimal supersymmetric Standard Model
  - An (almost) complete realization of low energy supersymmetry
- MSSM needs 2 Higgs doublets
  - analyticity of the superpotential and anomaly cancelation
  - CP-concerving potential at lowest order: 2 CP-even Higgs bosons (h and H), 1 CP-odd (A), 2 charged ($H^{+/-}$)

Very economical: only two SUSY parameters needed

$\Rightarrow m_A$ or $m_{H+}$ $\Rightarrow \tan\beta = \upsilon_2/\upsilon_1$ (ratio of Higgs v.e.v.s: up / down)

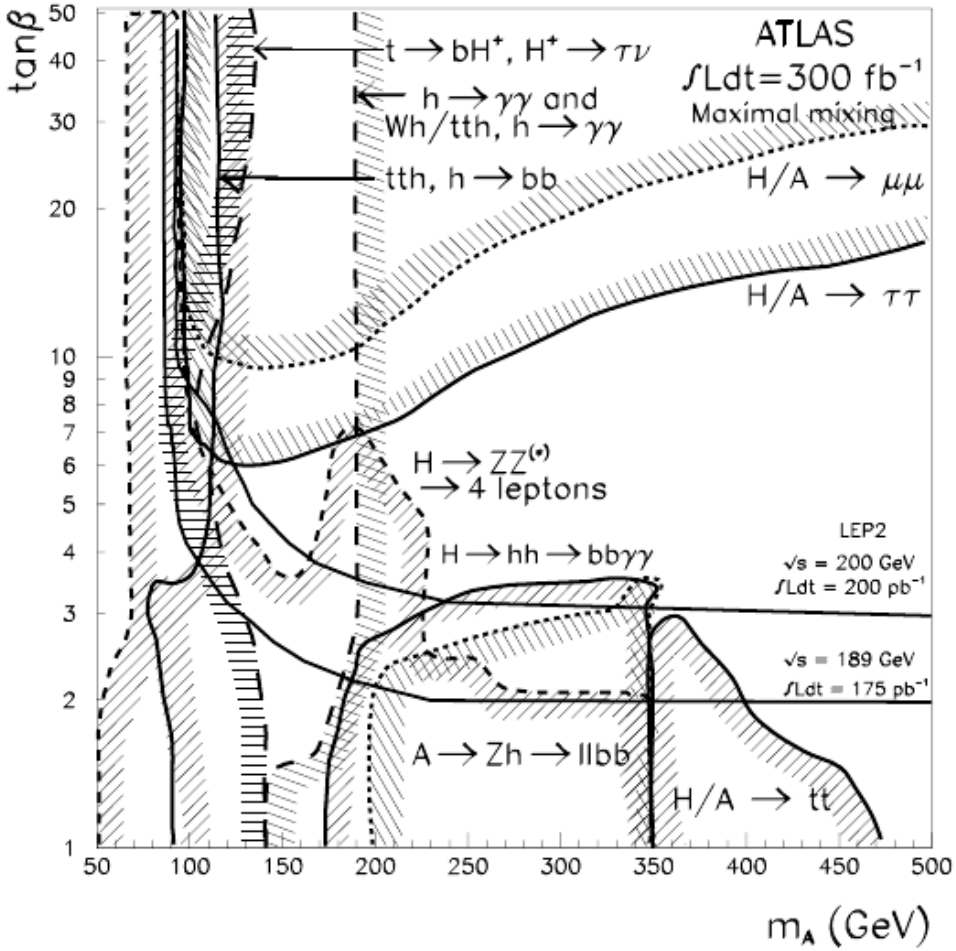
Very constraining: tight restrictions in Higgs masses

$\Rightarrow$ e.g. lightest CP-even Higgs is lighter than the Z boson at leading order (but large radiative corrections make it compatible with 125 GeV)

# MSSM Higgs searches

- The MSSM Higgs searches have been the workhorse of BSM Higgs searches from the time of LEP and the Tevatron

A very comprehensive BSM Higgs signature sensitivity in the maximal mixing scenario from ATLAS TDR in 1999 !!!




**Technical Design Report**

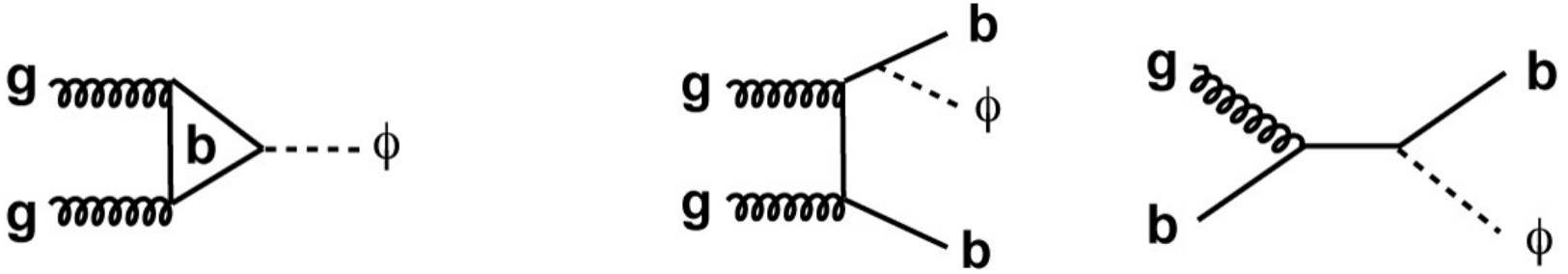
| | |
|---|---|
| Issue: | 1 |
| Revision: | 0 |
| Reference: | ATLAS TDR 15, CERN/LHCC 99-15 |
| Created: | 25 May 1999 |
| Last modified: | 25 May 1999 |
| **Prepared By:** | ATLAS Collaboration |

**Volume II**

# MSSM Neutral Higgses at LHC

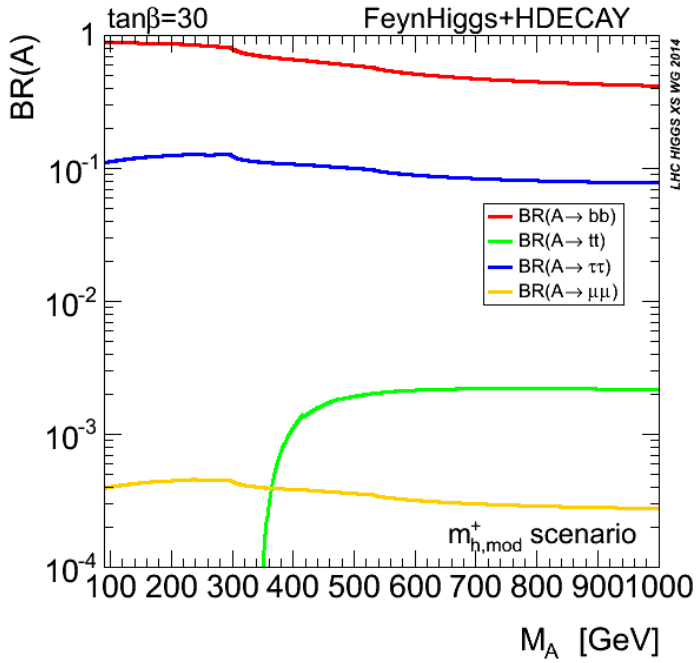
- Neutral Higgs production at the LHC

Gluon-fusion and "b-associated" production




- Preferred decays at large tanβ: h/H/A → ττ and bb

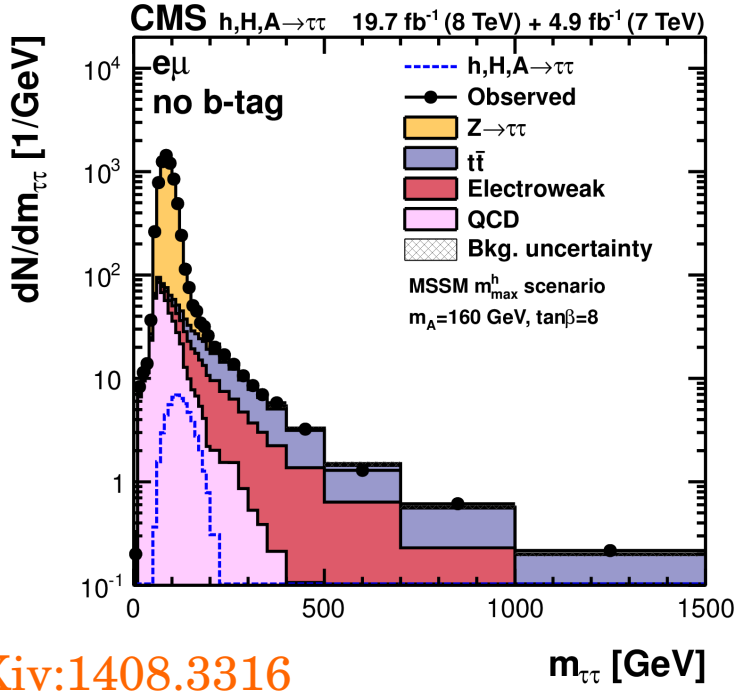
◊ BR(H/A → ττ) ~ 10%
◊ "ττ" modes have usually better sensitivity



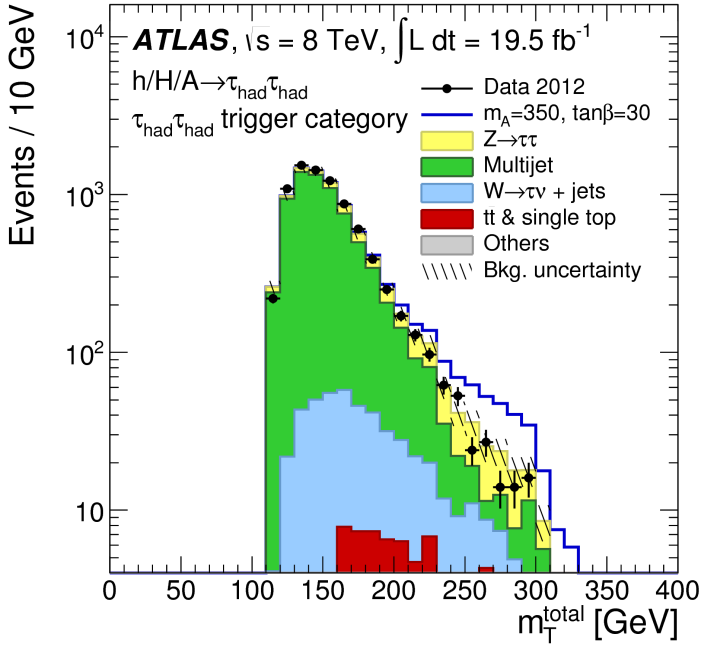

h/H/A → ττ: arXiv:1409.6064 (ATLAS), arXiv:1408.3316 (CMS), arXiv:1304.2591 (LHCb)
H/A → bb: arXiv:1302.2892 (CMS)

# h/H/A → ττ

- Final states categorization according to
  - TauTau pair decay: τ(lep)τ(lep), τ(lep)τ(had), τ(had)τ(had)
  - "b-tag" and "b-veto" to take advantage of the b-associated production



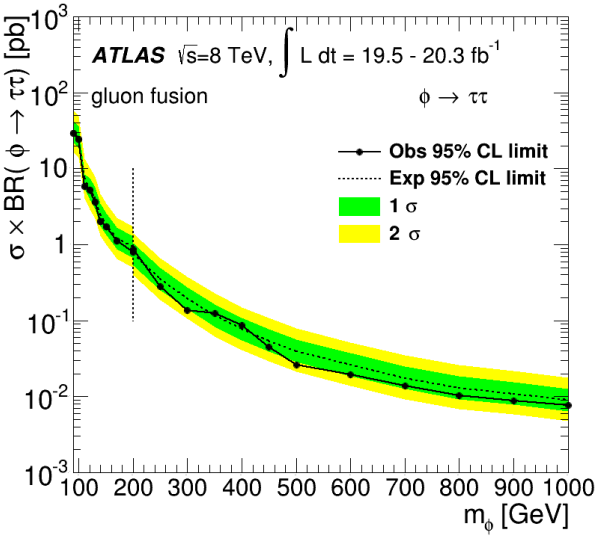

arXiv:1408.3316

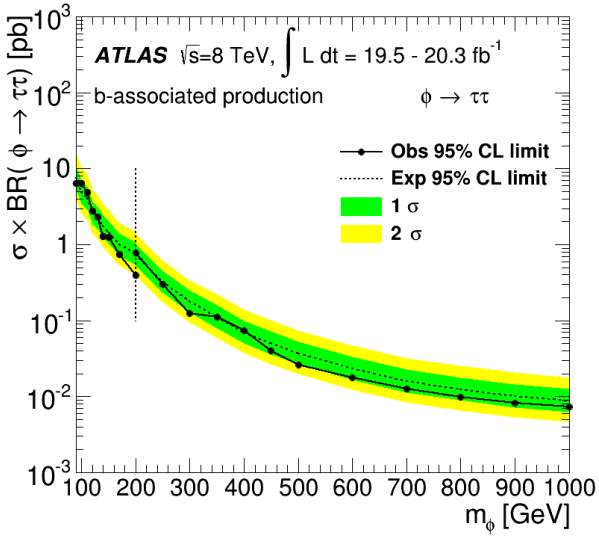



arXiv:1409.6064

# h/H/A → ττ

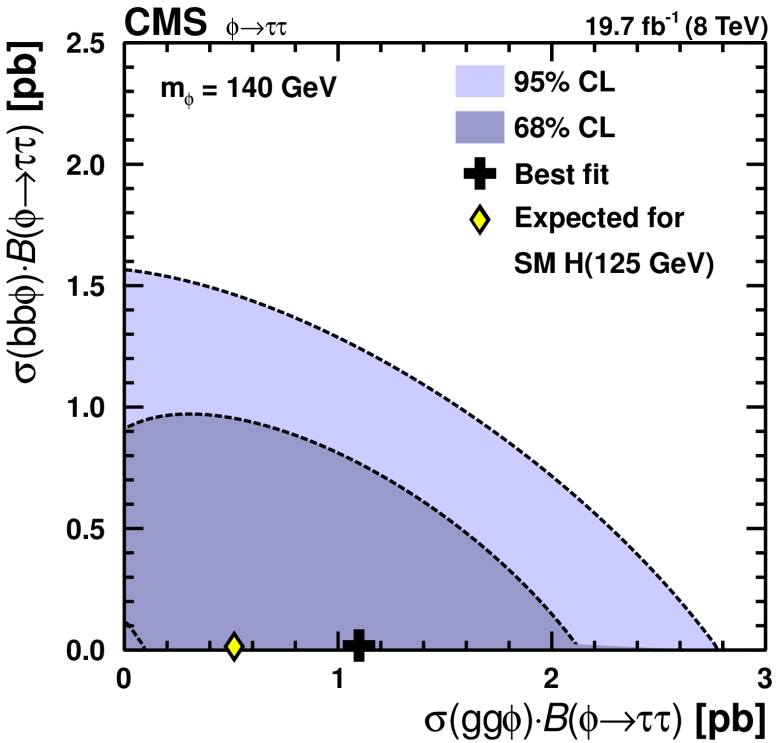
- Cross section limits



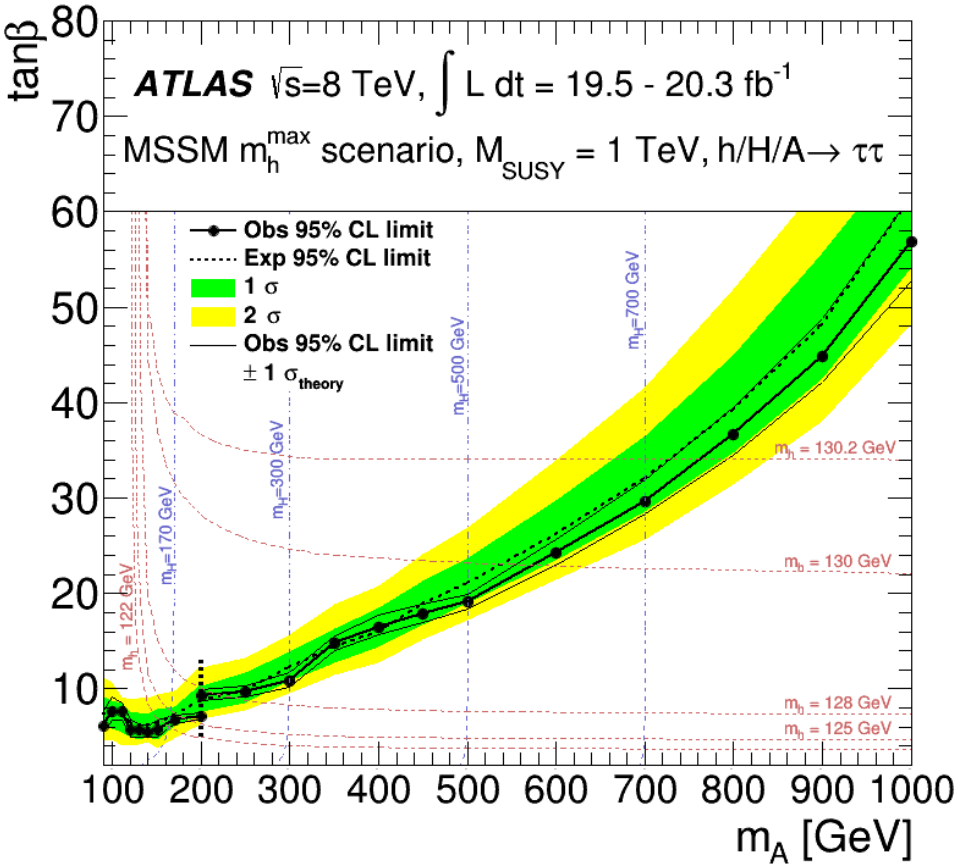

"Traditional" cross section limits for a single scalar produced either via gluon-fusion or b-associated production from ATLAS

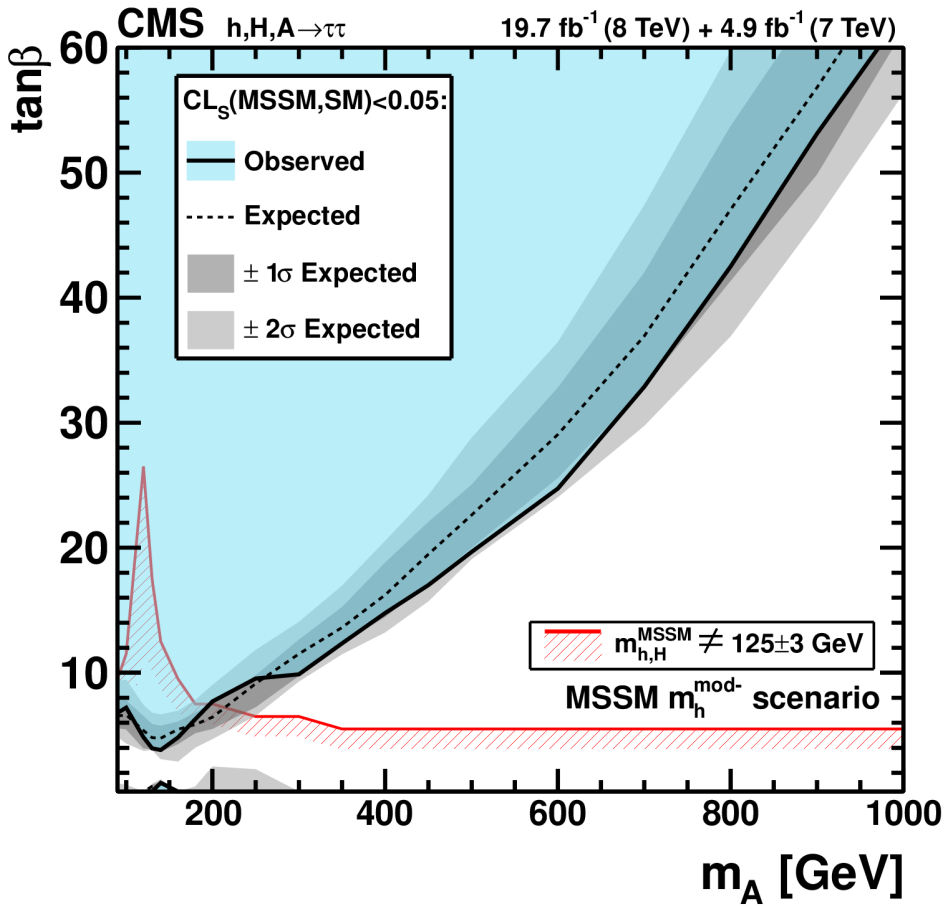
2D limit for a scalar particle that is produced by both gluon-fusion and b-associated production for a very fine grid of mass points by CMS.



# h/H/A → ττ

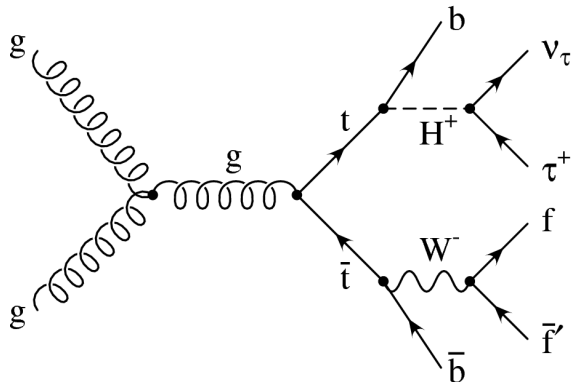
- Interpretation of the search in various MSSM scenarios

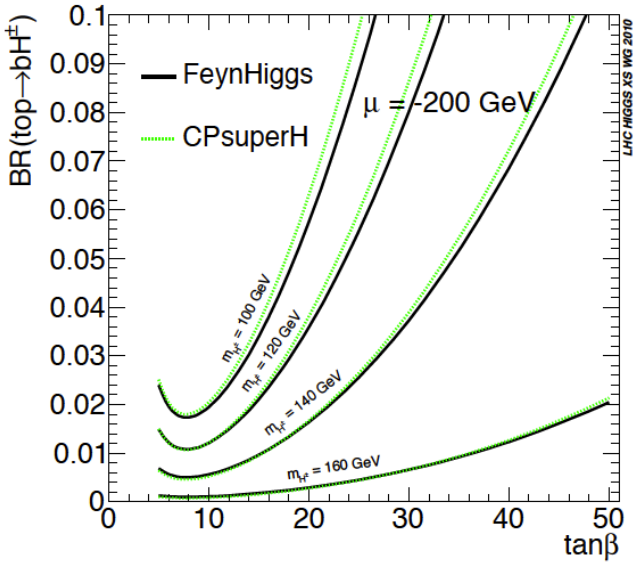


# MSSM Charged Higgs at the LHC

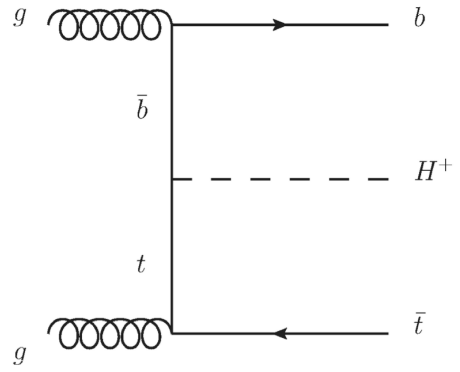
**Light Charged Higgs is produced mainly in top quark decays**



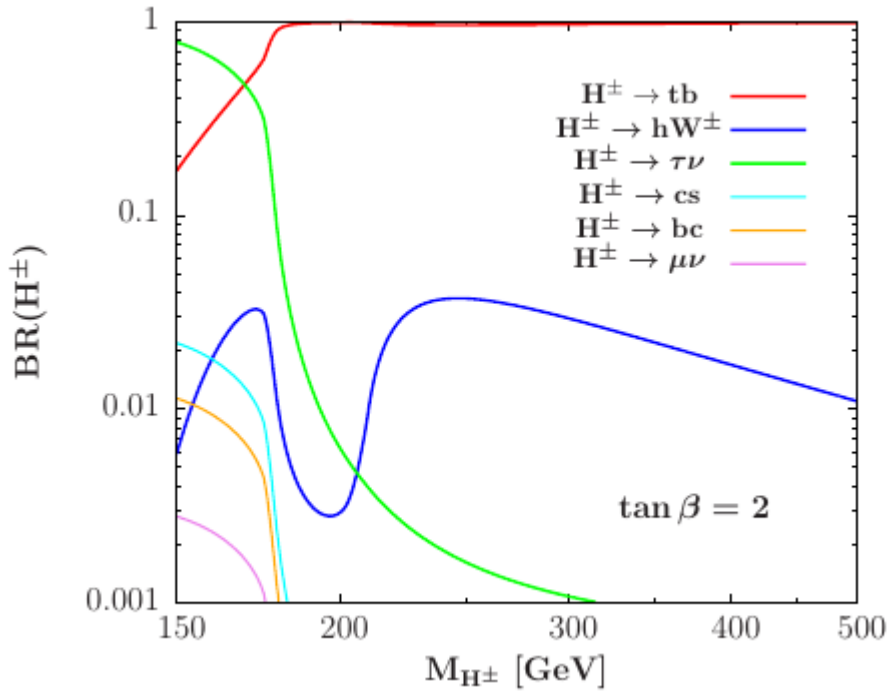

**BR(Top → bH⁺) vs tanβ**

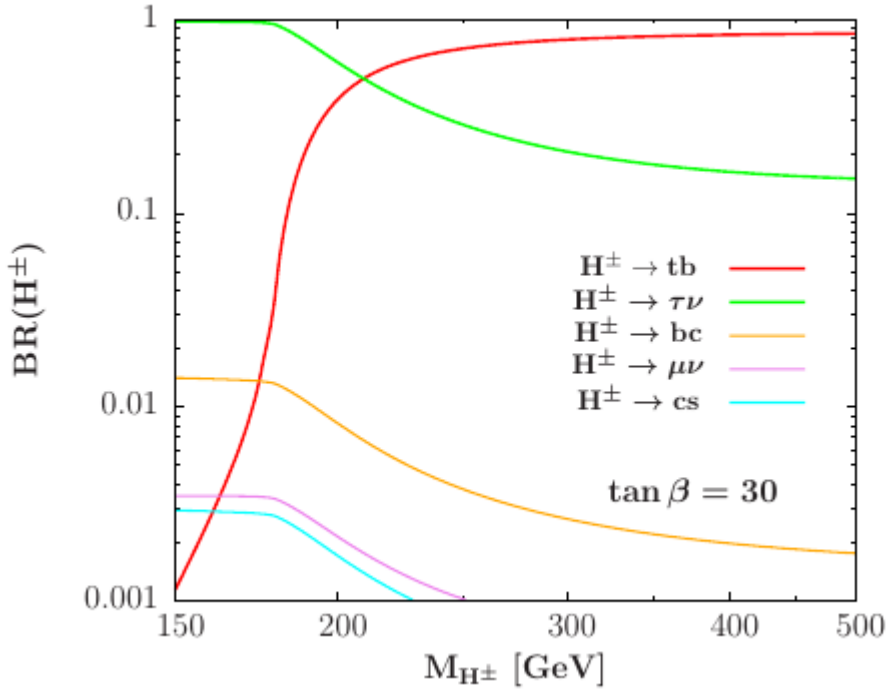
**Heavy Charged Higgs is produced mainly in association with a top quark**



# MSSM Charged Higgs at the LHC

**A Light Charged Higgs decays mostly to τν, whereas a Heavy Charged Higgs mostly to tb**




Djouadi et al, arXiv:1502.05633

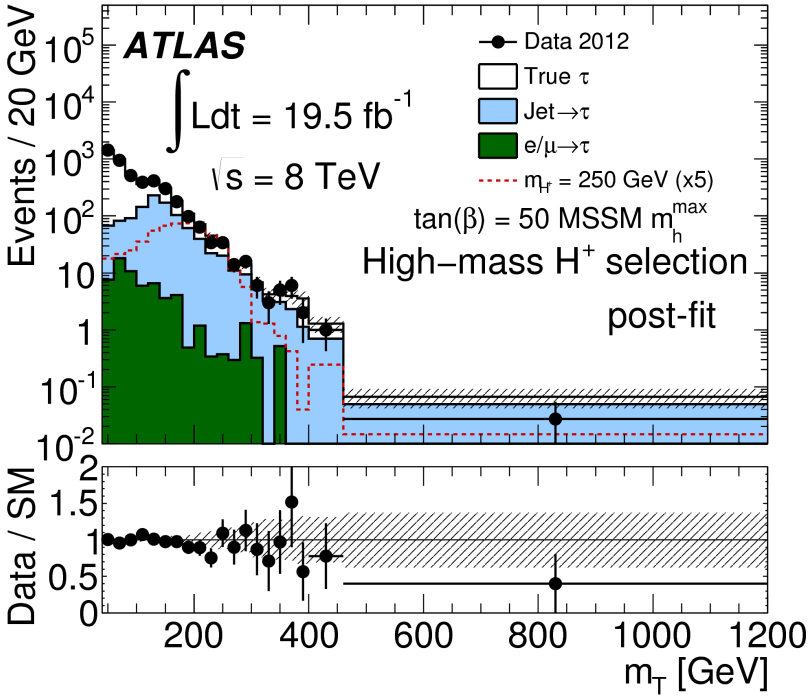
# H+ → τν

- Similar strategies in both ATLAS and CMS at the search for a light and heavy $H^+ \rightarrow \tau\nu$
- Here I will just mention few things for the ATLAS search

◊ "tau+jets" channel: one hadronic tau decay and jets from the full hadronic top decays
◊ Missing ET + tau trigger (very challenging)
◊ separate high and low mass categories

Example from the final discriminating distribution from the high mass category

arXiv:1412.6663

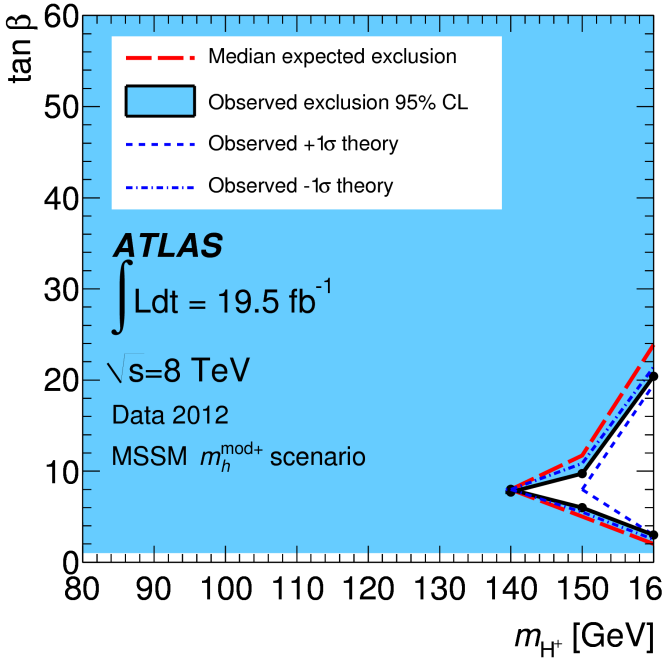


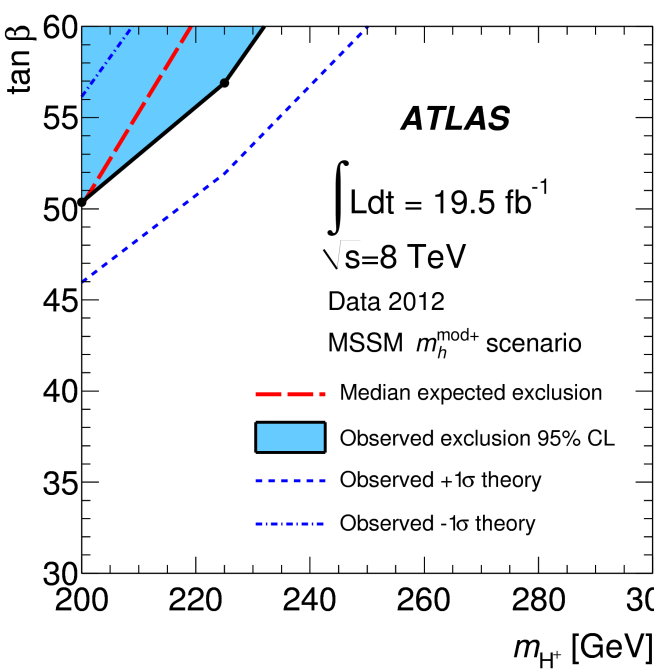

$$m_T = \sqrt{2 p_T(\tau) E_T^{miss} (1 - \cos \Delta\phi(E_T^{miss}, \tau))}$$

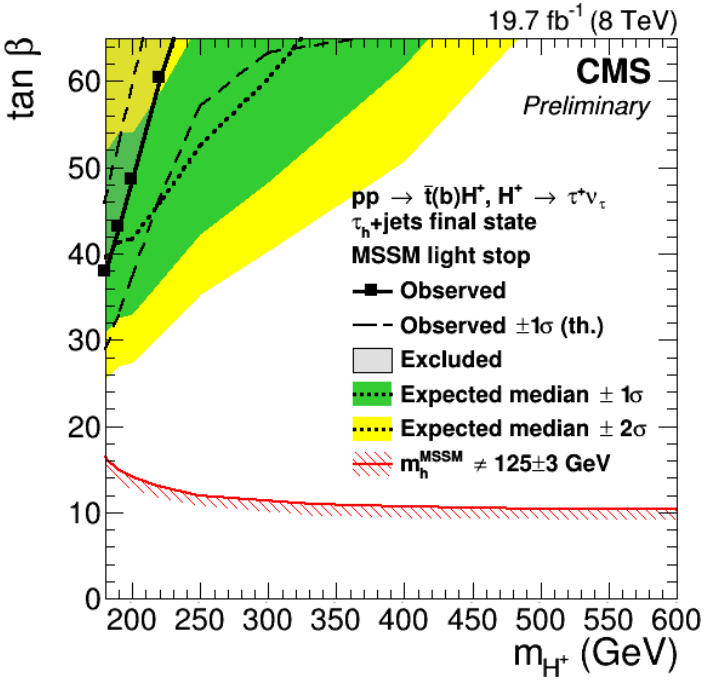
See the corresponding CMS result here: CMS-PAS-HIG-13-026

# H+ → τν

- Interpretation of the search in various MSSM scenarios (in addition to the cross section and BR limits)



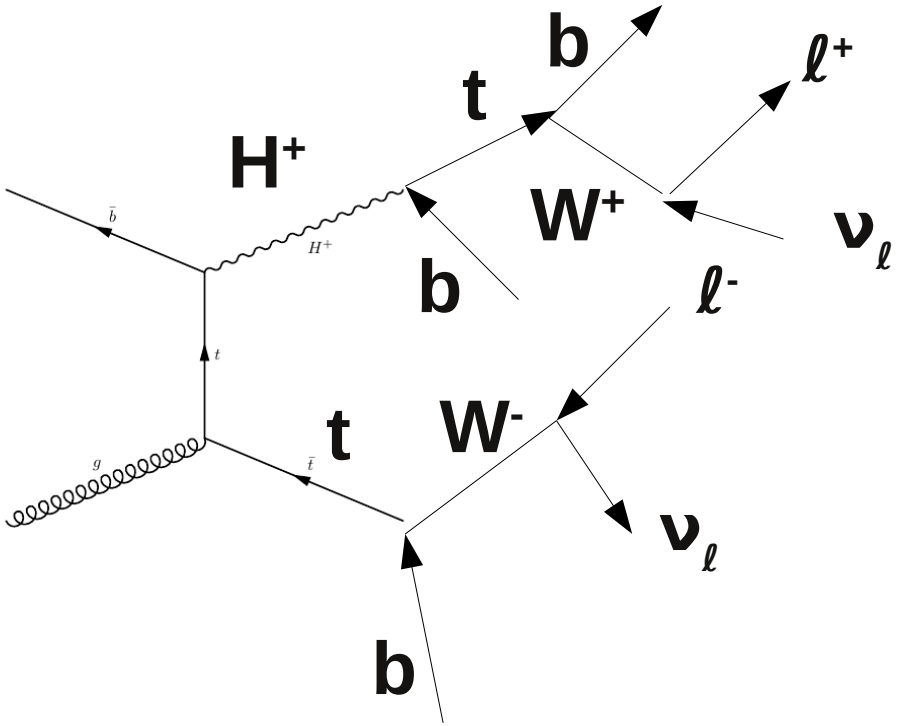




arXiv:1412.6663

CMS-PAS-HIG-13-026

# $H^+ \rightarrow tb$

- This is the most typical decay mode of a high mass Charged Higgs (MSSM or not!)
- The LHC has just started exploring that!

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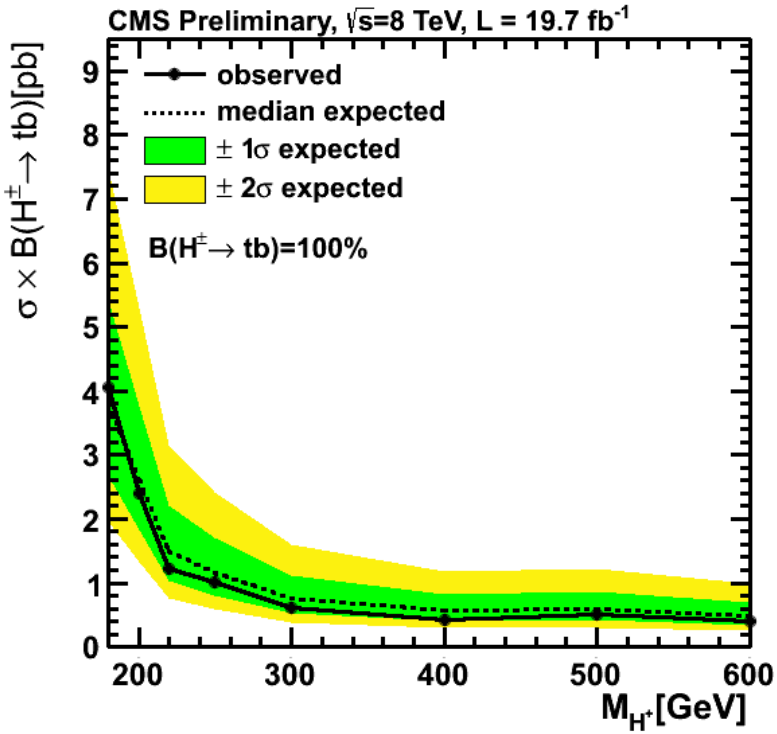
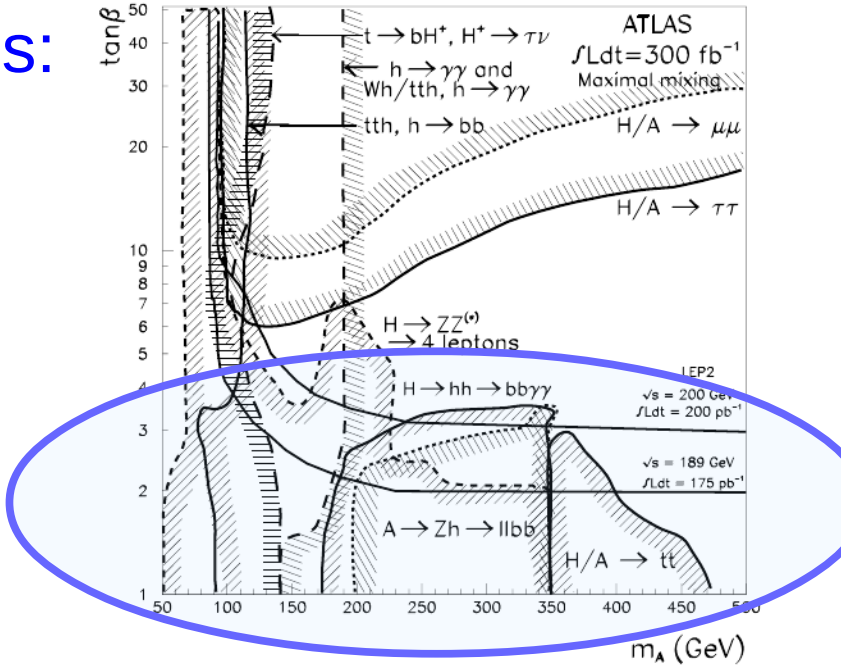


# MSSM: the low tanβ regime

- The low tanβ regime in the MSSM has a very rich decay spectrum of the MSSM Higgs bosons
  - However, the discovery of a light CP-even Higgs boson at 125 GeV has made life difficult for the MSSM: it requires a very high SUSY scale
  - Few examples of relevant searches:

◊ A → Zh: arXiv:1502.04478, arXiv:1504.04710
◊ H → hh: arXiv:1406.5053, arXiv:1503.04114, …
◊ H/A → tt
◊ H → WW/ZZ: arXiv:1504.00936
…

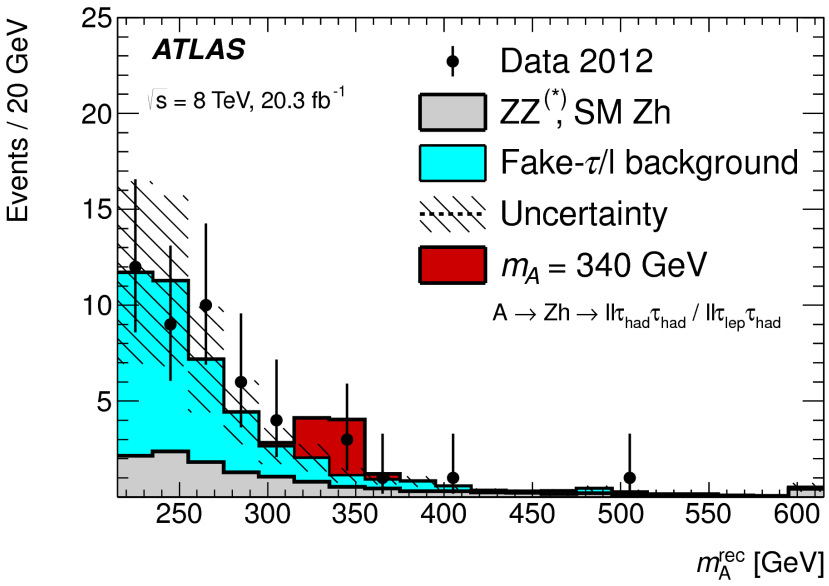


# MSSM: the low tanβ regime

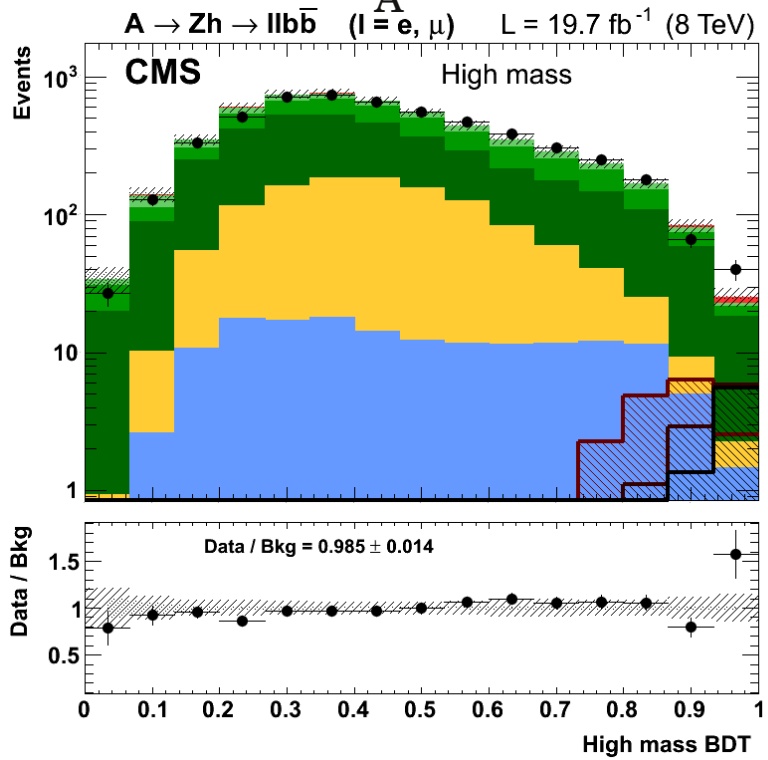
- Just an example here for the $A \to Zh$ searches in ATLAS and CMS

ATLAS: $A \to Zh \to \ell\ell bb$, $\nu\nu bb$ and $\ell\ell \tau\tau$ (arXiv:1502.04478)

CMS: $A \to Zh \to \ell\ell bb$ (arXiv:1504.04710)

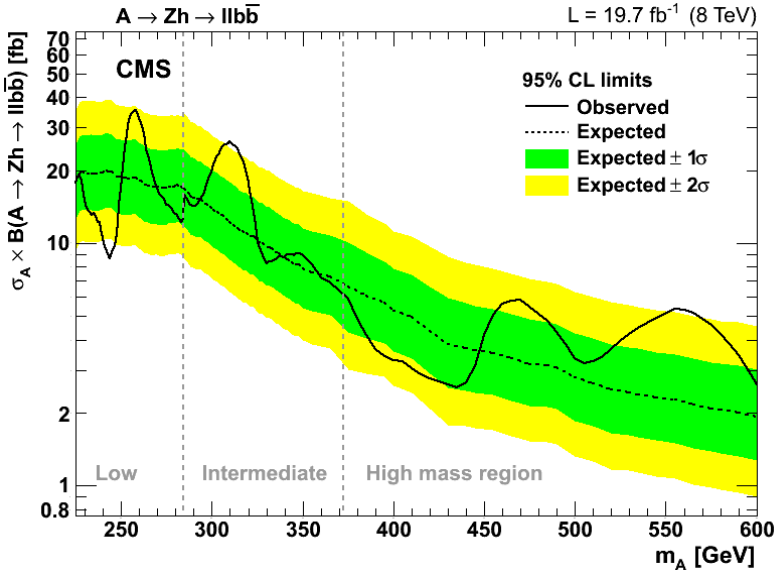


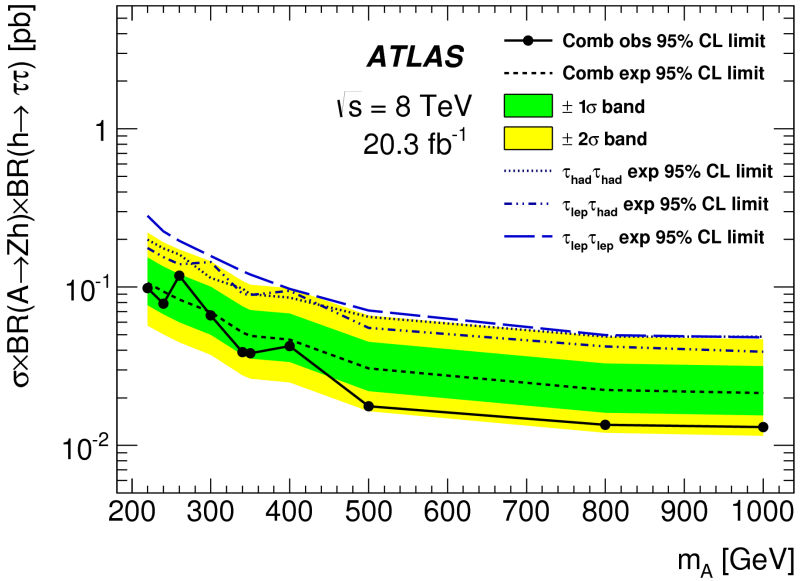

$370 < m_A < 600$ GeV

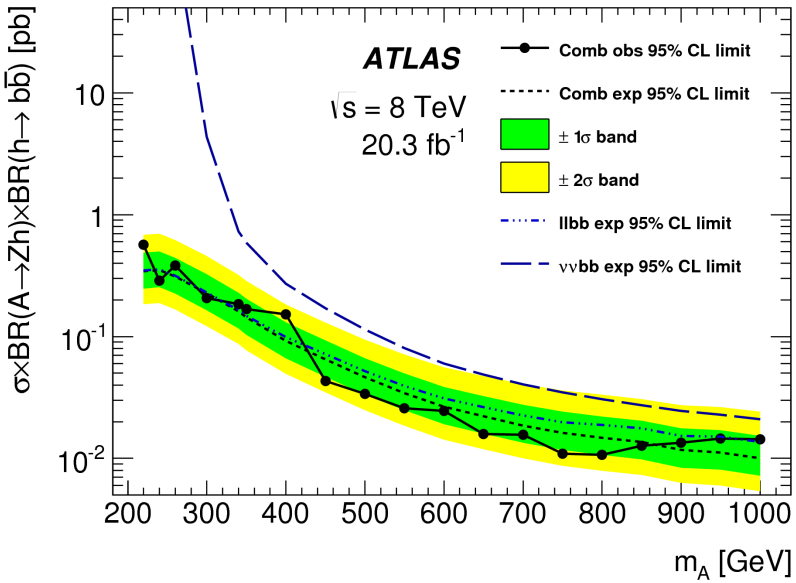


# MSSM: the low tanβ regime

- Constraints for a gluon-fusion produced heavy CP-odd Higgs boson A



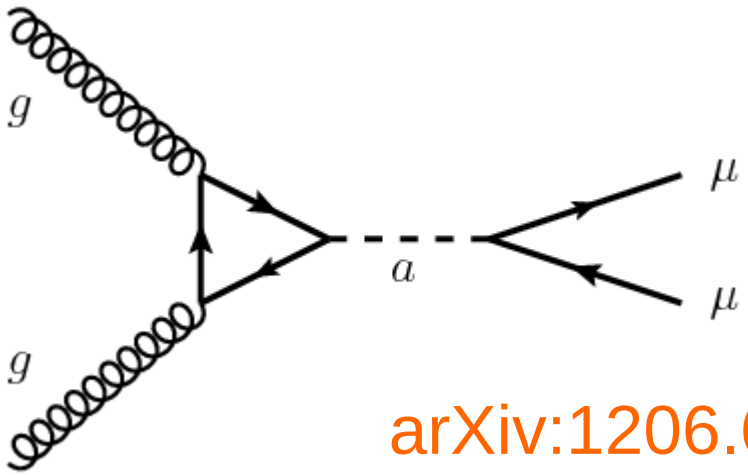



# Next-to-MSSM (NMSSM)

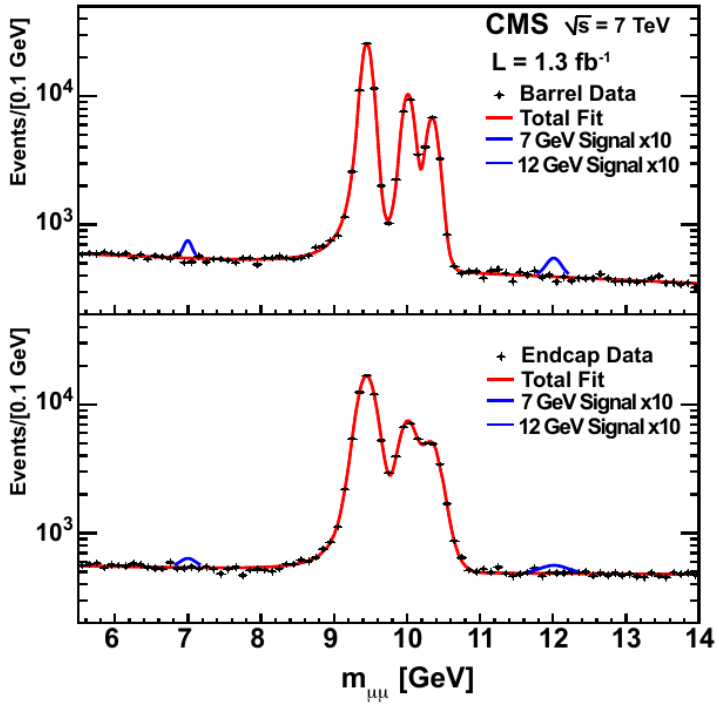
- NMSSM: next to minimal supersymmetric Standard Model
  - Addition of a singlet in the Higgs sector
  - 2 more Higgses and one more neutralino with respect to MSSM; more freedom with respect to the MSSM:
    - Higgs sector not necessarily CP conserving at lowest order (although usually CP-conservation is assumed)
    - Tree level MSSM relation "$m_h < m_Z$" is not valid any more
  - Typical signatures involve a light CP-odd Higgs
    - a->μμ, ττ, bb, h->aa, ...

NMSSM signatures may be shared with other new physics, so you will see them in other talks as well.

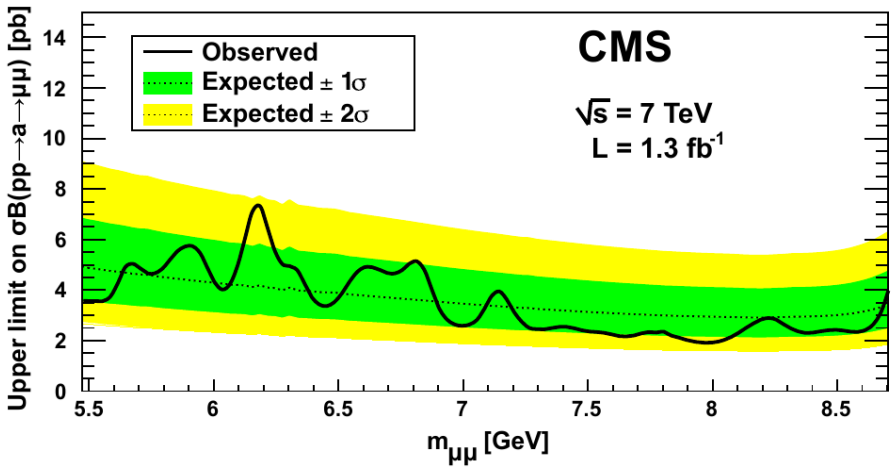
# a → μμ

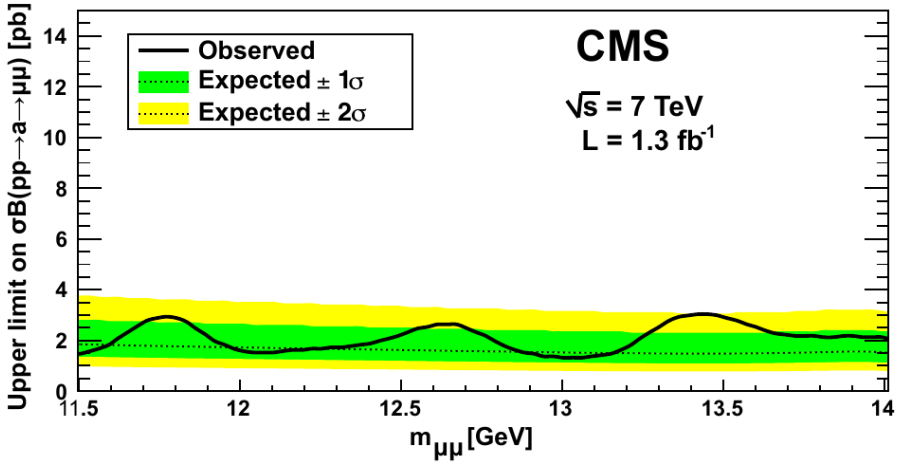



arXiv:1206.6326

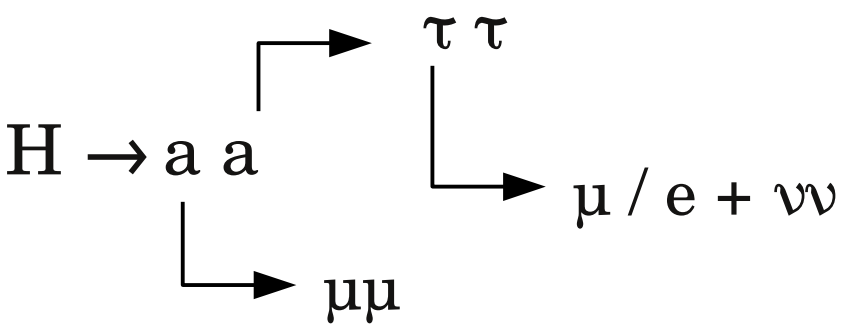



Search for a gluon-fusion produced, light CP-odd Higgs boson decaying to μμ



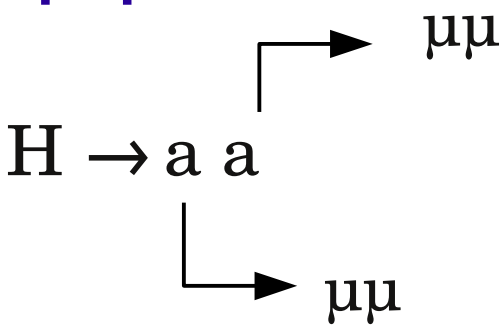



# $h \rightarrow aa \rightarrow \mu\mu\tau\tau$ or $\mu\mu\mu\mu$

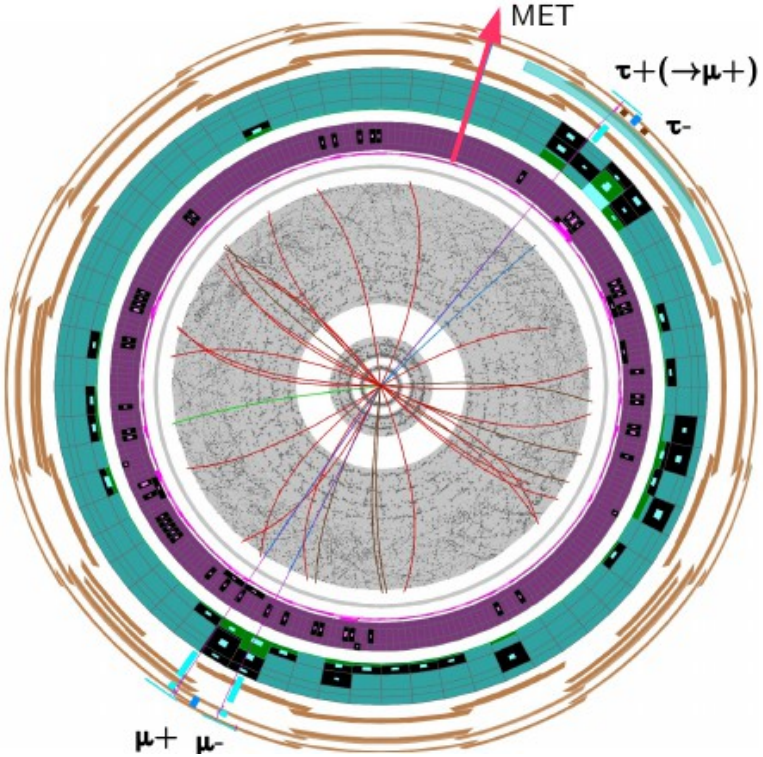


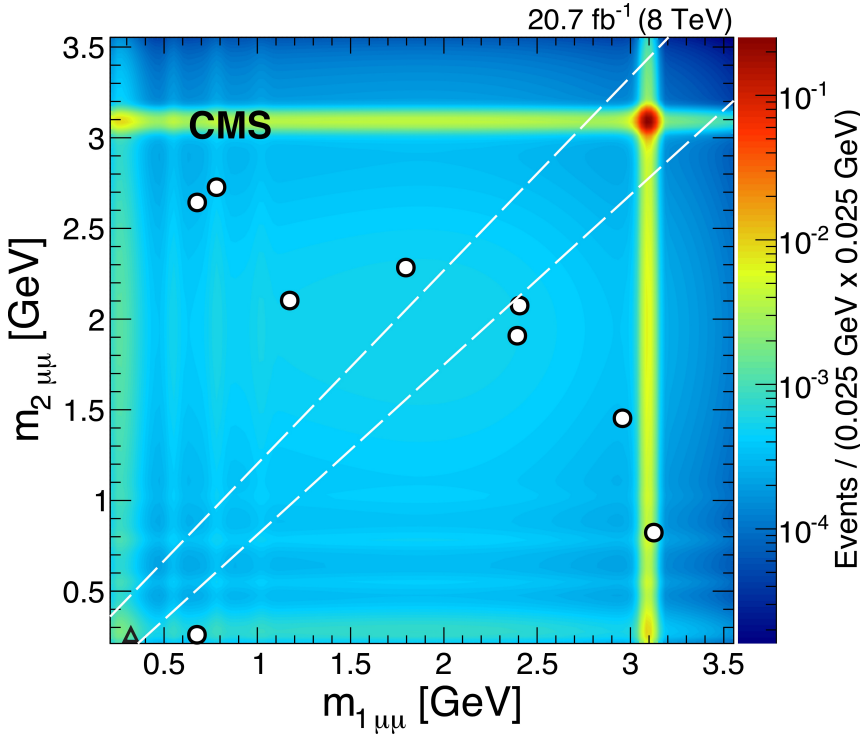

arXiv:1505.01609

arXiv:1506.00424




**Look for these decays in the talk by James Beacham tomorrow**

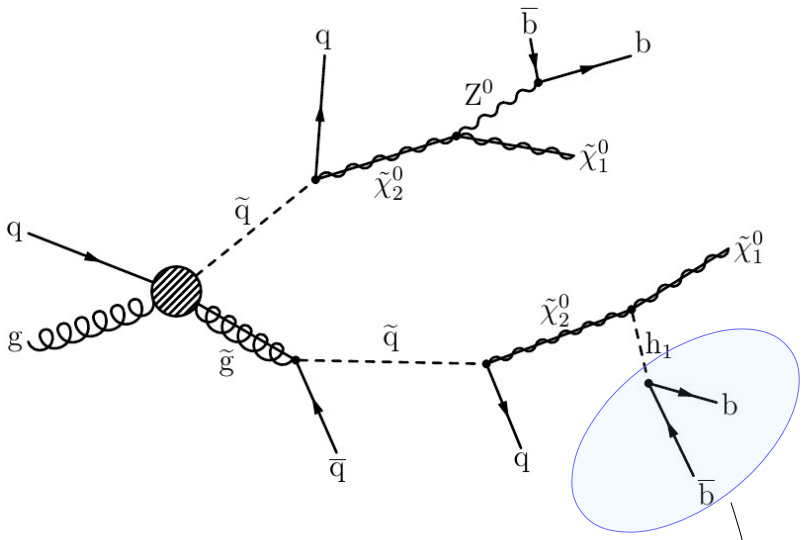


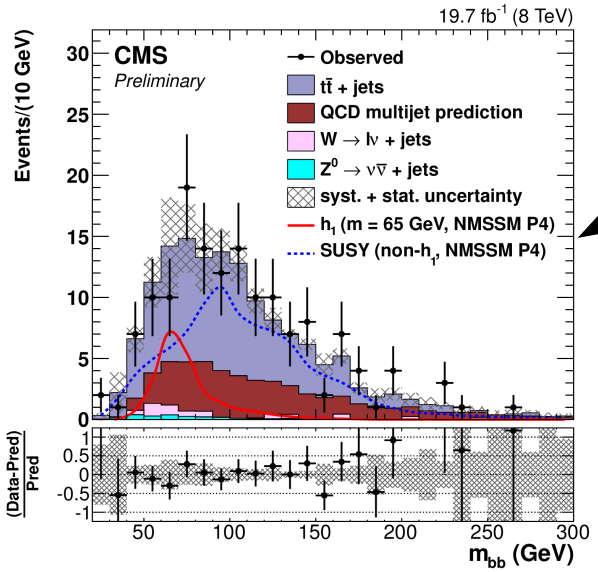



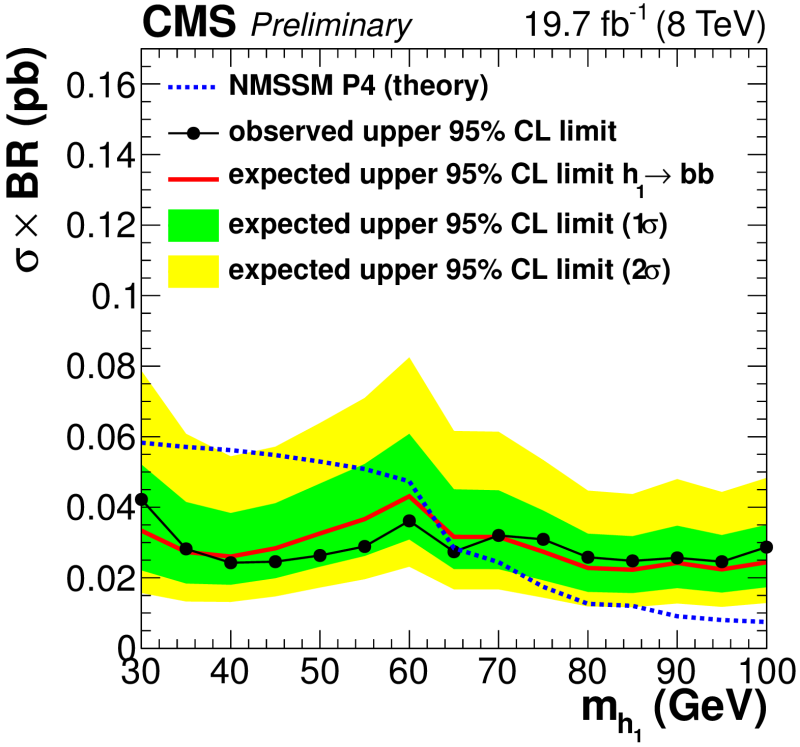
# $h_1$->bb in cascades

CMS-PAS-HIG-14-030

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



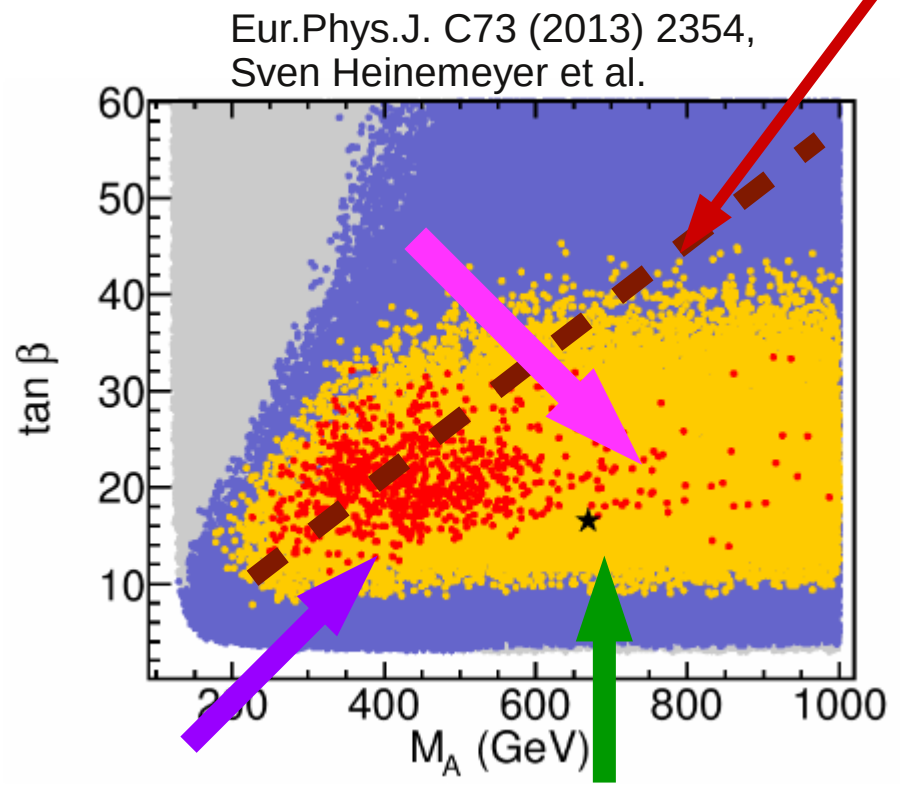




Shown prediction from an NMSSM benchmark taken from arXiv:0801.4321

# The future

- The future is bright: there is still a lot of way to cover and the Run-II results will be very interesting

MSSM ττ search constrain (red dashed line)




MSSM ττ and bb searches will continue digging into the parameter space at the high tanβ region

The low tanβ, high mass region is much more difficult to access experimentally (A/H->tt)

The low tanβ, low mA will continue being constrained via Zh, ττ, hh, ...

# The future

- The future is bright: there is still a lot of way to cover and the Run-II results will be very interesting
- For NMSSM
  - Direct production of light (pseudo)scalars may be challenging
  - But indirect production through Higgs decays or in cascades is very promissing
    - e.g. notice that even in HL-LHC there is a large fraction of width (~10%) that is available for exotic Higgs decays

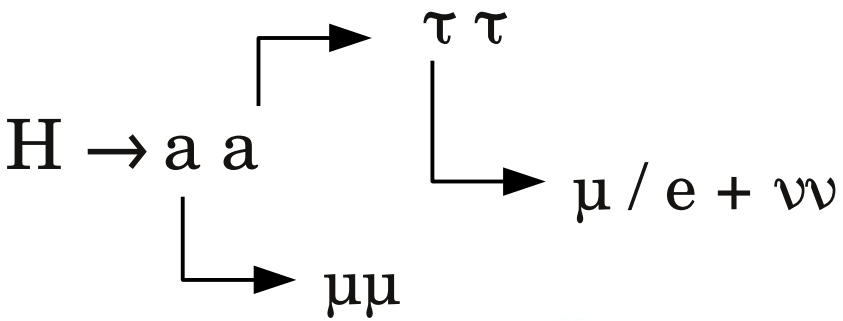
# Concluding remarks

- The searches for supersymmetric Higgs bosons in hadron colliders are very active for ~20 years now
  - c.f. CDF first susy Higgs result in PRL79(1997)357
  - Looking for light pseudo-scalars you may get more than 30 years before!
- We went a very long way to constrain large parts of the parameter space
  - But there is still a lot of things to be done and searches that haven't even properly started!
  - Expect that this will continue to be hot area in Run-II

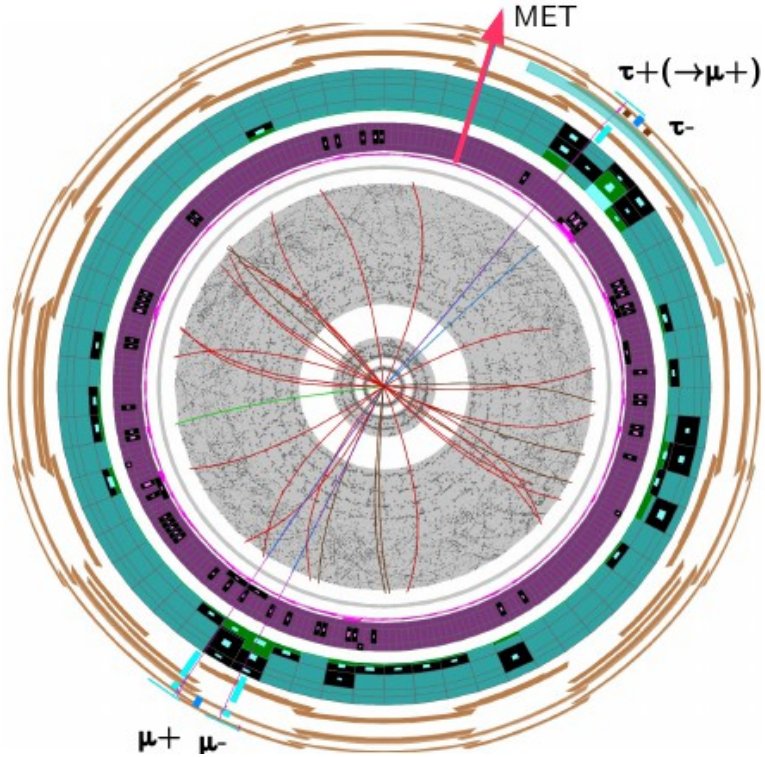
# Additional slides

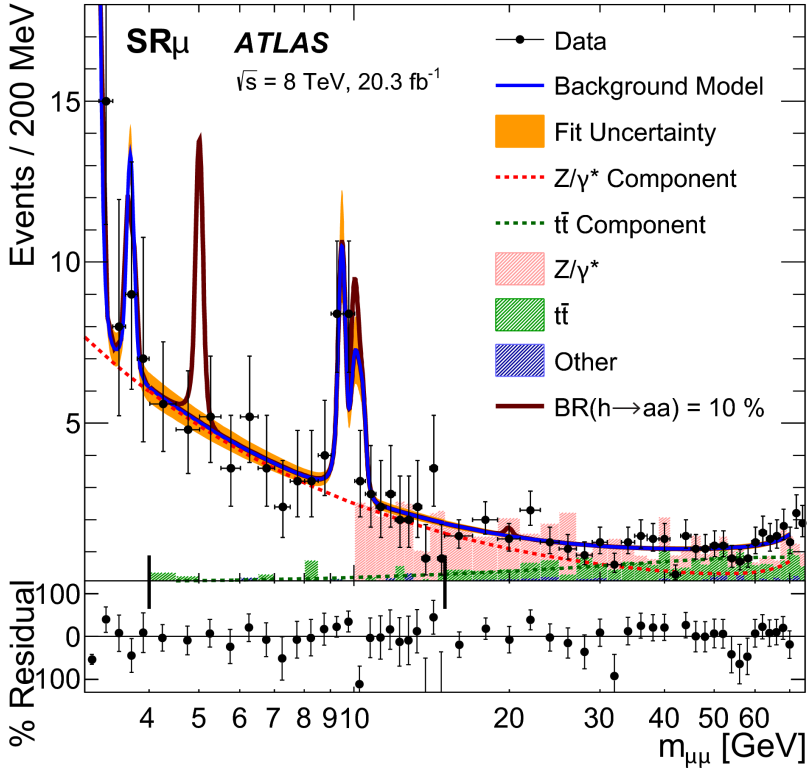
# $h \rightarrow aa \rightarrow \mu\,\mu\,\tau\,\tau$

**arXiv:1505.01609**




Searching for a bump in the μμ spectrum:



# $h \to aa \to \mu\mu\tau\tau$

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