# Search For Rare & Exotic Higgs Decay And Production: Status and Perspectives

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on behalf of the ATLAS and CMS collaborations

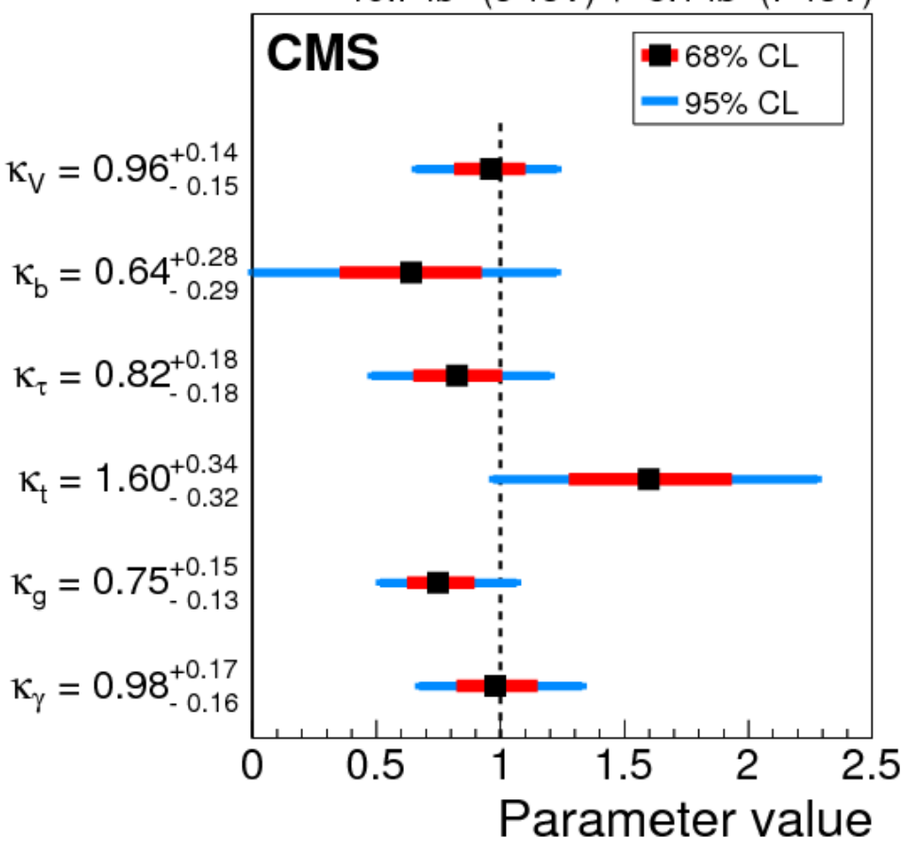
**Moriond EWK - La Thuile - 17/03/2015**

# BSM Higgs Physics

## Unveil new physics in the Higgs sector

### Measurement of Higgs couplings

probing direct couplings to third generation fermions,W/Z, BSM contribution to ggH and Hγγ




### Direct searches

- Rare SM Higgs decays (e.g 2nd generation fermions, Z/γ*+γ)
- Decays not allowed in the SM (e.g. LFV H→μτ)
- Rare SM production modes (e.g t+H, HH)
- Invisible or quasi-invisible Higgs decays (H→XX,H→γX)
- Search for extended Higgs sector: additional neutral or charged scalars

**DISCLAIMER: Focus on most recent Run I results/updates, perspectives for Run II**

# H→μμ & H→ee

BR(H→μμ)=2.2x10$^{-4}$ ~ 1/10 x BR(H→γγ)

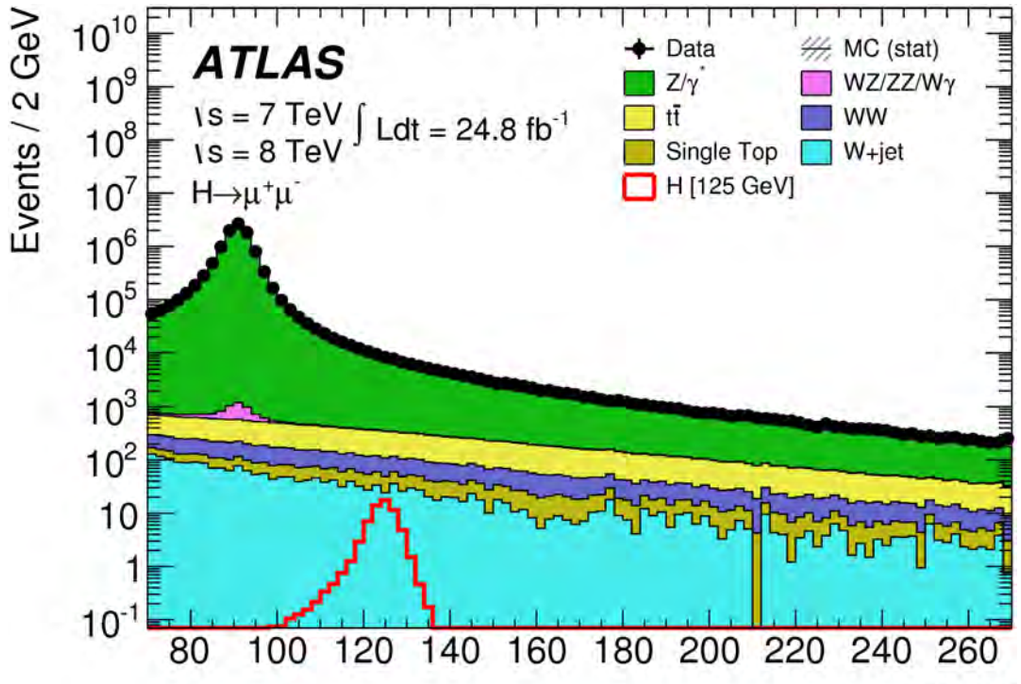
H(125)→μμ 95% CL observed (expected) limits on $\sigma/\sigma_{SM}$

| | |
|---|---|
| ATLAS: PLB 738 (2015) | 7.0(7.2) |
| CMS: arXiv:1410.6679 | 7.4(6.5) |

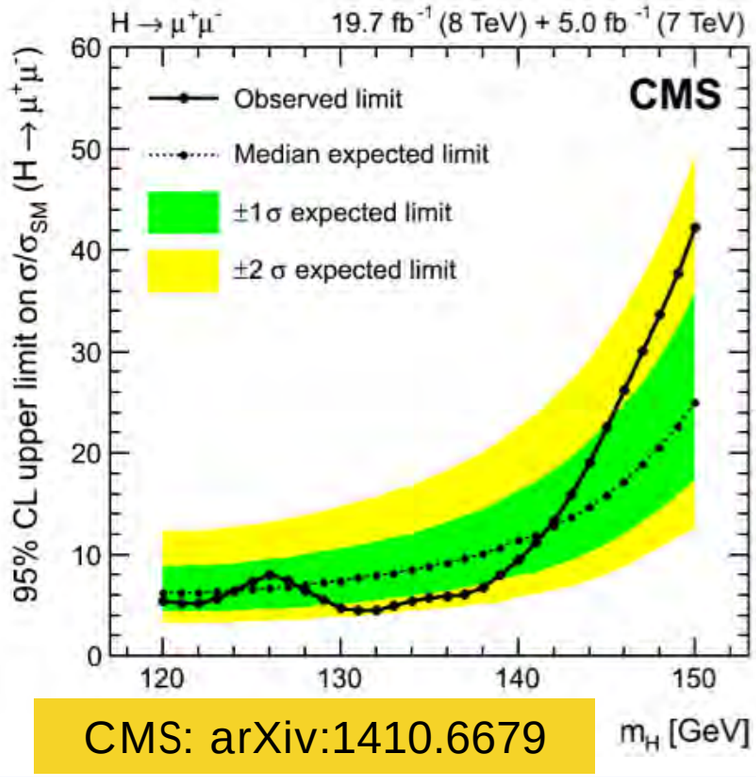
Together with evidence of H→ττ, confirm lepton non-universality

With 300 fb$^{-1}$ @ 13 TeV sensitivity to ~exclude H→μμ

H→ee: CMS put 95% CL exclusion limit on σ x BR(H(125)→ee)=41fb




ATLAS: PLB 738 (2015) 68



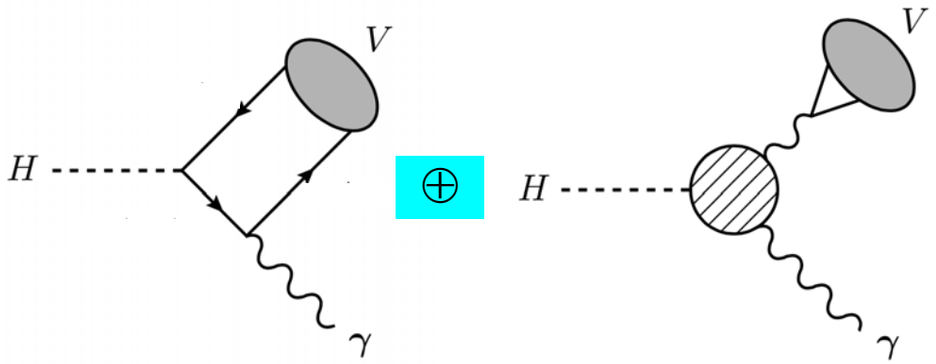

CMS: arXiv:1410.6679

# H→J/ψγ,ϒγ

Very small BR

BR(H→J/ψγ) ~ 3x10$^{-6}$

Proposed to probe $Y_c$ coupling @ HL-LHC



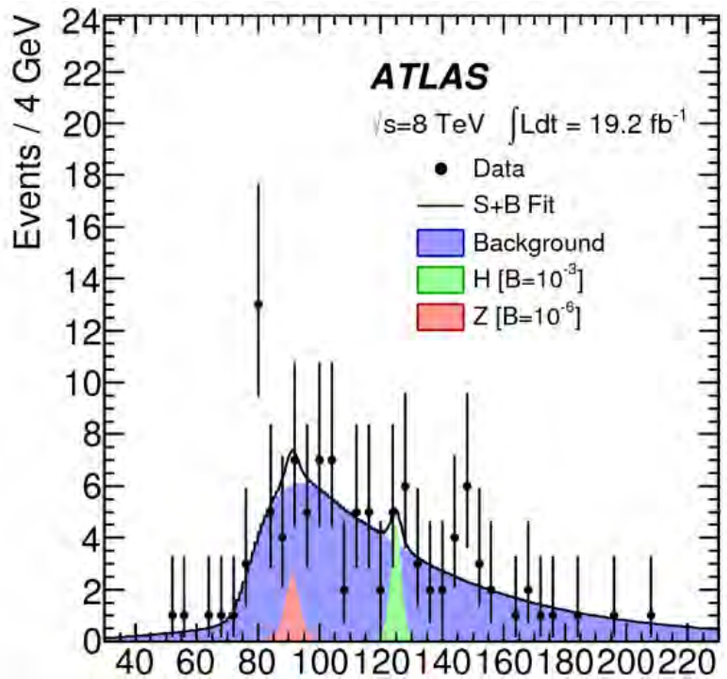

Main background

quarkonium production + fake photon

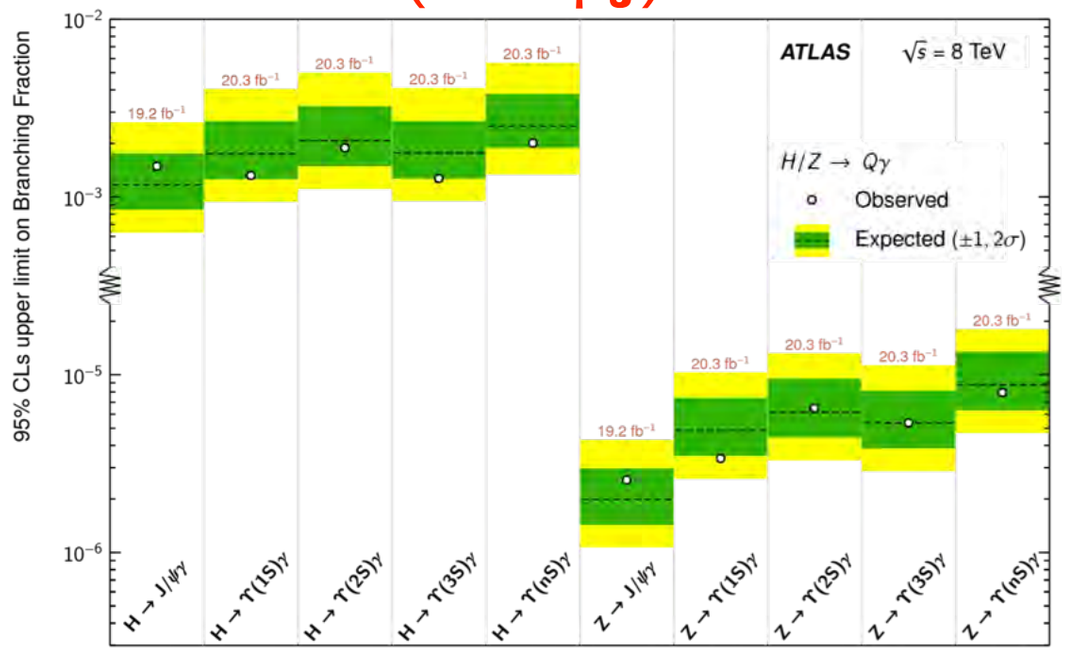
Multidimensional likelihood fit

H→Vγ & Z→Vγ signal hypotheses are considered

J/ψ+γ candidates




Limit on H(→J/ψγ) ~ x 540 SM




ATLAS: arXiv:1501.03276 NEW

# LEPTON FLAVOUR VIOLATING DECAYS

Lepton flavor violating decays can arise in several BSM theories with >1 Higgs doublet

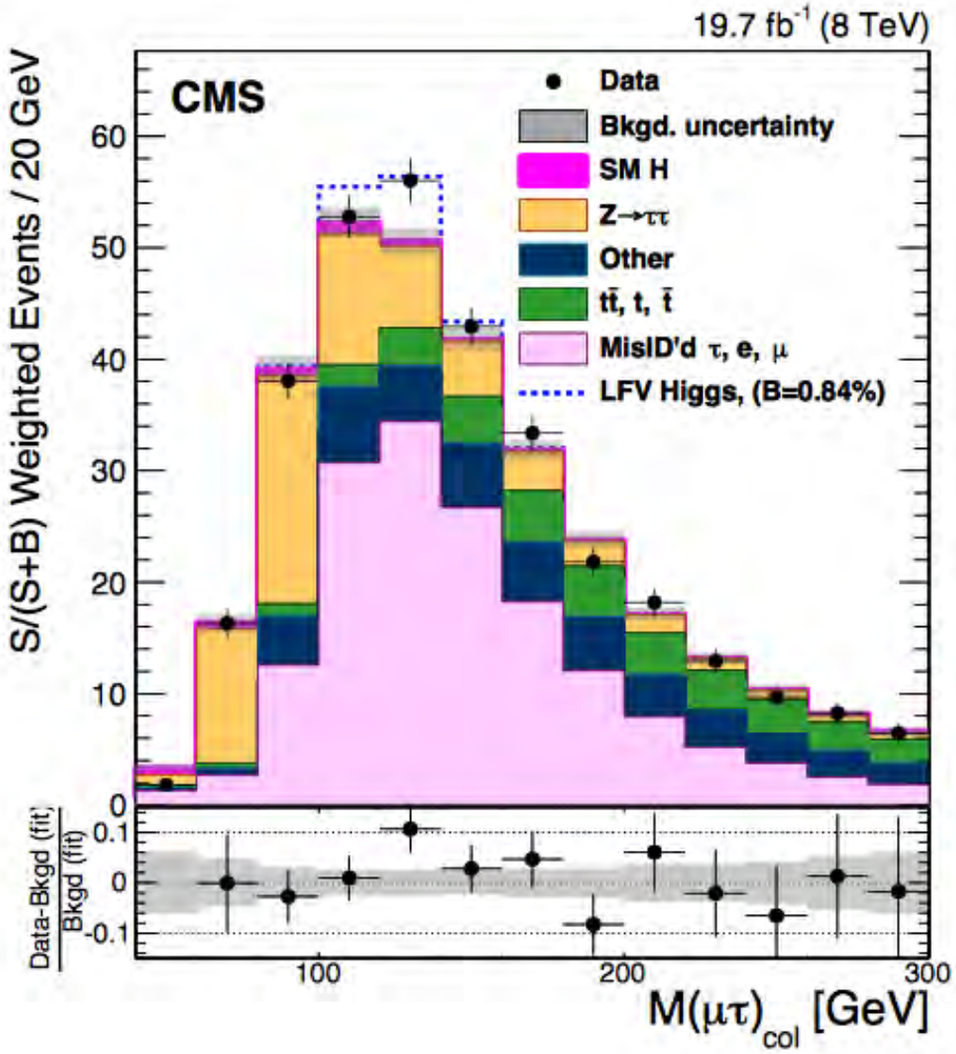
$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

Indirect limits on BR(H→μτ)<~10% from τ rare decays search (τ→3μ,τ→μγ)

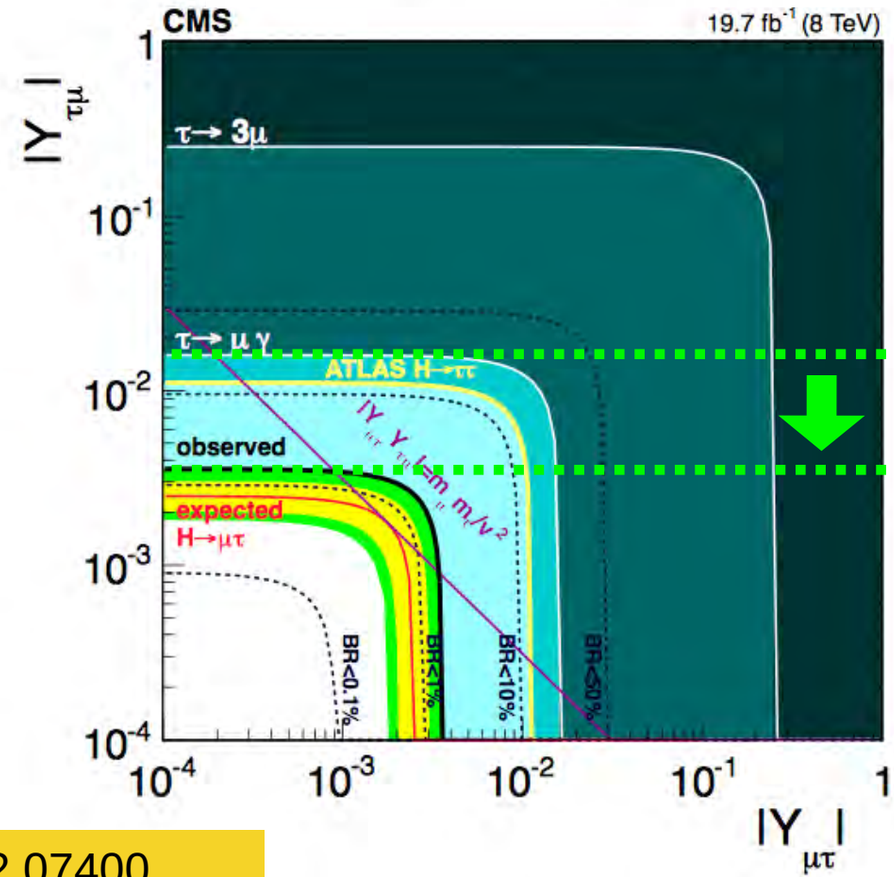
Indirect limit can be obtained re-interpreting H→ττ search

First direct limit on BR(H→μτ) < 0.75%

(2.4σ excess)




$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$




CMS: arXiv:1502.07400

# INVISIBLE HIGGS DECAYS

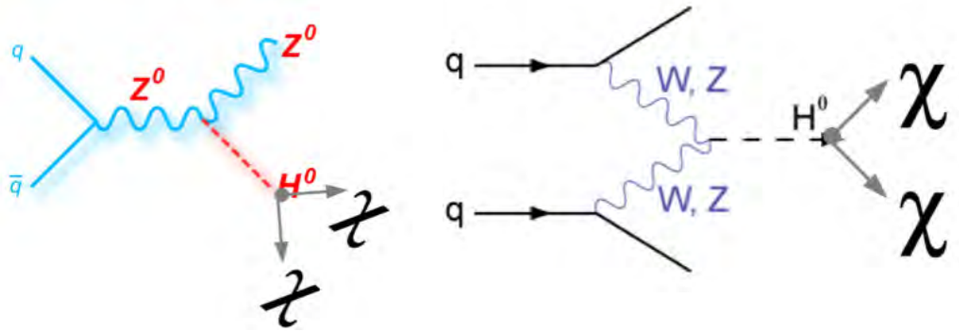
## Indirect constraint on undetected decays

- $\Gamma_{tot}$ from measured Higgs decay and production rates

## Direct search: exploit associated VH and VBF production

## New channels entering into the game

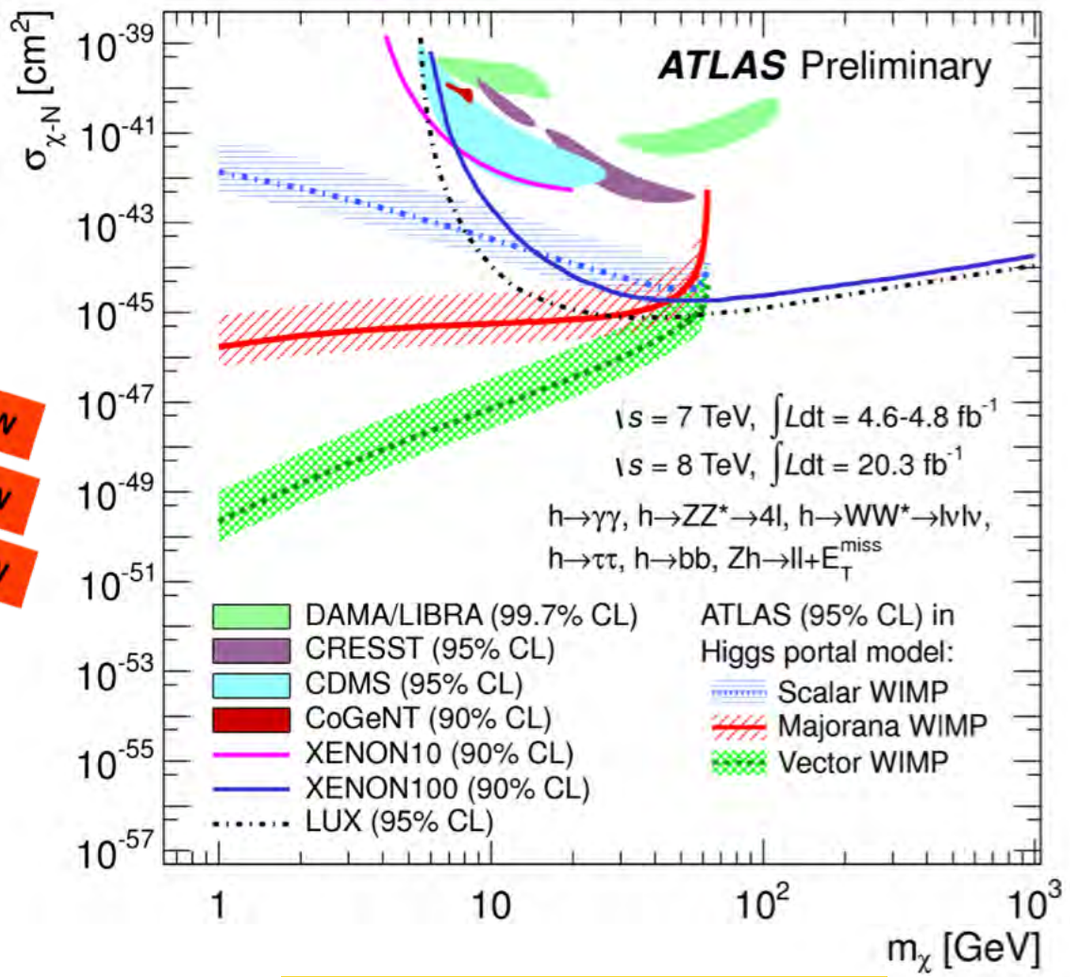
- mono-jet & tt+MET searches, will be more important in Run 2
- see C. Doglioni's & D. Pinna's talks




95% CL upper limits on BR(H→inv)

| | |
|---|---|
| ATLAS: PRL 112, 201802 (2014) Z(→ll)H | 75(62)% |
| ATLAS-HIGG-2014-007: W/Z(→had)H | 78(86)% |
| ATLAS-CONF-2015-004: VBF | 29(35)% |
| ATLAS-CONF-2015-007: indirect | 27% |
| CMS: Eur. Phys. J.C. 74 (2014) VBF+Z(→ll)H | 58(44)% |
| CMS: arxiV:1412.8662 indirect | 32(42)% |

NEW NEW NEW




ATLAS-CONF-2014-010

## BR limit also interpreted as DM limit

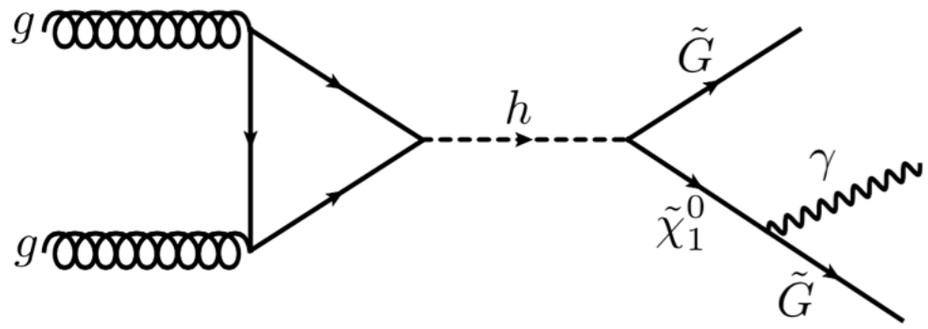
- Higgs portal models, better interpretation in using simplified models (LHCDM)

# QUASI INVISIBLE HIGGS DECAY

Higgs decays to neutralinos/ gravitinos: **γ**+MET final state

GMSB $h \to \tilde{G}\,\tilde{\chi}^0 \to \tilde{G}\,\tilde{G}\,\gamma$

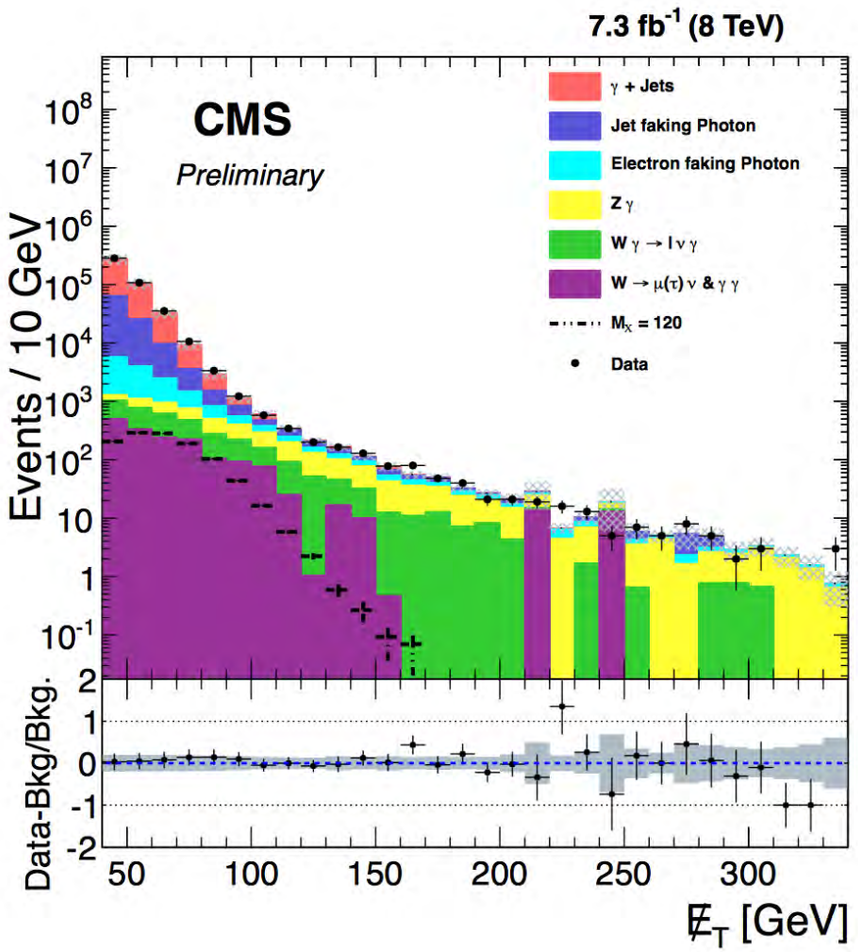
NMSSM $h \to \tilde{\chi}_2^0\,\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0\,\gamma$

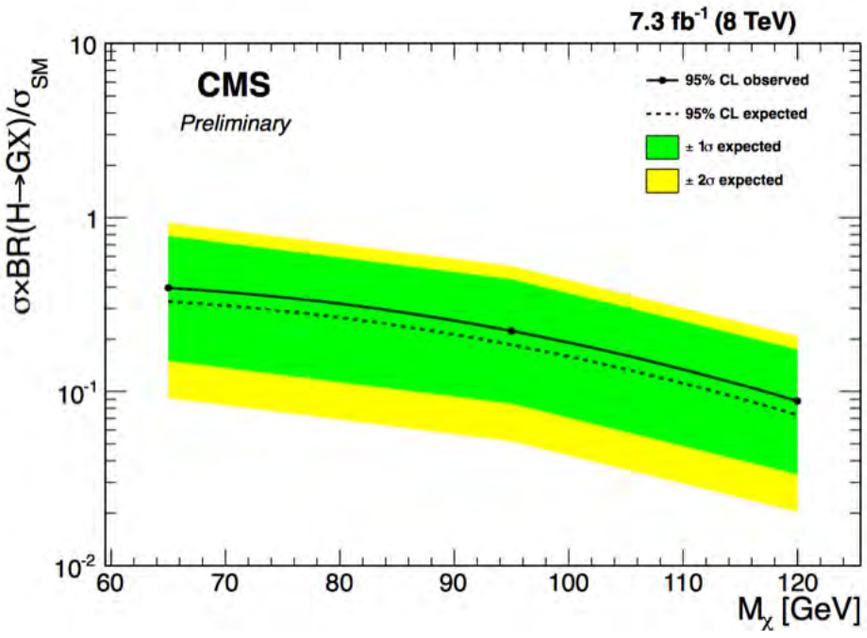



Inclusive analysis: high trigger rate, requires a special parked dataset

**γ** $p_T$>45 GeV

Difficult to be performed in Run 2



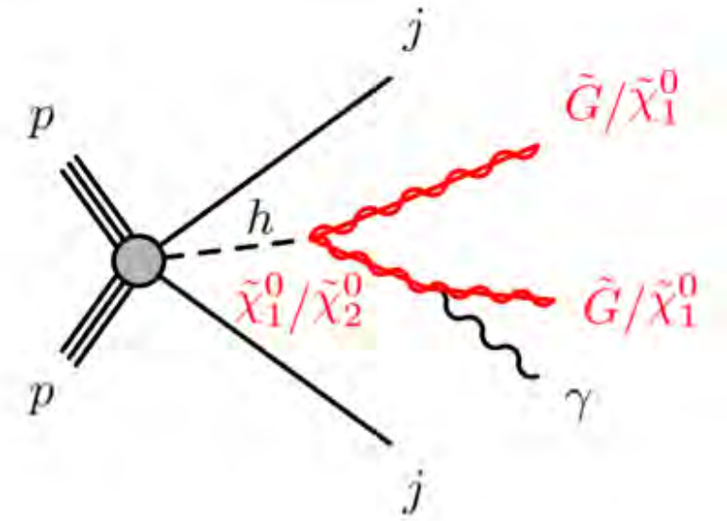

Optimized for $m_h/2 < m_{\tilde{\chi}_1^0} < m_h$ below **γγ**+MET will dominate

CMS: HIG-14-024 NEW

# QUASI INVISIBLE (VBF)

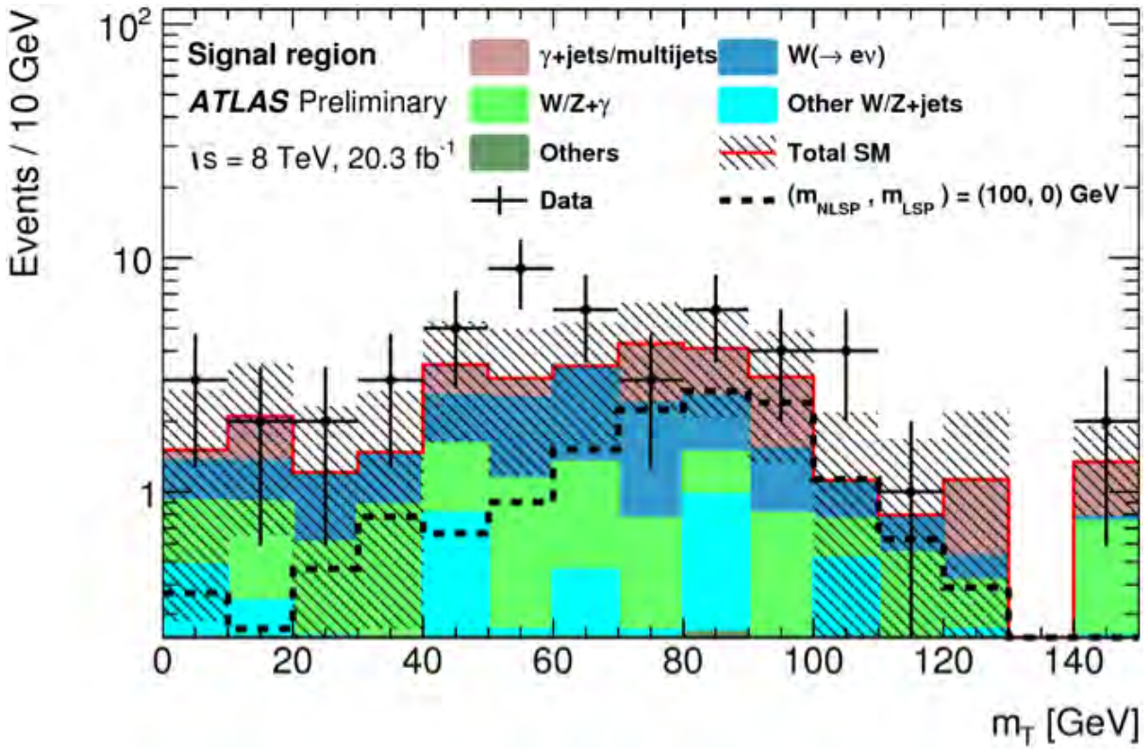
Associate Higgs production can be exploited to improve S/B & facilitate trigger in Run2

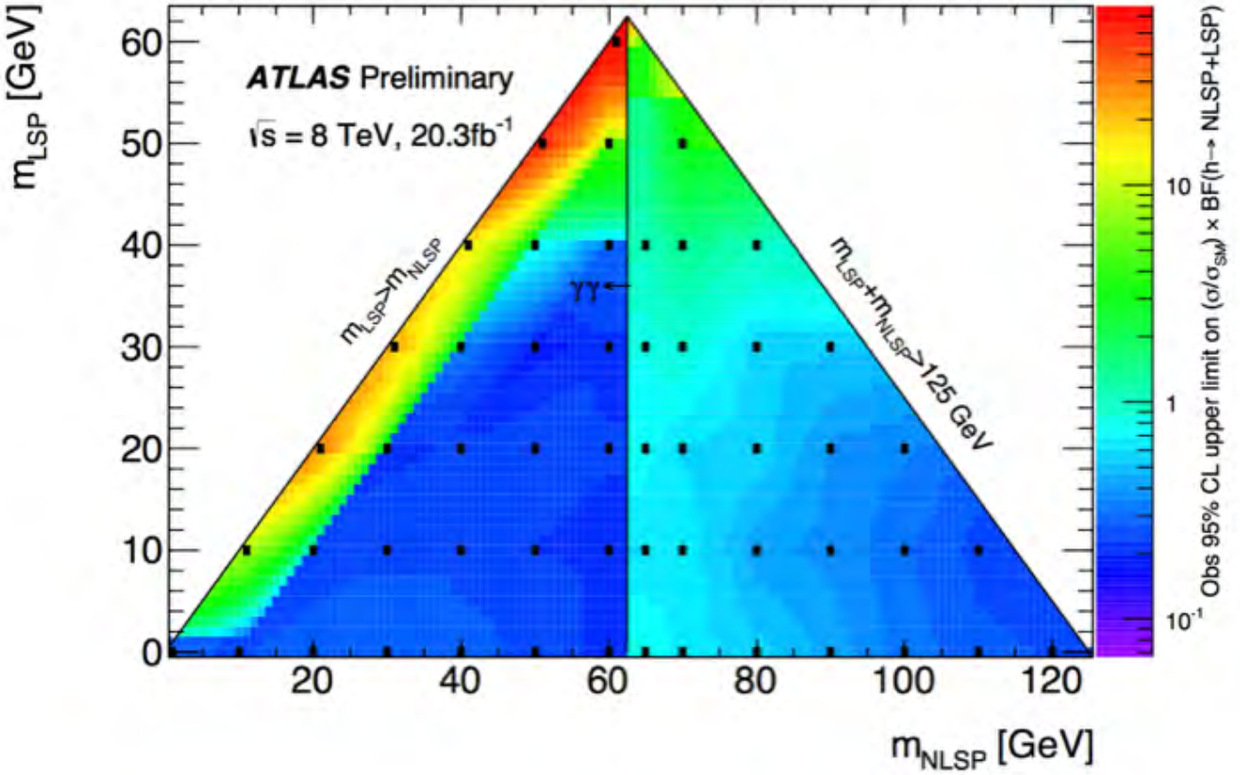
VBF




1 **γ** ($p_T$>40 GeV), 2 jets (VBF topology), $E_T^{MISS}$

Main background
γ+jets, W(→eν)+jets




ATLAS-CONF-2015-001 NEW

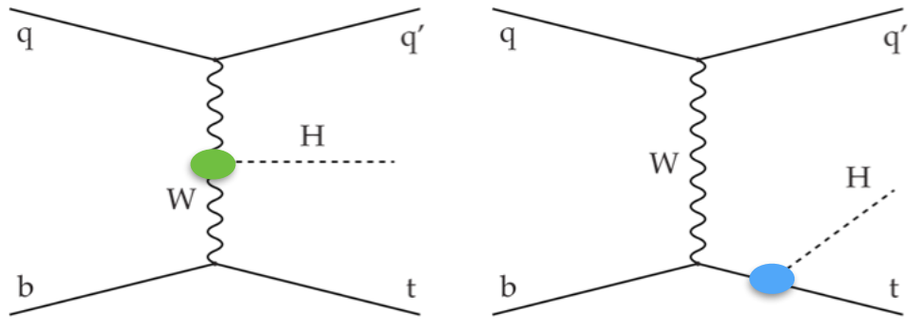
# Top+Higgs Production

## t+H production

SM: destructive interference between t-channel diagrams ($\sigma$ ~ 1/10 of ttH)

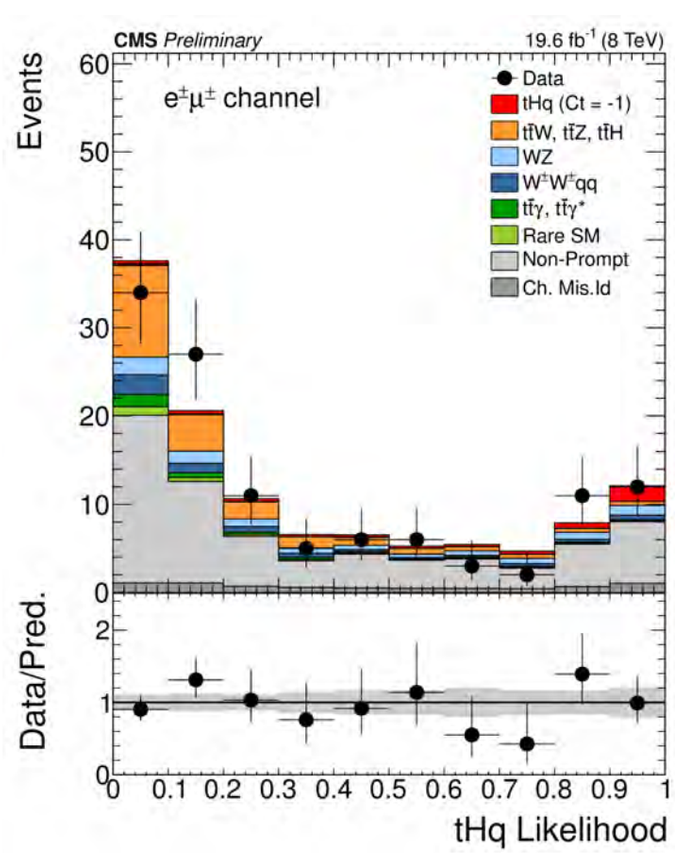
sensitive to relative sign between $Y_t$ and $g_{HWW}$

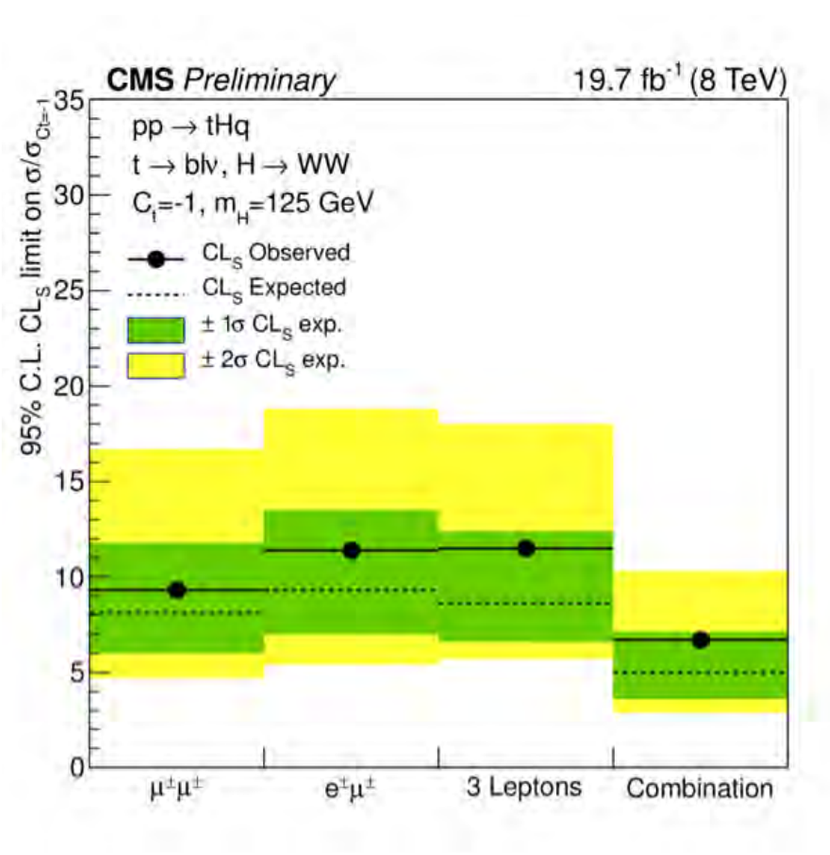
x15 $\sigma$ if $Y_t$ relative sign reversed wrt SM




Direct search for t+H: new multi-lepton analysis from CMS (H→WW,H→$\tau\tau$)

2 same-sign leptons, 3 leptons final state




CMS: HIG-14-026 NEW

Previous results
95% CL exclusion limits on $\sigma/\sigma(k_t=-1)$

| | |
|---|---|
| CMS HIG-14-001 t+H(→$\gamma\gamma$) | 4.1(4.1) |
| CMS HIG-14-015 t+H(→bb) | 7.6(5.2) |
| CMS HIG-14-026 t+H(WW,$\tau\tau$) | 6.7(5.0) |

Combination to be published soon

# Search For Extended Higgs Sector

Several SM extensions foresee additional neutral or charged scalars

- SM+ heavy EW singlet "prototype": 2 CP-even h,H
- MSSM: 2 Higgs doublets → 2 CP-even h,H, 1 CP-odd A, 2 charged $H^{\pm}$
  - More generally 2HDM
- NMSSM: MSSM + singlet → 3 CP-even, 2 CP-odd, 2 charged $H^{\pm}$.
  - Lightest scalars can be lighter then H(125)
  - ....

## Searches not covered in this talk:

A/H→$\tau\tau$: ATLAS: JHEP11(2014) 056, CMS: JHEP 10 (2014) 160

A/H→$\gamma\gamma$: ATLAS: Phys. Rev. Lett. 113, 171801, CMS: HIG-14-006

See M. Pelliccioni's talk

High mass H→WW/ZZ: ATLAS: ATLAS-CONF-2013-067, CMS: HIG-13-031 being submitted

$H^{\pm}$→cs: ATLAS: Eur. Phys. J. C, 73 6 (2013) 2465, CMS: HIG-13-035

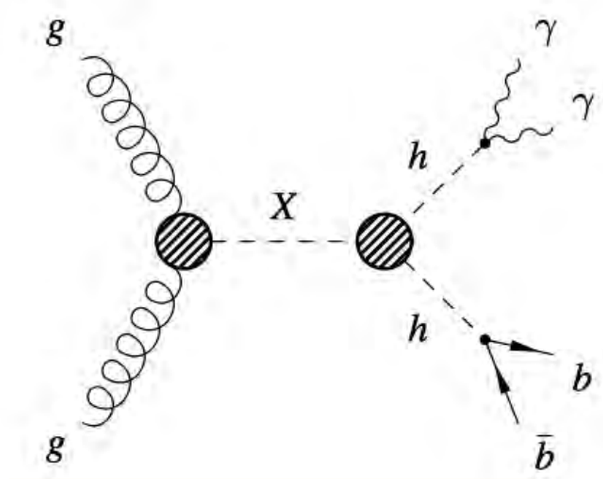
For other scalar searches in "exotic" models see K. Leney's & D. Paredes talks

# HH Searches in Run I

Best channel at low $m_{HH}$ is $\gamma\gamma$bb
- allows exclusion of some region of 2HDM space parameter ($m_X<2m_t$)

4b analysis most sensitive at high $m_{HH}$

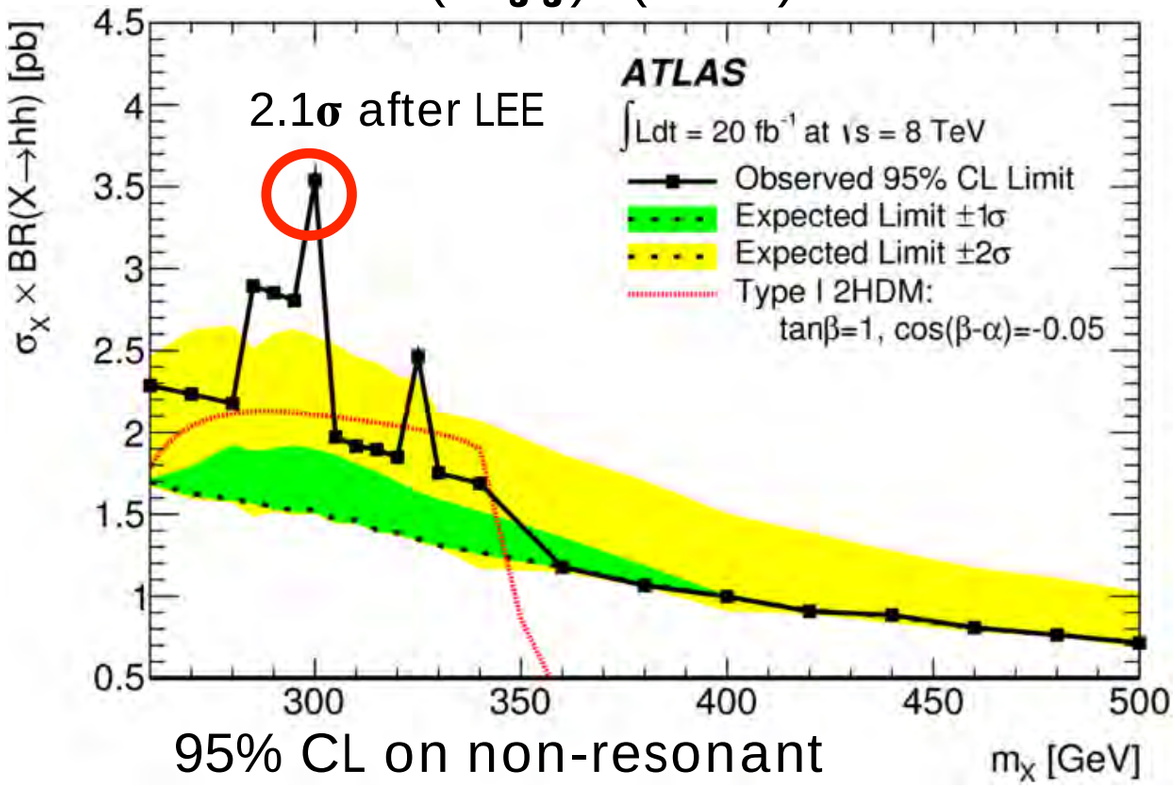
Non-resonant SM HH production too small to be probed during RunI: $\sigma_{NNLO}(pp\rightarrow HH)$ @ 8 TeV=9.96 fb
- non-resonant production $m_{HH}$ ~ 300-400 GeV



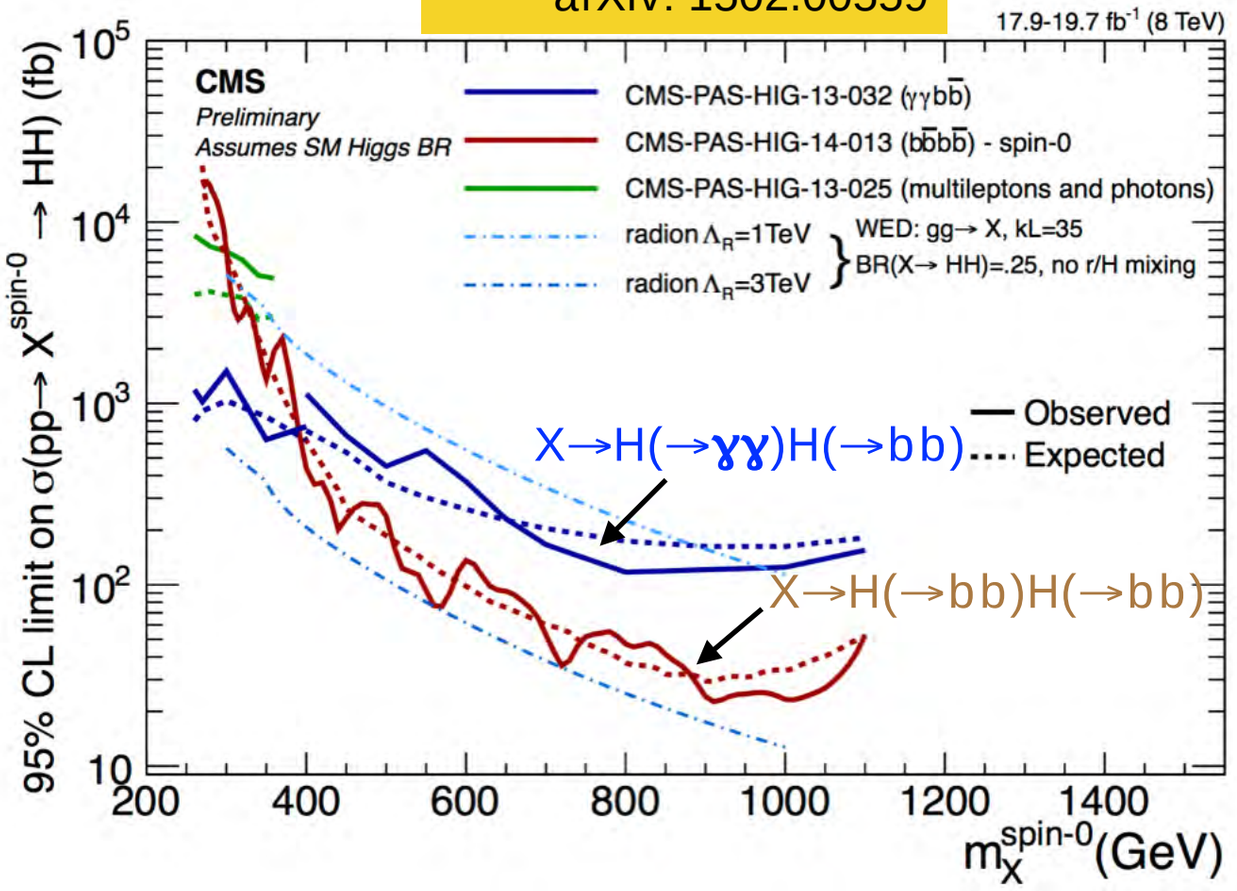

CMS: PRD 90, 112013
HIG-13-032
arXiv: 1502.00559

ATLAS: Phys. Rev. Lett. 114, 081802 (2015)

$X\rightarrow H(\rightarrow\gamma\gamma)H(\rightarrow bb)$




95% CL on non-resonant
$\sigma(pp\rightarrow HH)$=2.2 pb



# ATLAS: A→ZH

A: Neutral CP-odd scalar

2HDM, MSSM…

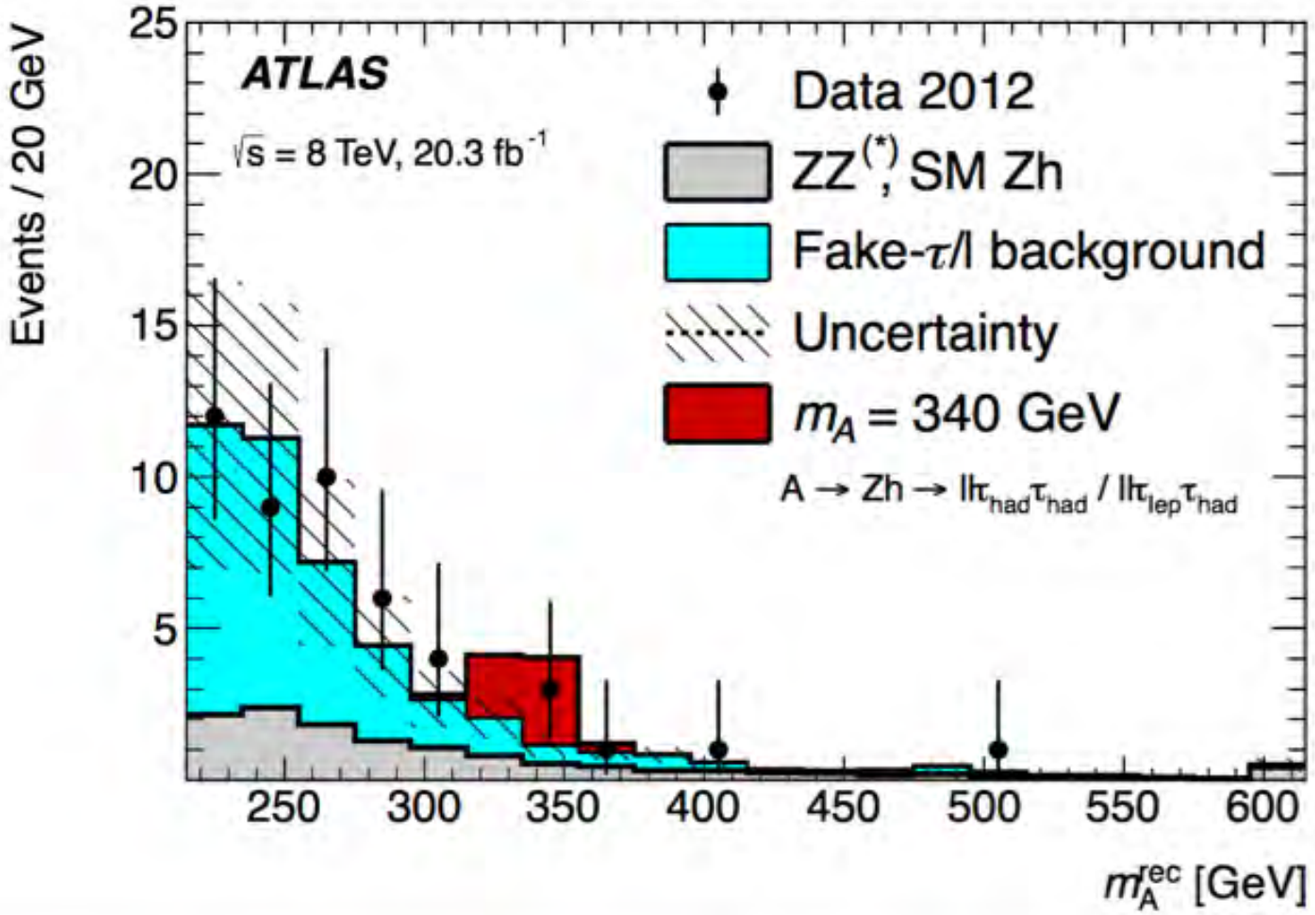
Produced via gluon fusion

A→ZH:

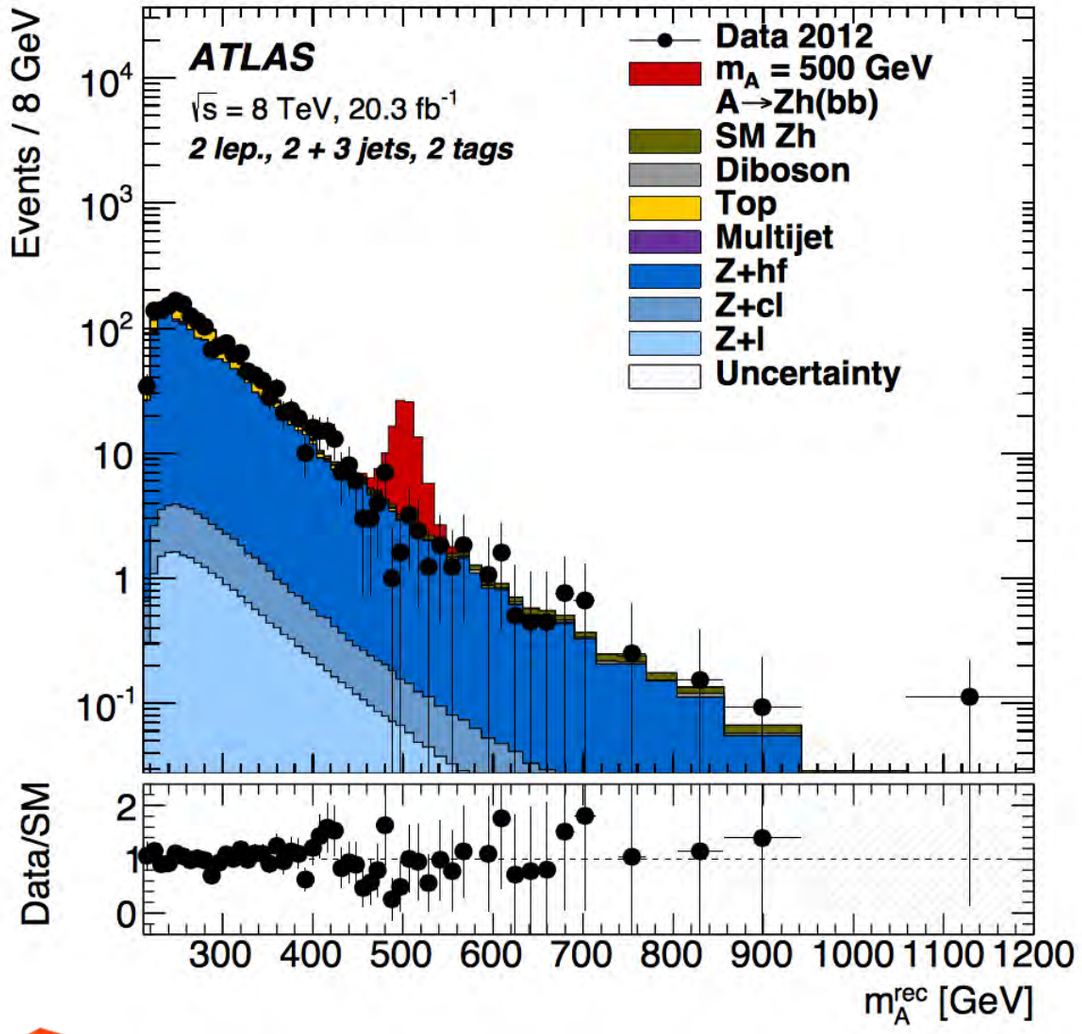
Z(→ll)+H(→$\tau_{had/lep}\tau_{had/lep}$,→bb)

Z(→νν)+H(→bb)

A→Z(→ll)H(→$\tau\tau$)



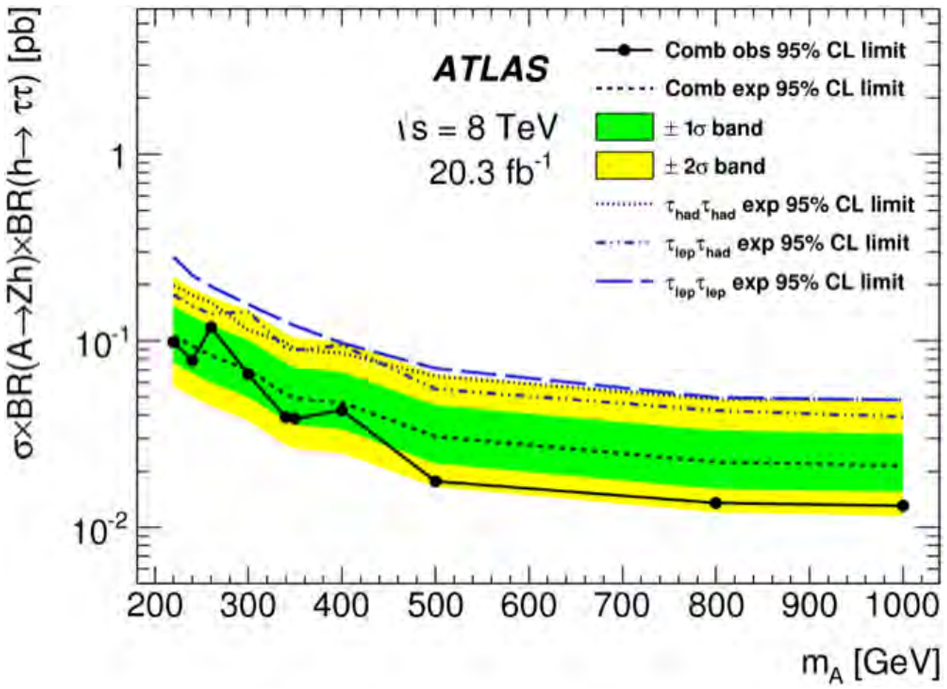

A→Z(→ll)H(→bb)



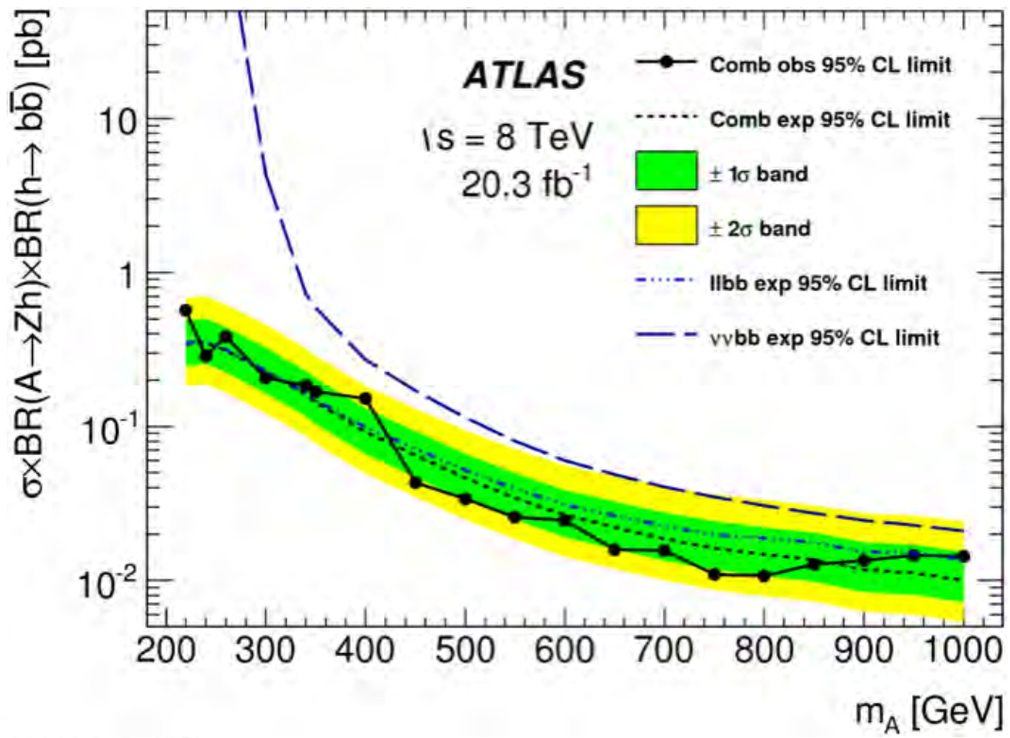

ATLAS: arXiv:1502.04478 NEW

# ATLAS: A→ZH

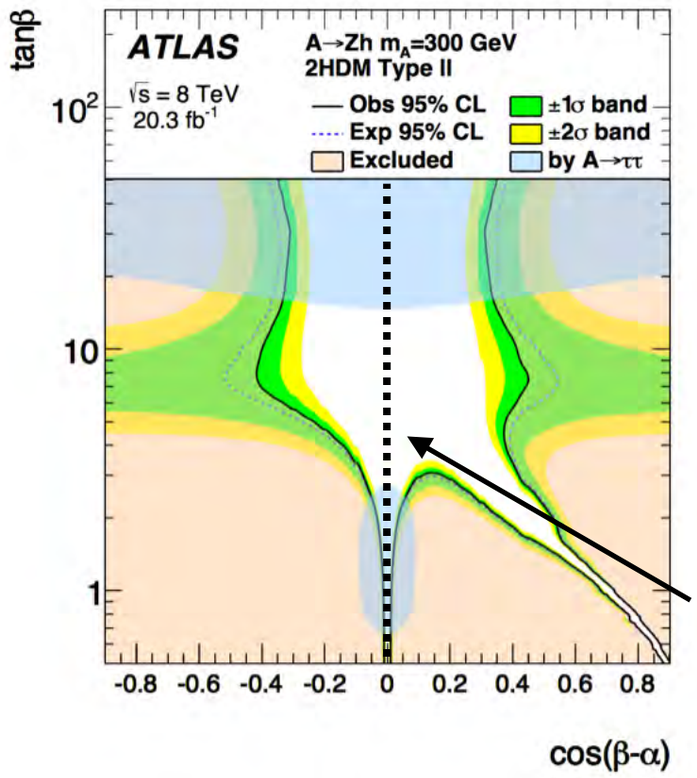
A→Z(→ll)H(→ττ)




A→Z(→ll,→νν)H(→bb)




Extend sensitivity in low tanβ regions not covered by the $\phi \to \tau\tau$ search (for $m_H + m_Z < m_A < 2m_t$)




2HDM

Type I: $\Phi_1$ coupled to V, $\Phi_2$ coupled to f

Type II: $\Phi_1$ coupled to u type quarks, $\Phi_2$ coupled to d type quarks

$\tan\beta = v_1/v_2$

$\alpha$ mixing angle h/H

SM: decoupling limit

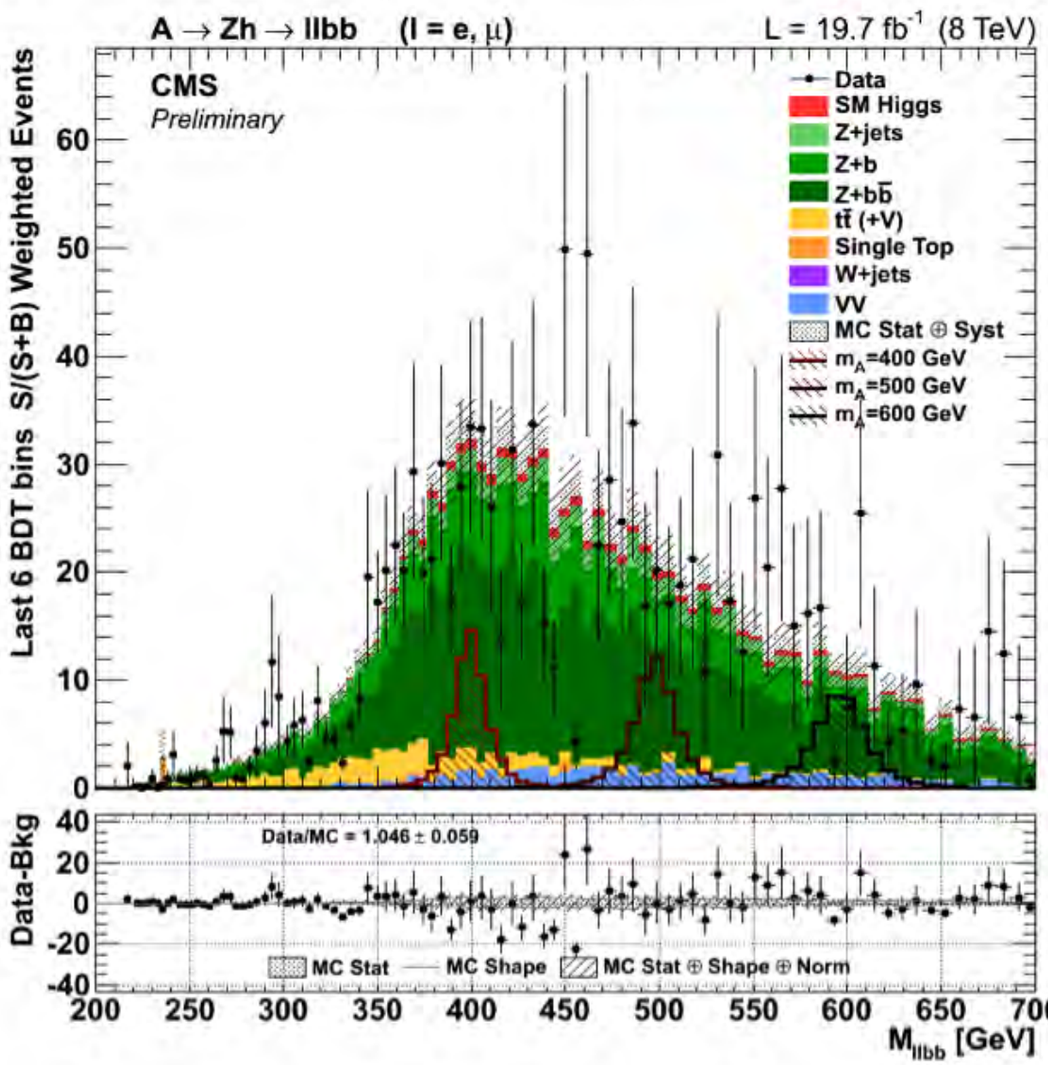
ATLAS: arXiv:1502.04478

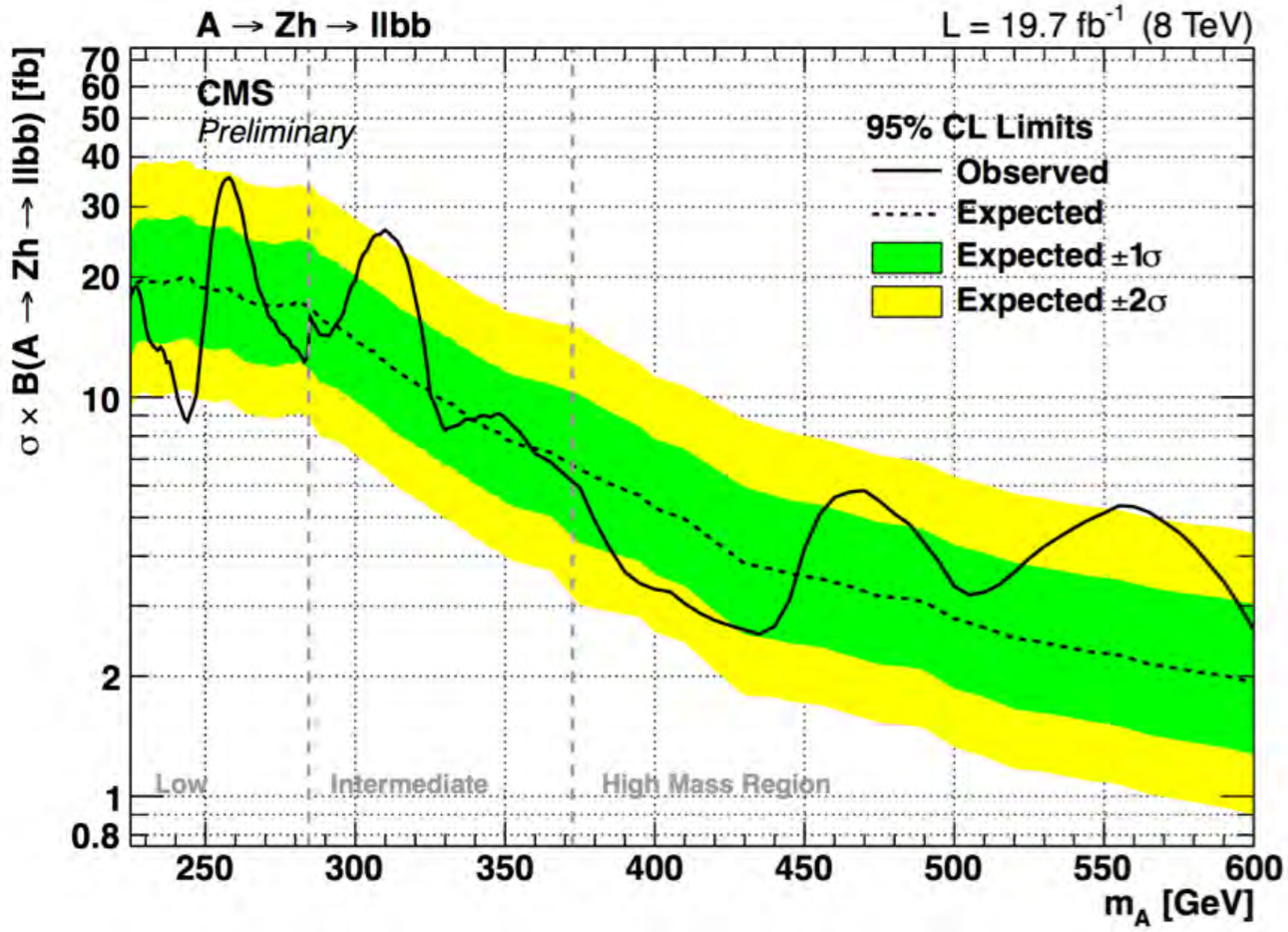
NEW

# CMS: A→ZH

A→Z(→ll)H(→bb)
BDT optimised in 3 mass regions
Model independent + 2HDM interpretation

High mass region

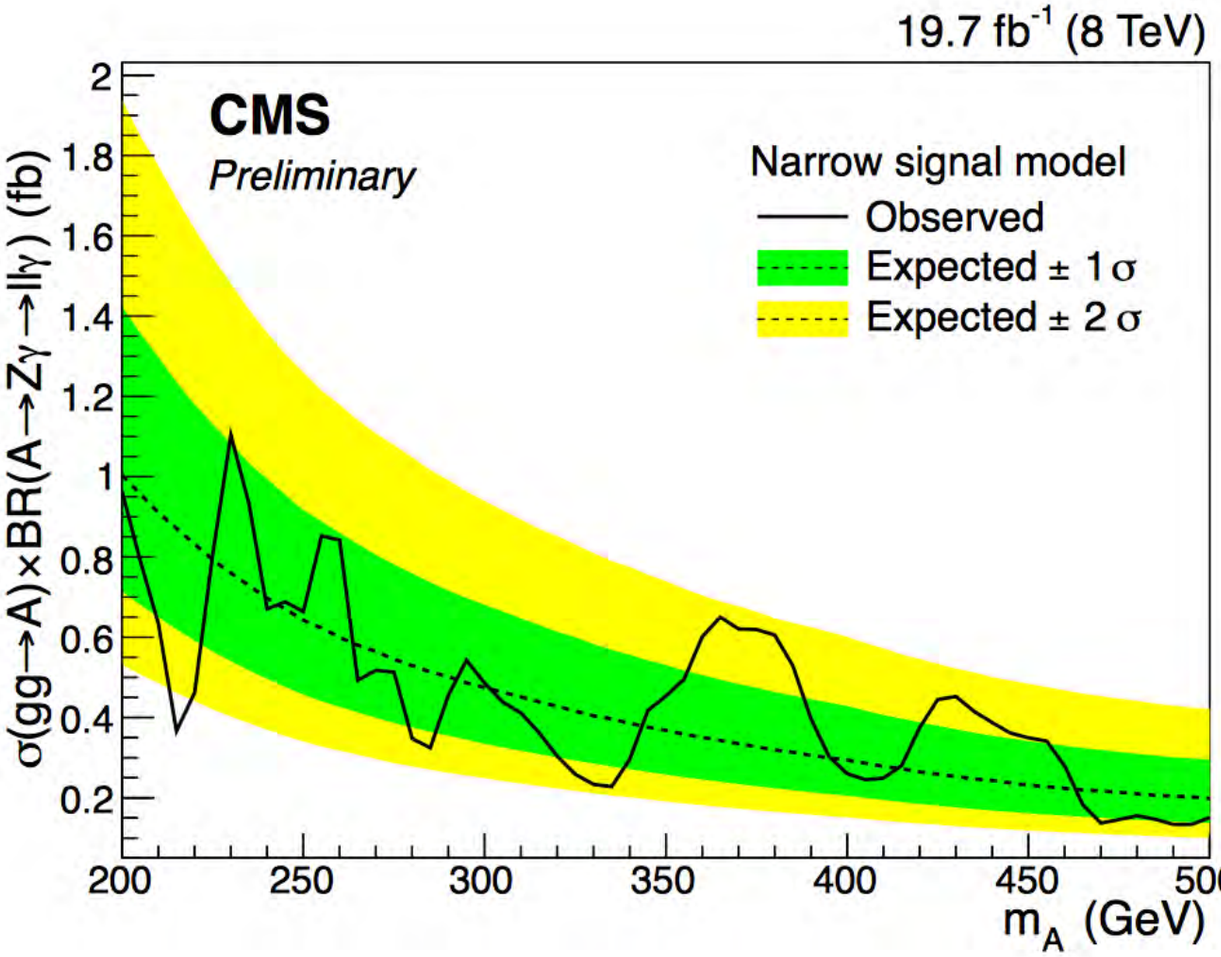


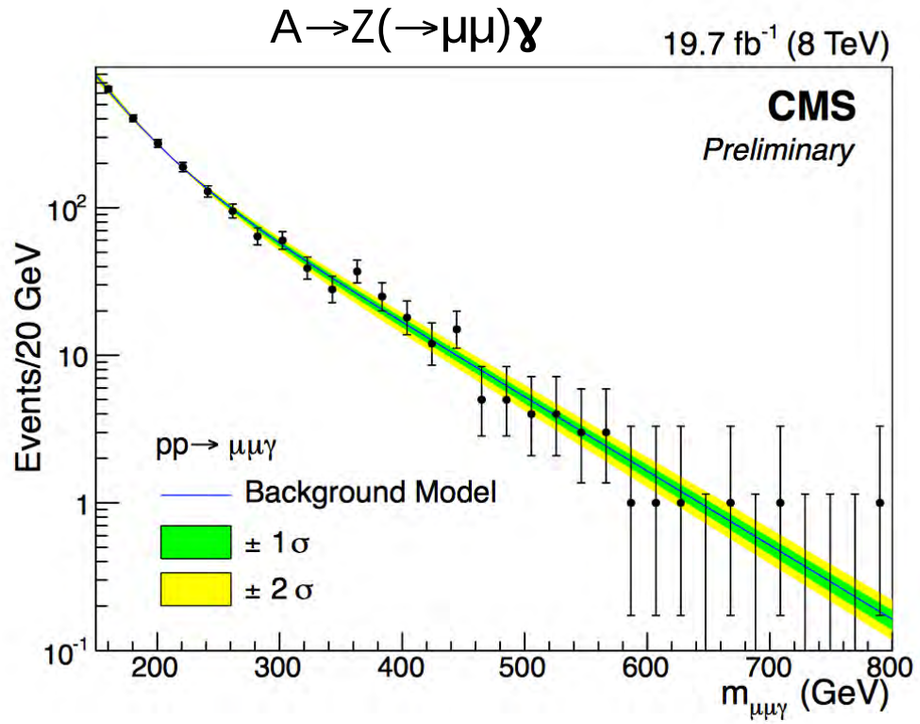



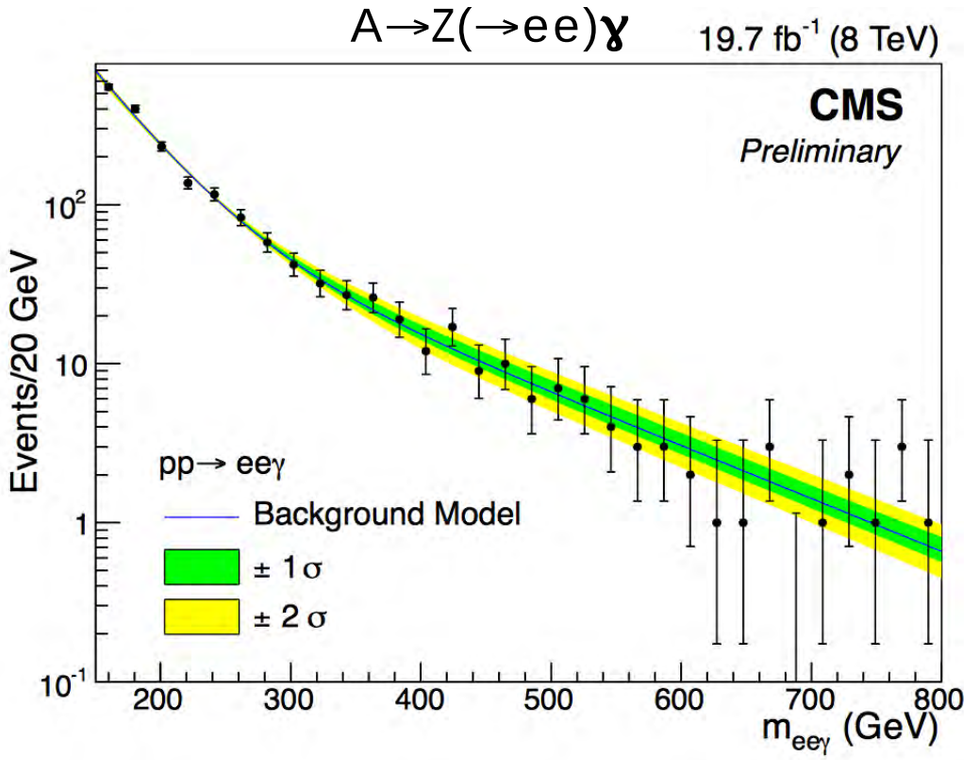

CMS-HIG-14-011 NEW

# A→Zγ

CMS: A→Z(→ll)γ
A→Zγ can be significantly enhanced in some BSM models (e.g. composite Higgs)




CMS-HIG-14-031 NEW

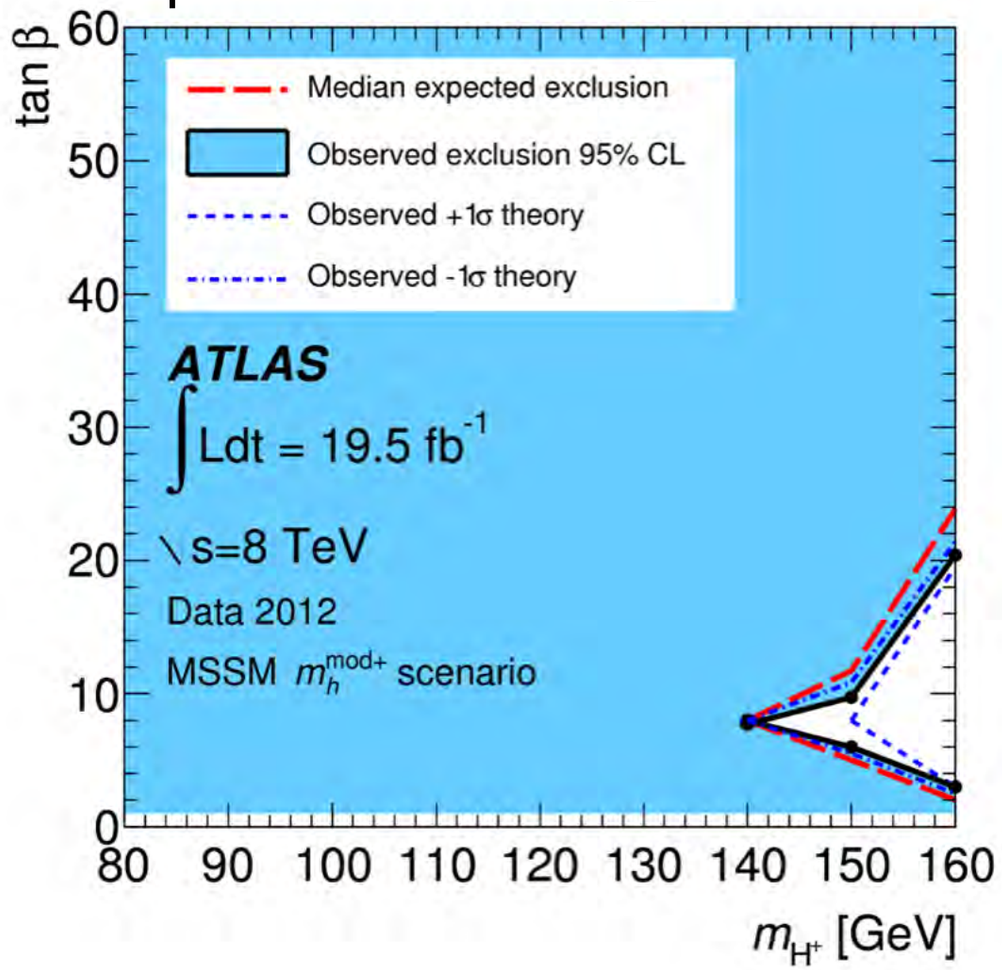
# CHARGED HIGGS: $H^{\pm}\rightarrow\tau^{\pm}\nu$

## $M_{H^{\pm}}<m_{top}$: production in tt decay [$tt\rightarrow HbWb$]

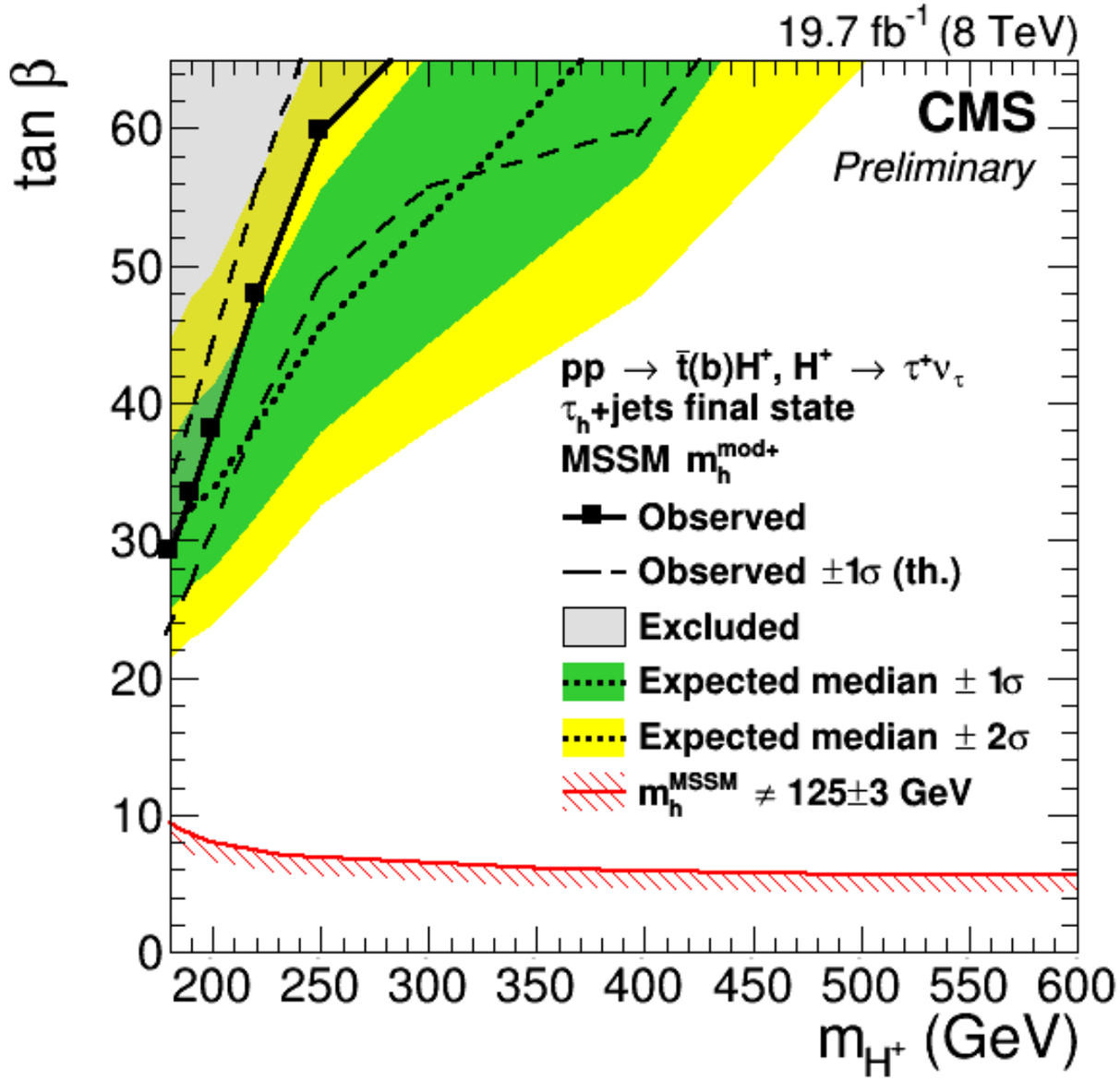
MSSM: BR($H^{\pm}\rightarrow\tau^{\pm}\nu$) ~100%

$\tau$+jets final state: hadronic $\tau$ decay

almost able to exclude full MSSM phase space for $90<m_{H^{\pm}}<160$ GeV




## $M_{H^{\pm}}>m_{top}$: associated production with top [tH(b)]




ATLAS: arXiv: 1412.6663 NEW CMS-HIG-14-020

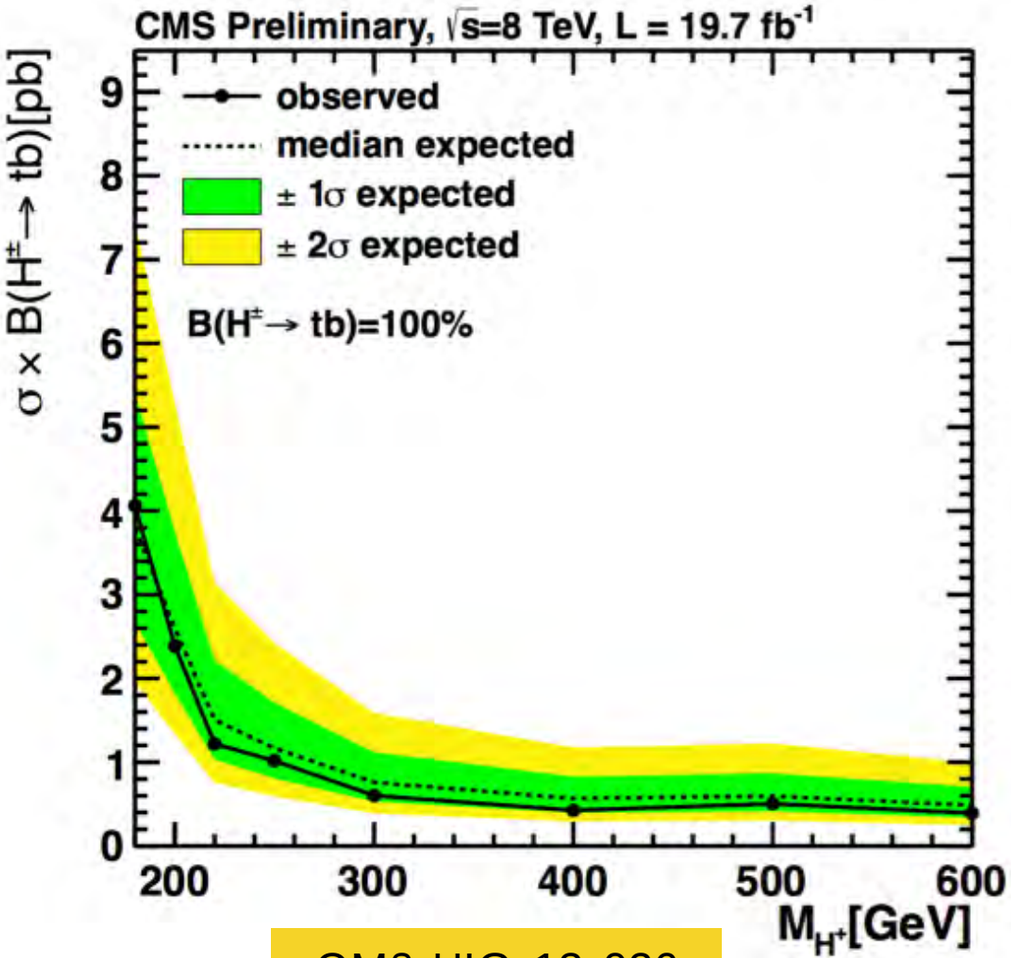
# CHARGED HIGGS

$H^+ \to tb$: important decay for 2HDM @ high $m_{H+}$ mass

di-lepton + b-jets final state

sensitive to both $H^+ \to tb$ & $H^+ \to \tau\nu$

interpretation provided for BR($H^+ \to tb$)=1 or BR($H^+ \to \tau\nu$)=1

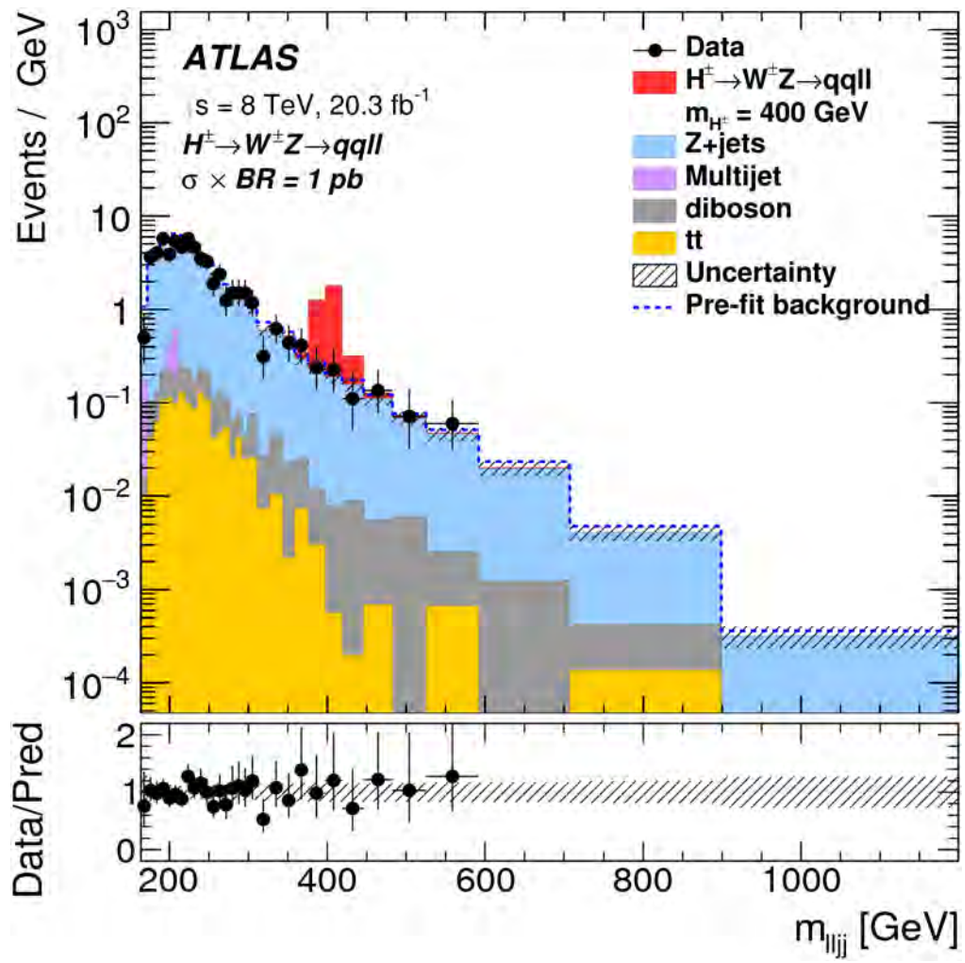



CMS-HIG-13-026

Higgs triplet model: $H^\pm \to W^\pm Z$ allowed at tree level

Search performed with VBF production of charged Higgs

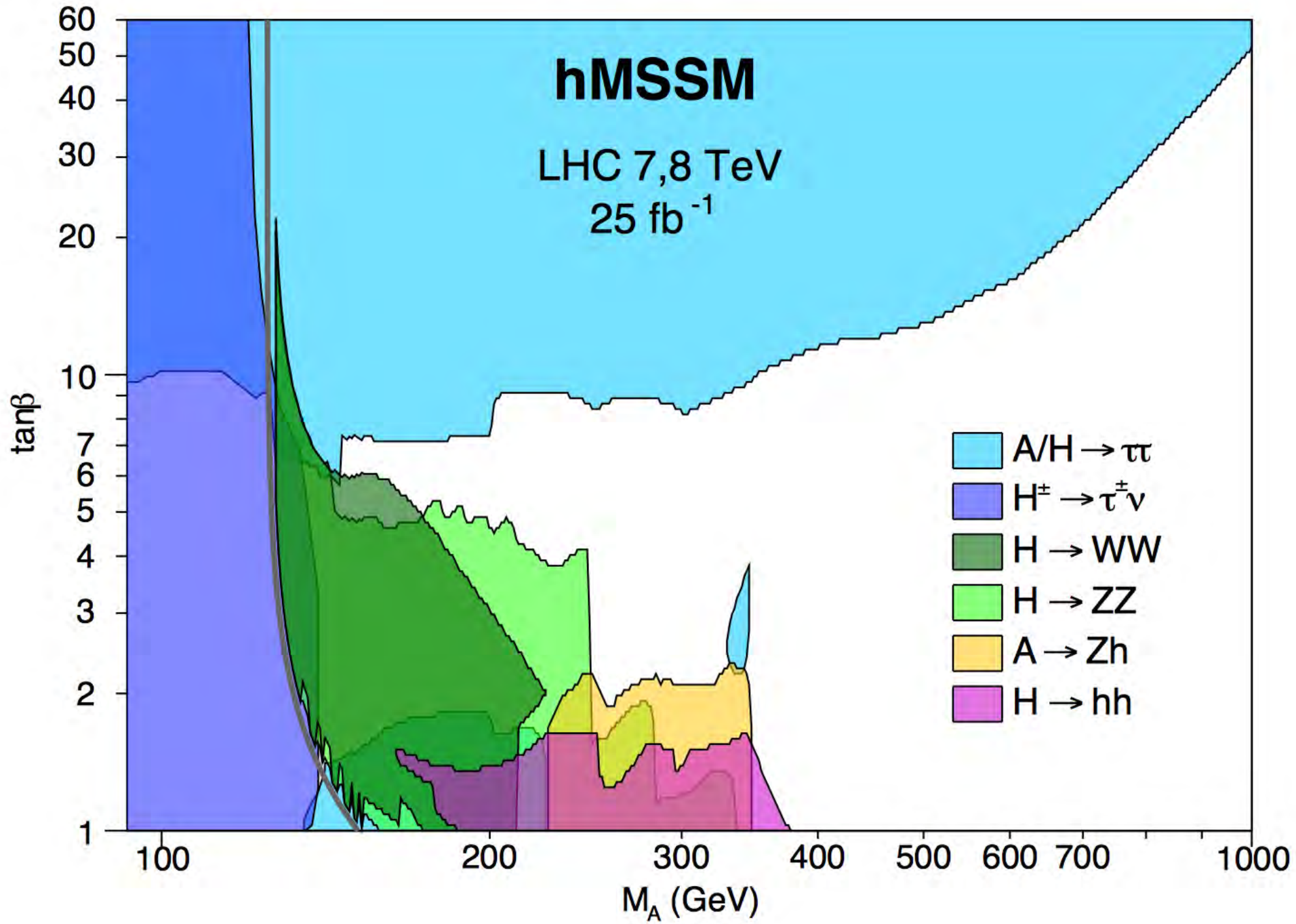
2 jets (VBF topology), 2 central jets (W decay), 2 leptons (Z)




ATLAS-HIGG-2014-13 NEW

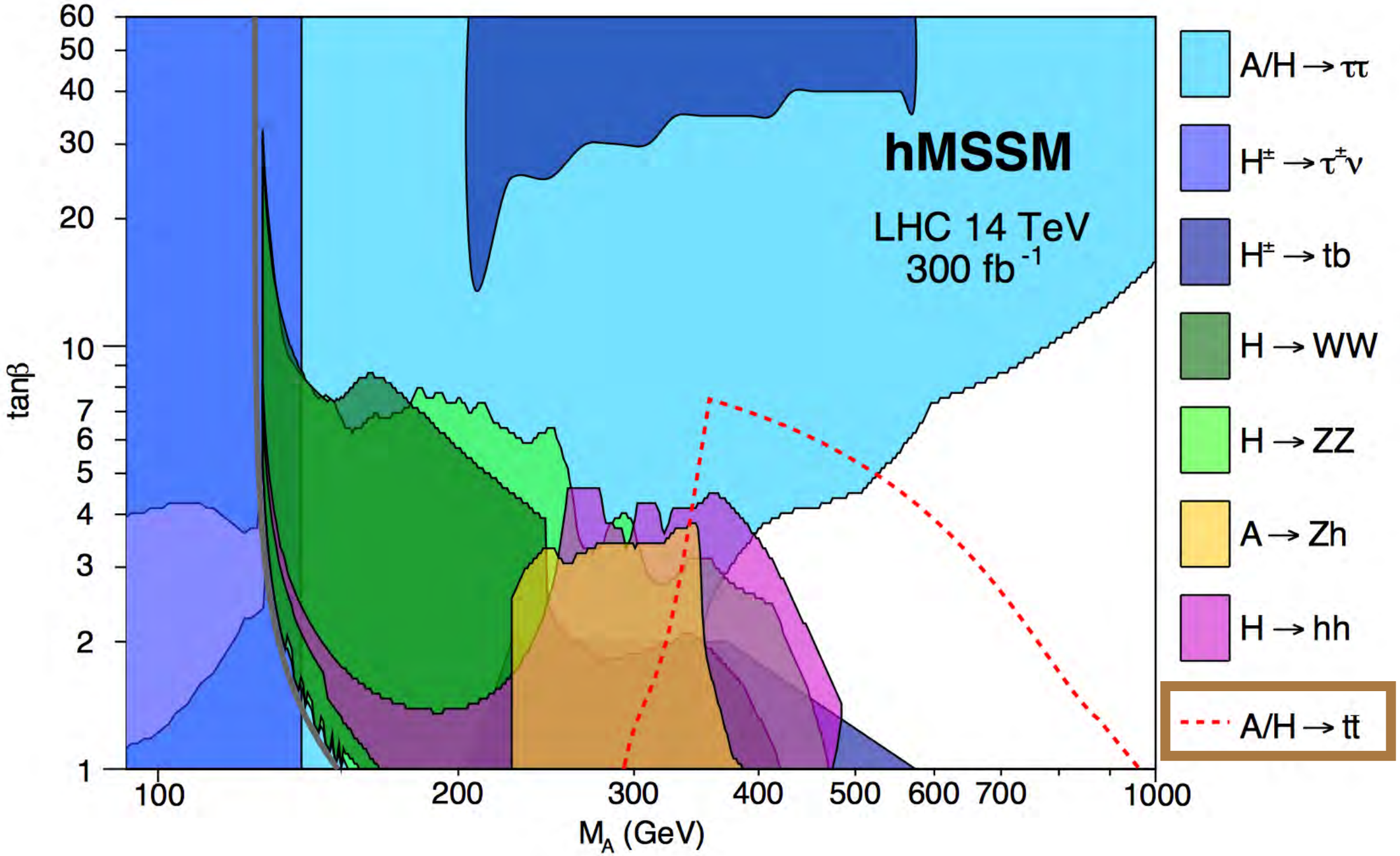
# hMSSM: Run I Summary

A. Djouadi et al: arXiv:1502.05653



# hMSSM @ 300fb$^{-1}$

A. Djouadi et al: arXiv:1502.05653

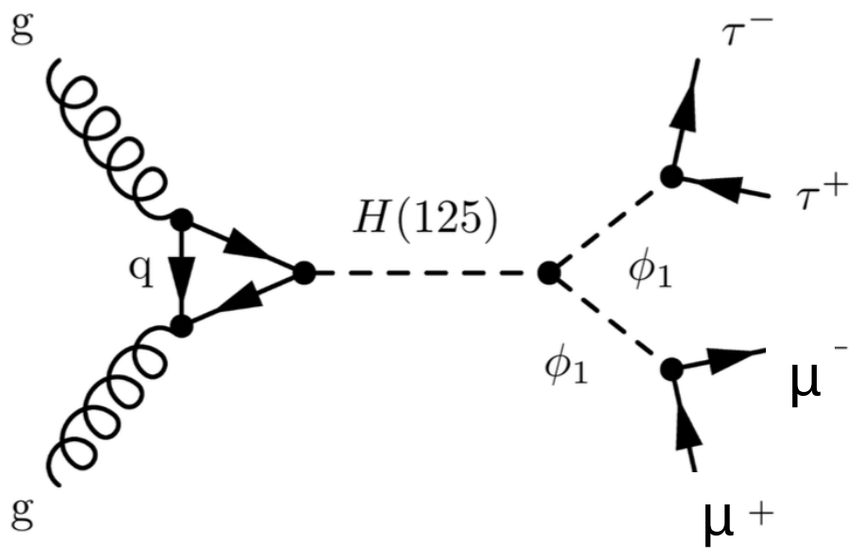


# LIGHT SCALARS: $H \to a_1 a_1 \to 2\mu 2\tau$

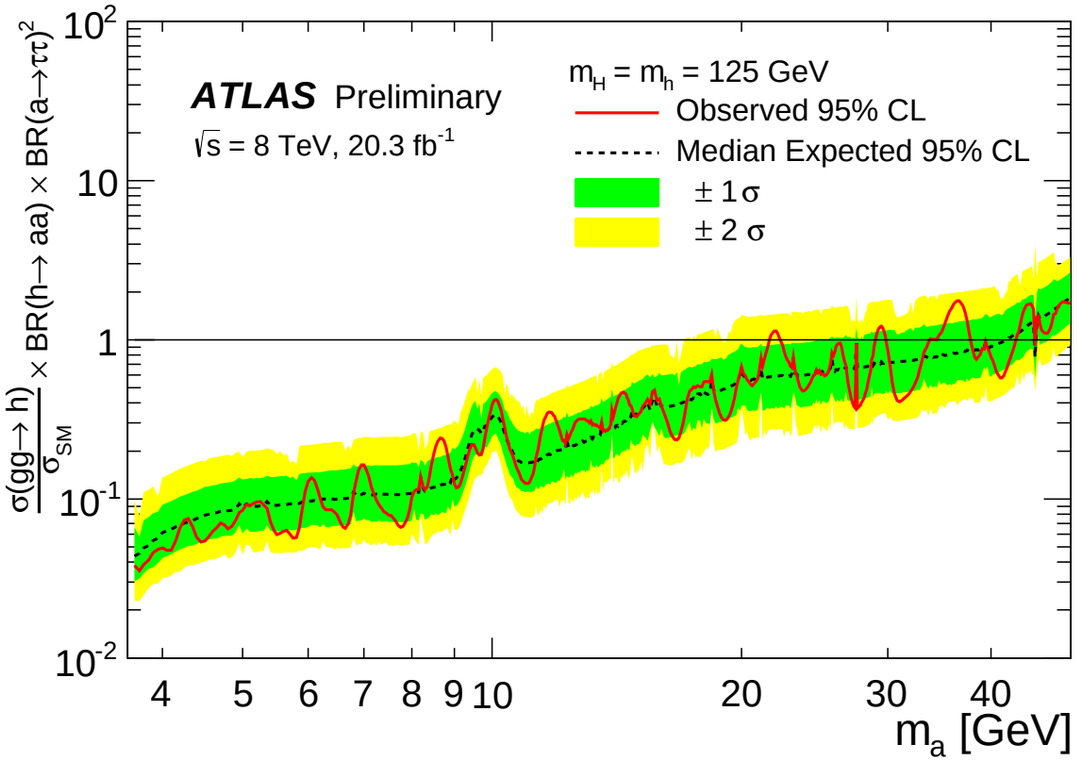
NMSSM CP-odd scalar
assumed to be light

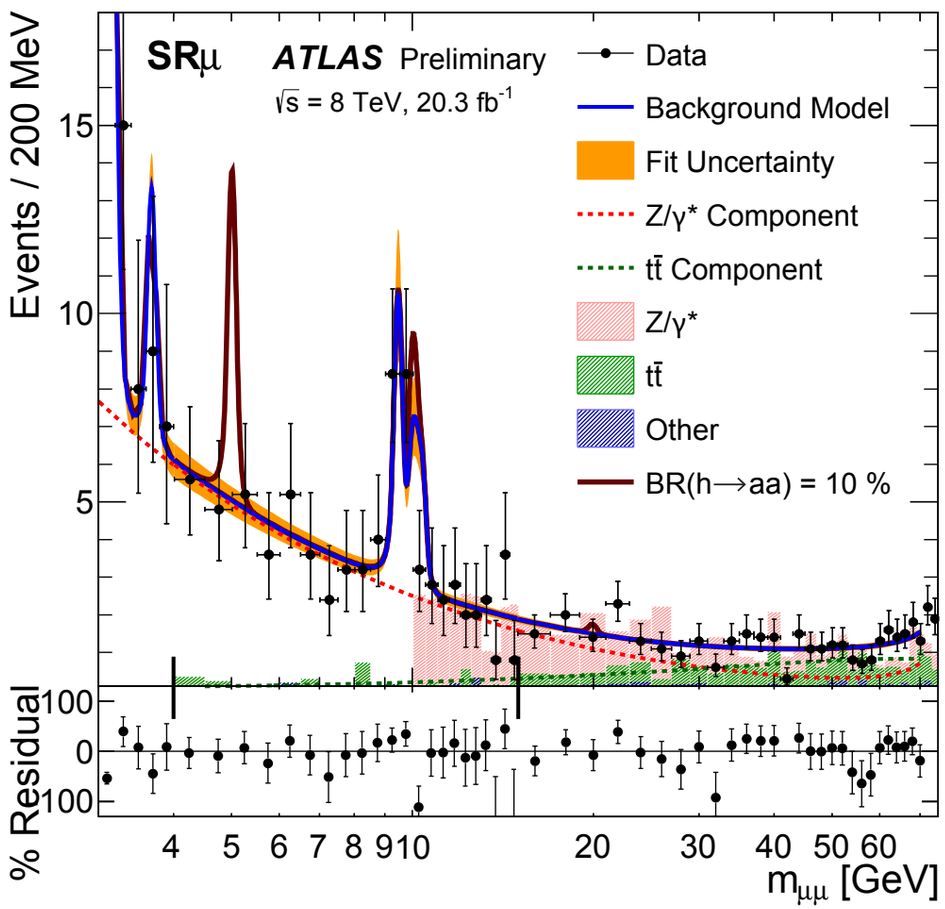
$H \to a_1 a_1 \to 2\mu 2\tau$ offers advantages wrt $4\tau$
despite the smaller BR
use $m_{\mu\mu}$ as final observable

$\tau_{lep}$ decay
Boosted $a_1$ decays: special $\tau_{had}$ ID




search performed in range
$2m_\tau < m_{a1} < 50$ GeV




ATLAS HIGG-2014-02

NEW

# PERSPECTIVES FOR RUN 2

## Run I sensitivity/precision will be reached for H analyses ~10 $fb^{-1}$ @ 13 TeV

Increasing precision on Higgs properties will further constraint BSM models

New scalar searches will benefit from high stat

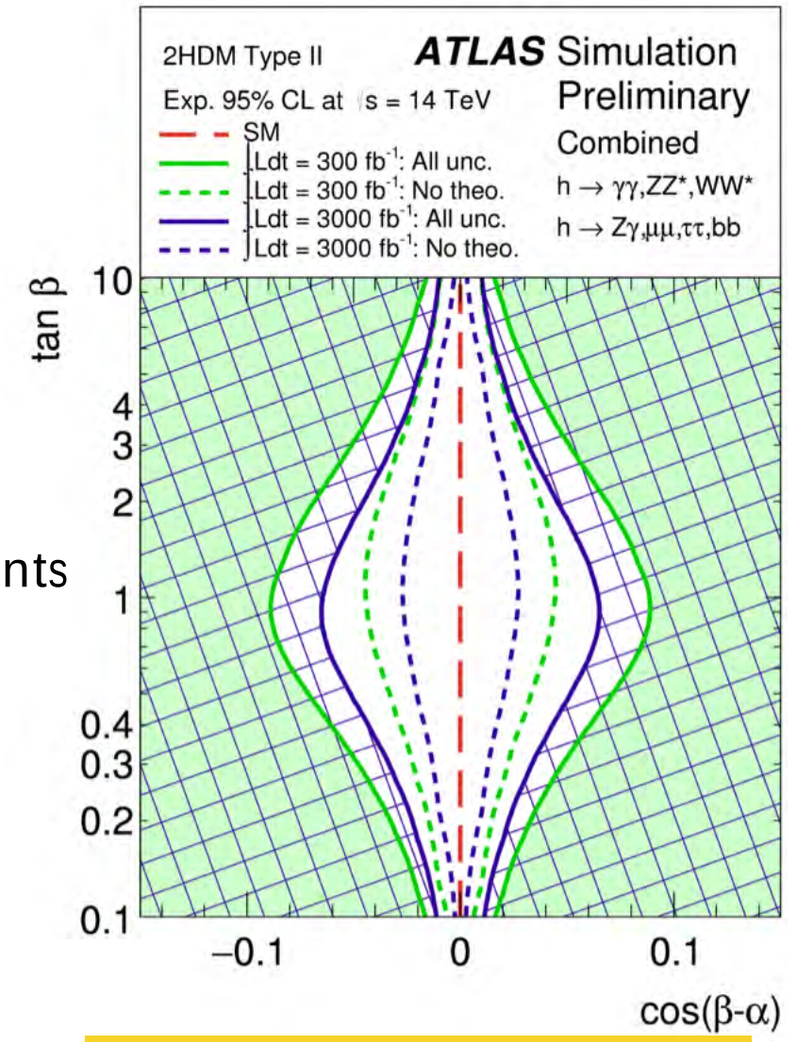
Run 2 + HL-LHC: a unique opportunity to look for Higgs rare production & decay modes

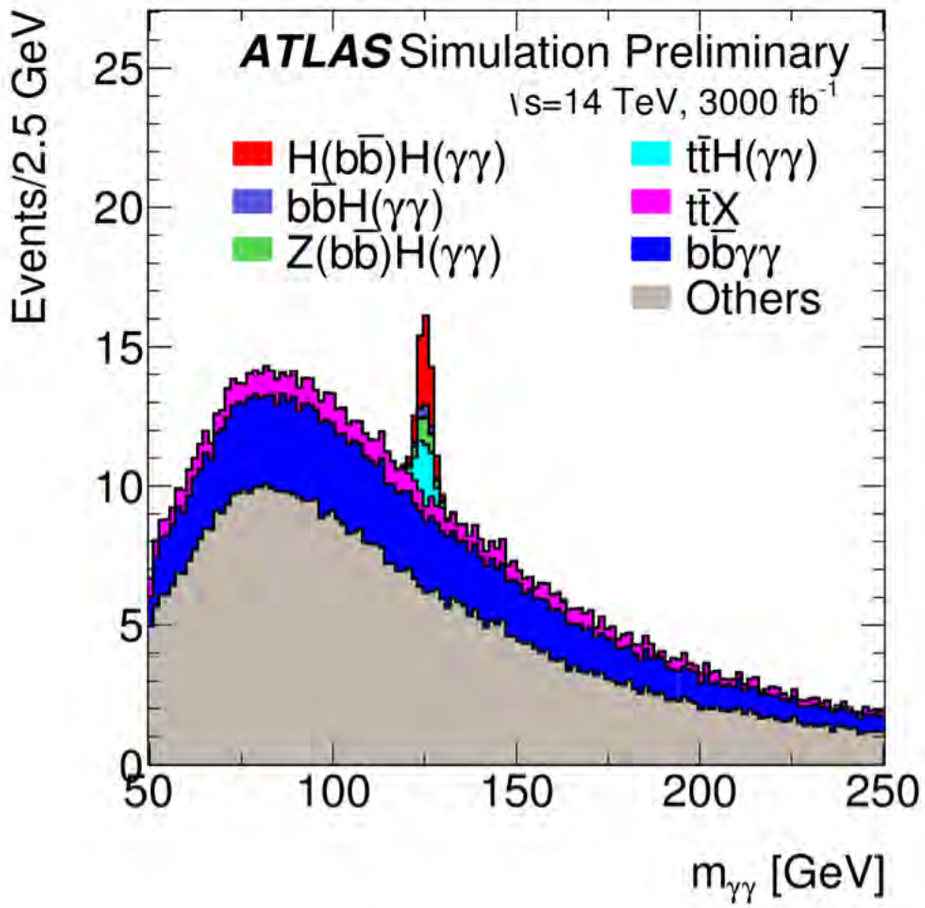
- possibility to reveal anomalous couplings

Run 2:

~10M H produced

~400k H useful for precision measurements




HH @ 3000$fb^{-1}$:

~2$\sigma$ per experiment in $\gamma\gamma$bb



ATLAS-PHYS-PUB-2014-017

ATLAS-PHYS-PUB-2014-019

# CONCLUSIONS

Extensive searches performed in Run I for rare & BSM Higgs decays and production modes

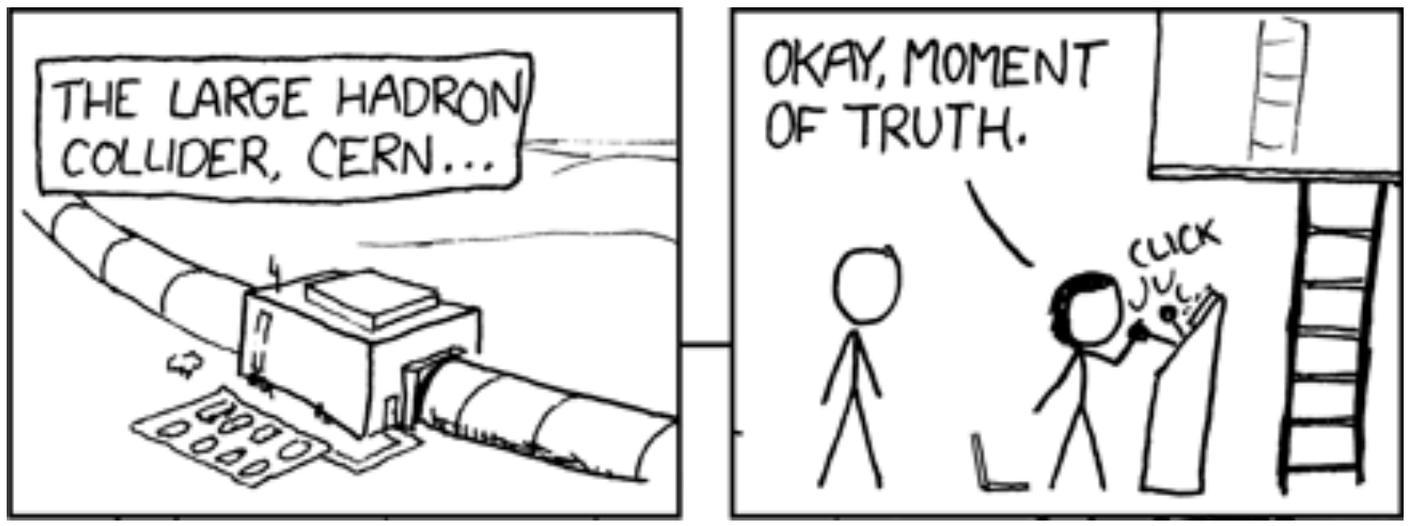
- BR for Higgs un-detected decay modes constrained <30%, several other BSM decay modes significantly constrained

Extended Higgs sector probed in many ways for additional neutral and charged scalar

- large phase space covered, no luck so far…
- new results on Run I data still in the pipeline

Run 2 offers a great potential to further probe BSM Higgs scenarios

- ~10 $fb^{-1}$ @ 13 TeV needed to achieve Run I sensitivity
- then precision studies & search for small signals

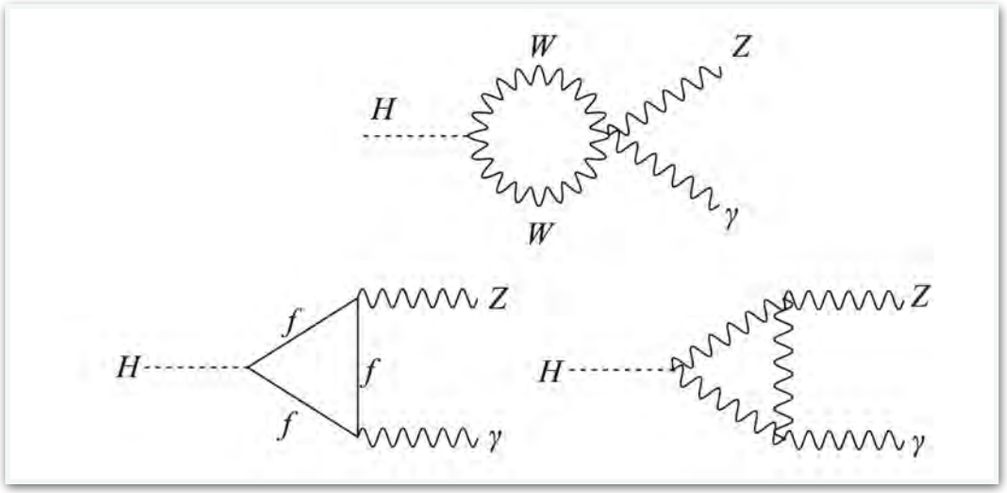



Eagerly awaiting LHC restart!

# BACKUP

# RARE HIGGS DECAYS: H→Zγ & H→γ*γ→μμγ

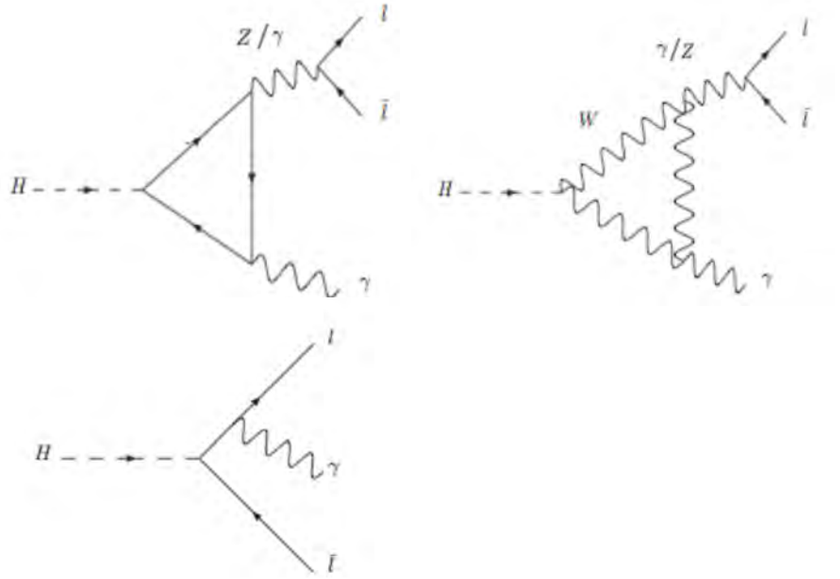
- Search performed in Z(→ee)+γ and Z(→μμ)+γ channel




- Very small BR expected in SM ~0.1%.
  - New particles/couplings (e.g composite higgs) can be revealed in decays involving loop
- For h(125) excluding BR enhancement >~ x10 @ 95% CL

| | |
|---|---|
| ATLAS: arXiv:1402.3051 | >11(9) |
| CMS: Phys. Lett. B 726(2013) 587 | >9.5(10) |

- Dalitz decay
  - different contributions to the same final state, not yet disentangled
  - wrt to Zγ: $m_{\mu\mu}$<20 GeV

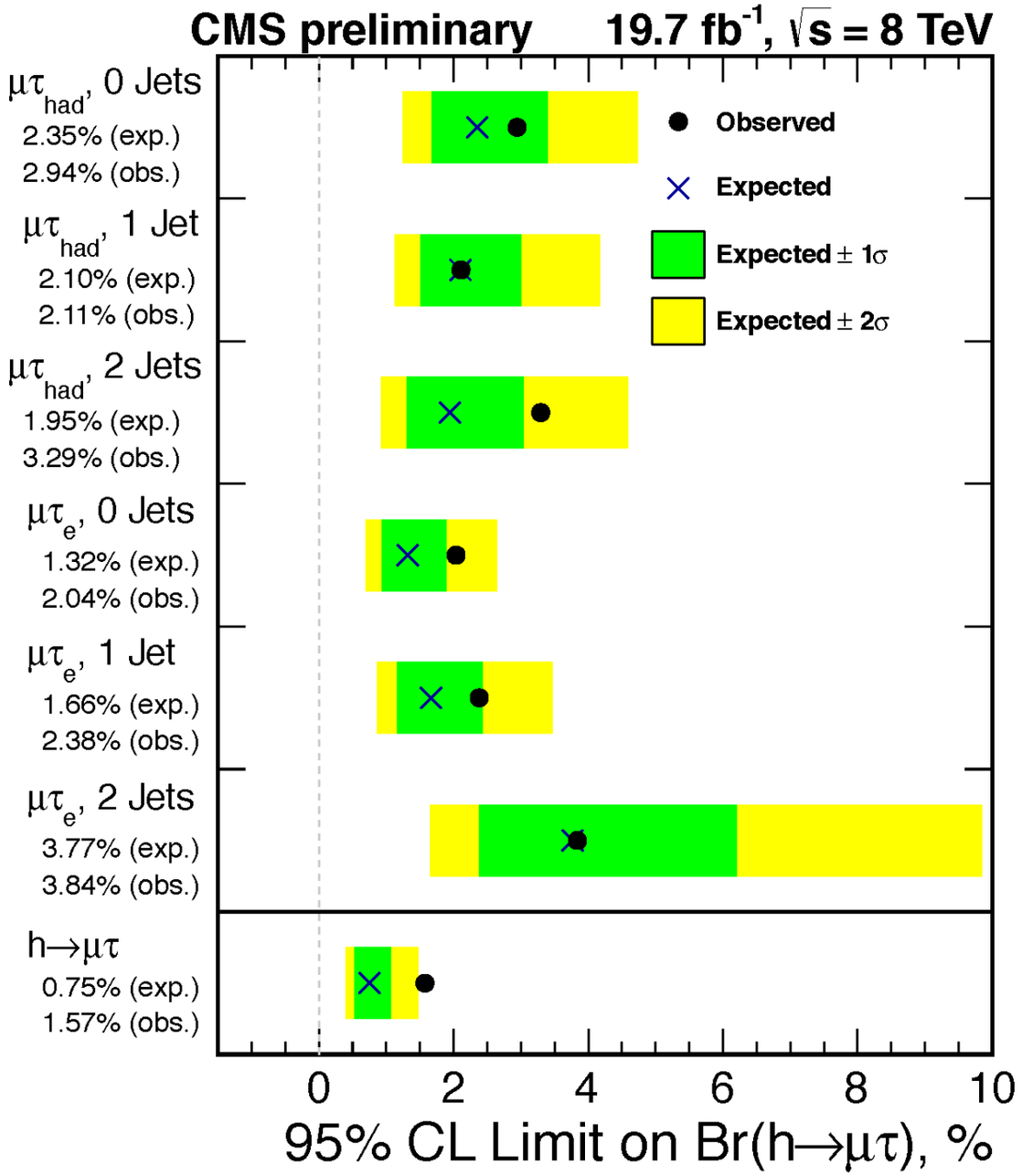


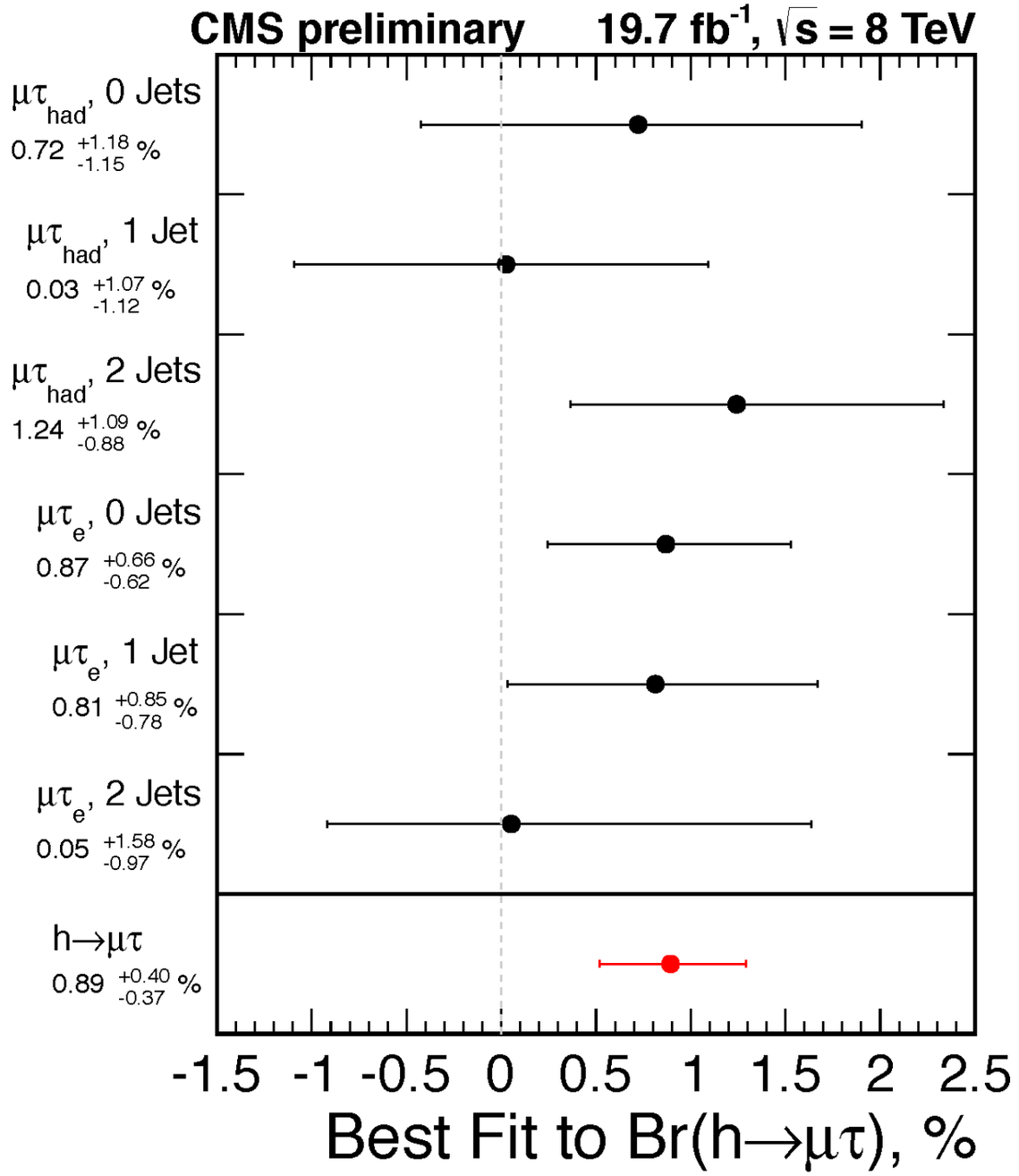

- Sensitivity similar to Zγ: excluding >x11 @ 95% CL

| | |
|---|---|
| CMS HIG-14-003 | >11(7) |

NEW

# CMS LFV: CHANNELS

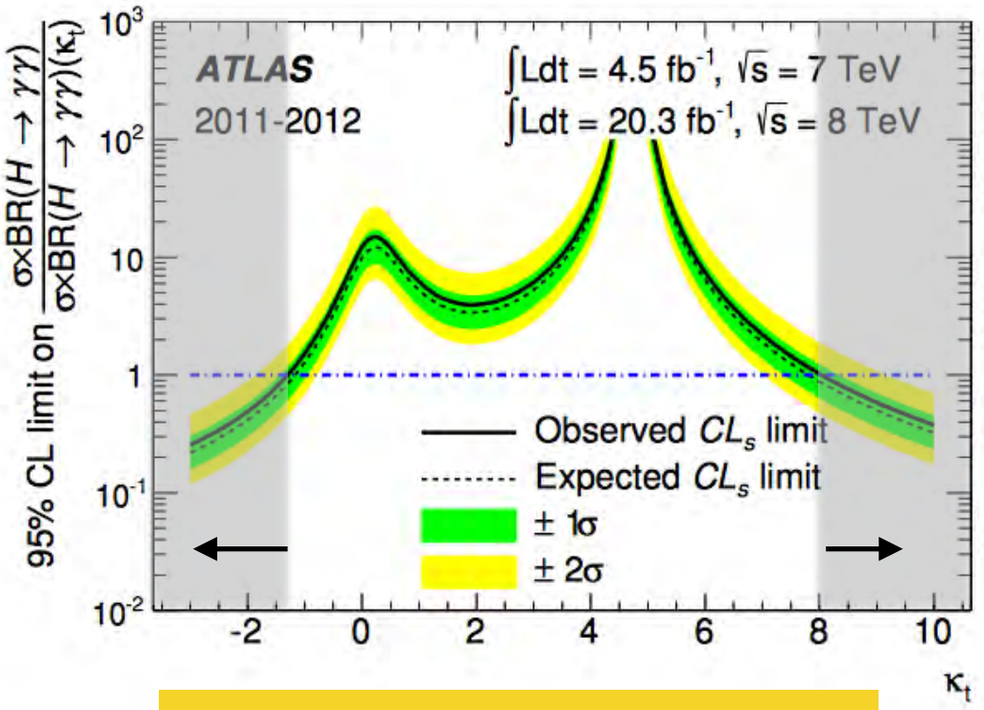


# Yt: ATLAS

Re-interpretation of the ttH(→γγ) search

H→γγ ~ x 2 if relative sign reversed




ATLAS: PLB 740(2015) 222-242

# DOUBLE HIGGS PRODUCTION

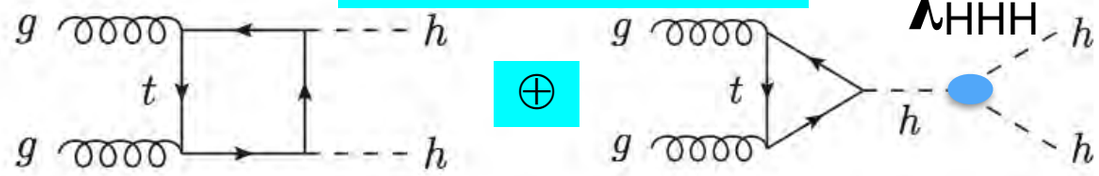
SM non-resonant HH production too small to be probed in Run I

- negative interference between 2 diagrams
- $\sigma_{NNLO}(pp \rightarrow HH)$ @ 8 TeV=9.96 fb

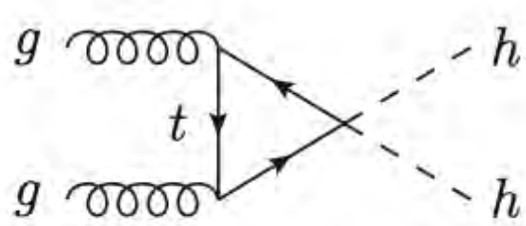
Non-resonant production can be enhanced if new BSM couplings

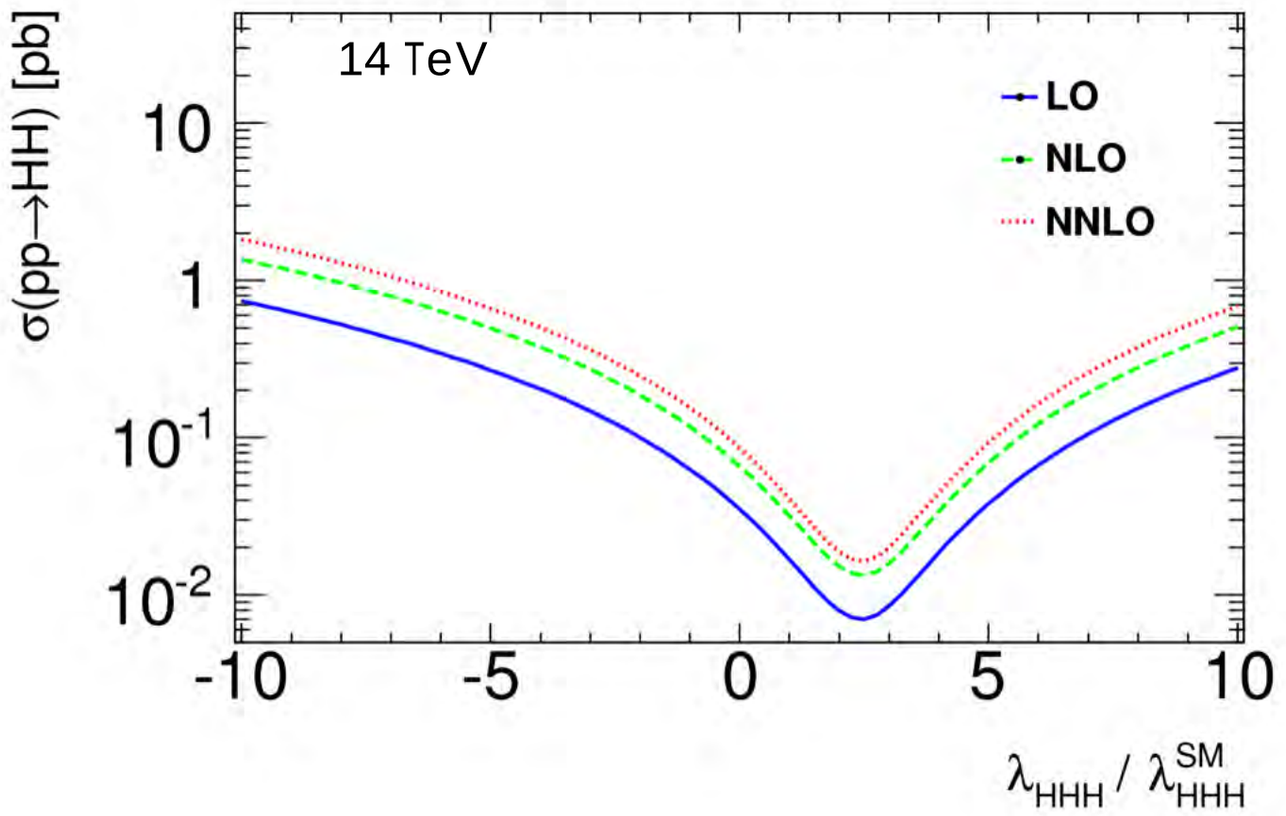
- HH kinematics can be affected too

SM hh production

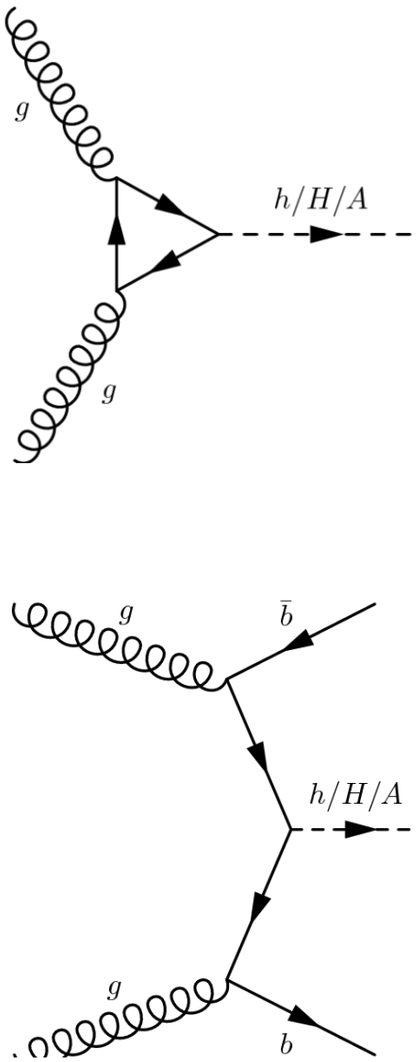


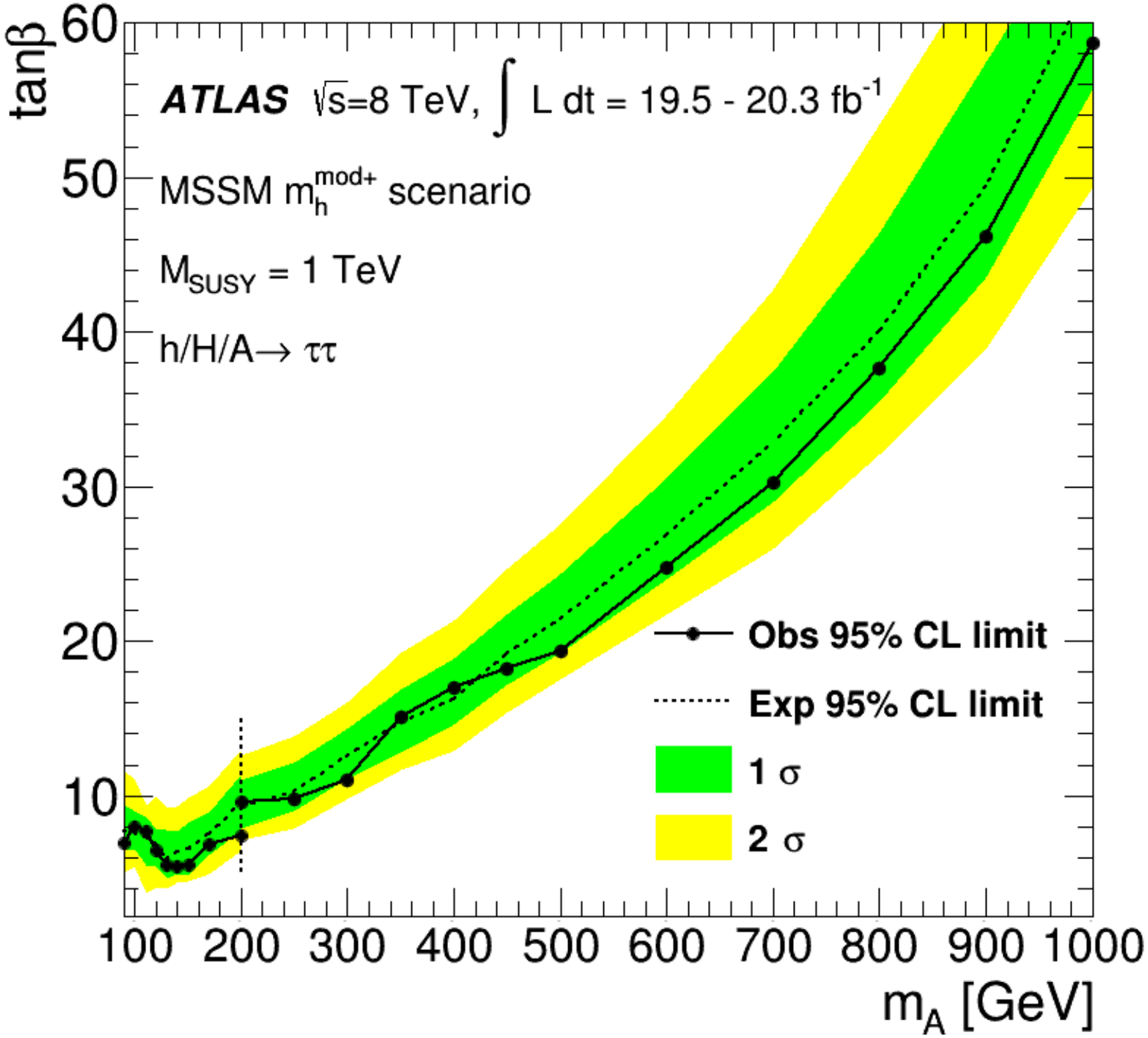

Anomalus BSM hh production



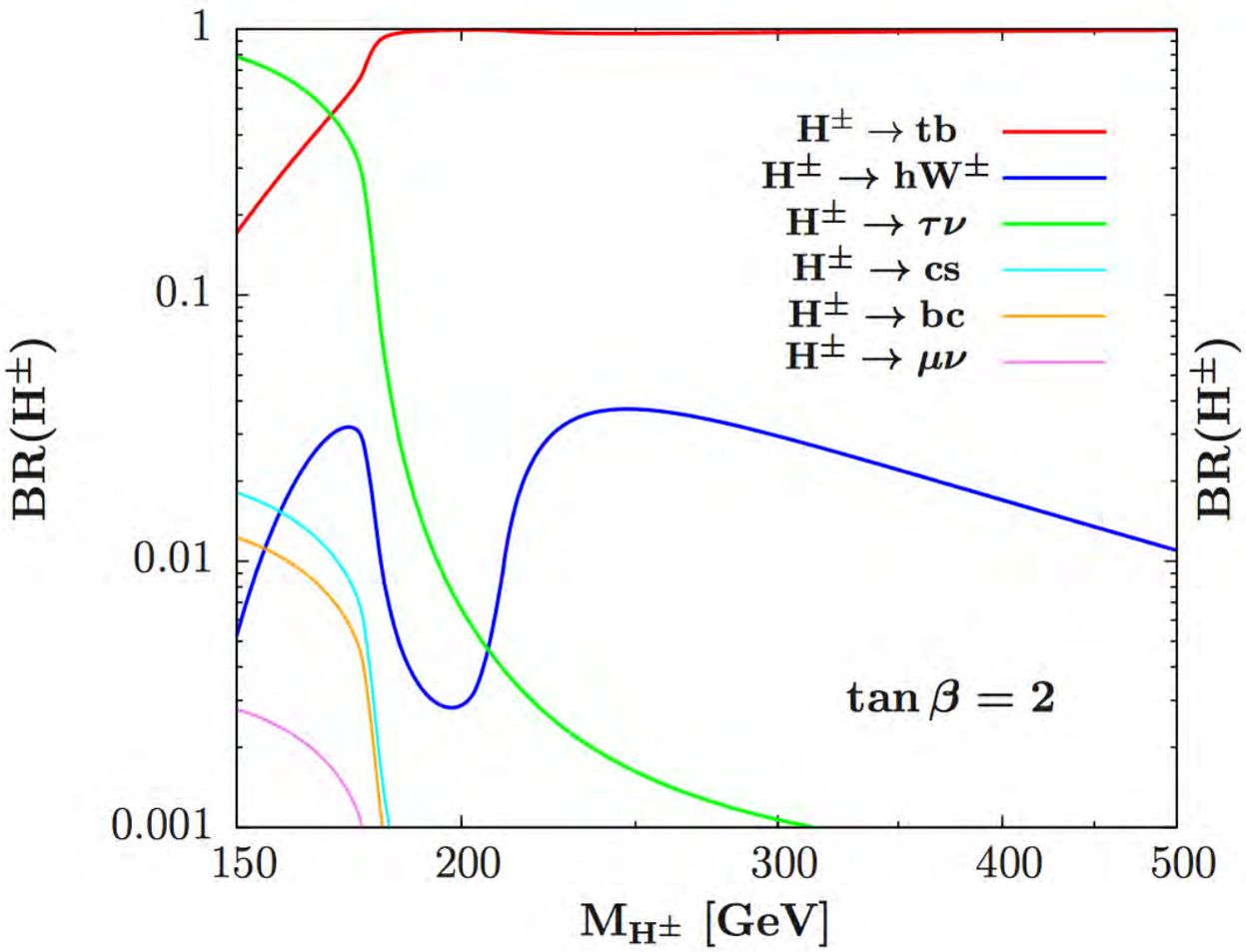



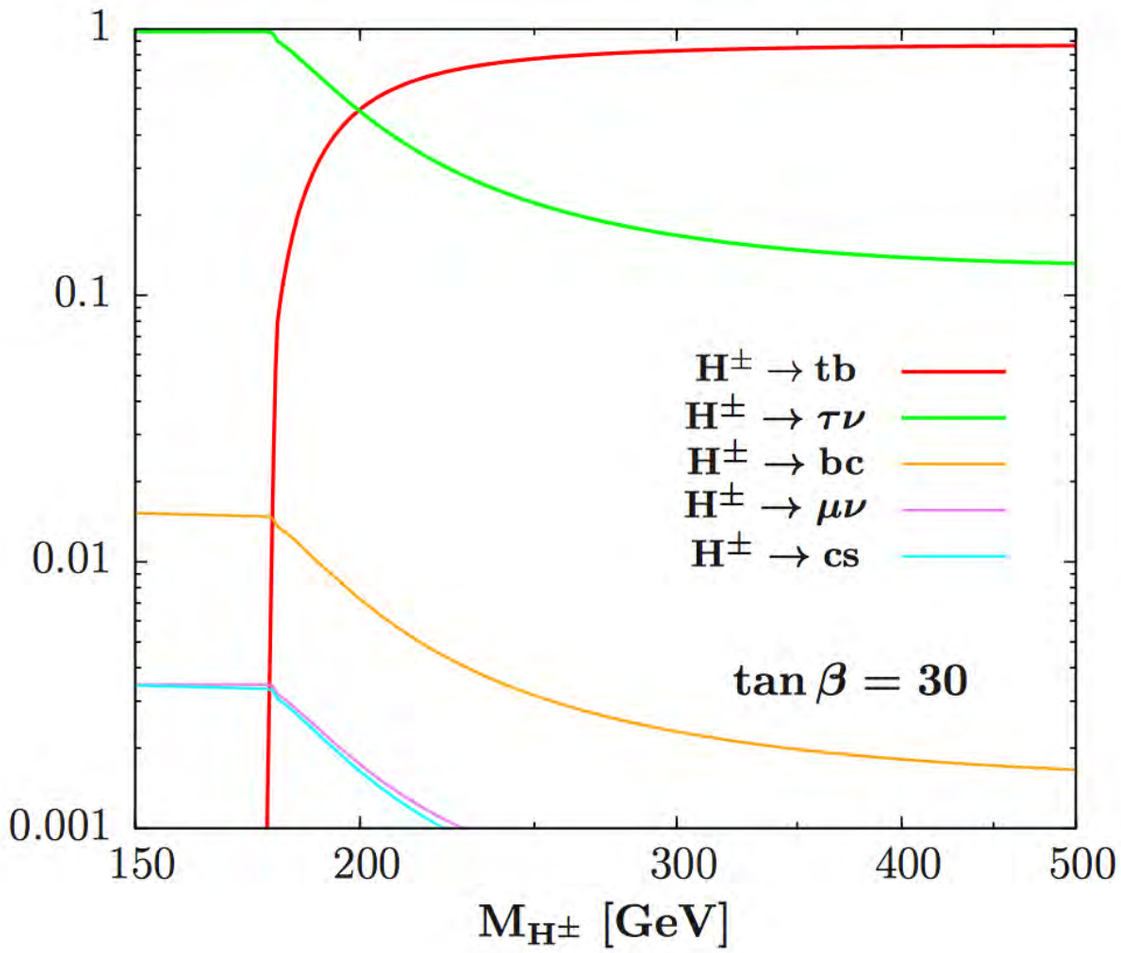
# MSSM: $\phi \to \tau\tau$



# MSSM: Charged Higgs Decay



# hMSSM @ 3000fb$^{-1}$

arXiv: 1502.05653