



BSM Higgs status at the LHC

LHCP 2015

St. Petersburg, Russia, 31.08-05.09.2015

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on behalf of the ATLAS & CMS Collaborations
(Institute of Nuclear Physics P.A.N., Cracow PL)

CERN, 4 July 2012

Ladies and gentlemen,
I think we've got it!

Discovery of a Higgs-like particle
coupling to gauge bosons



Introduction

$$m_W = \frac{1}{2} g_W v \quad m_H = \sqrt{2\lambda} v$$

❖ SM Higgs sector is a single free parameter model.

❖ Fixing the model by measuring the Higgs mass completes the SM scenario.

❖ The model predicts couplings to all SM particles ($\sim m$ for fermions, $\sim m^2$ for bosons)

❖ Everything else is testing for **BSM** !

ATLAS & CMS combined mass:
PRL 114, 191803 (2015)

The big picture

dedicated talks:
 Marco Pieri,
 Kerstin Tackmann,
 Manuela Venturi,
 Wouter Verkerke

ATLAS & CMS combined couplings:
ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002

ATLAS J^{CP} : **arXiv:1506.05669**
 CMS J^{CP} : **Phys. Rev. D 92, 012004**

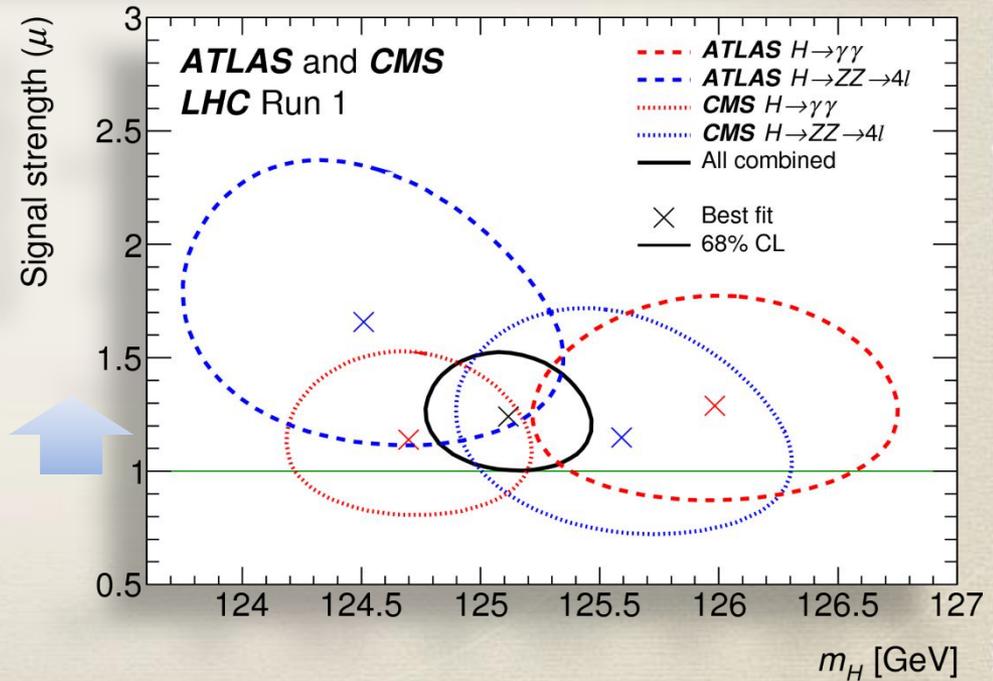
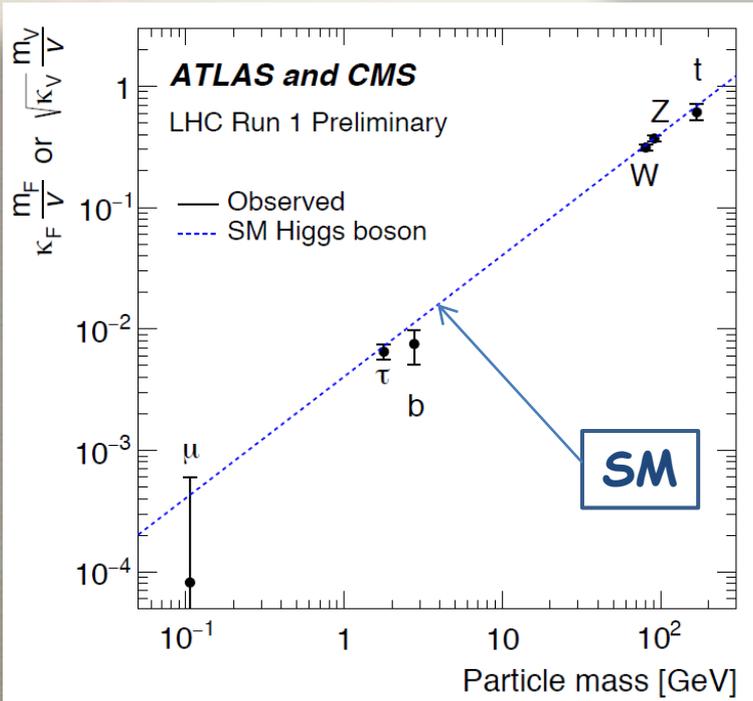
ATLAS $d\sigma/dx$: **arXiv:1508.02507**
 CMS $d\sigma/dx$: **CMS-PAS-HIG-14-028**

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)} \text{ }^{+0.04}_{-0.04} \text{ (expt)} \text{ }^{+0.03}_{-0.03} \text{ (thbgd)} \text{ }^{+0.07}_{-0.06} \text{ (thsig)}$$

top from ggH production x-section



So far the Higgs...
looks like SM,
sounds like SM,
smells like SM.



T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

But:

CONSISTENT with SM \neq INCOMPATIBLE with BSM

❖ Essential questions:

- Is the 125 GeV Higgs the only one (extended sector)?
- Is it responsible for all the particle mass?
- Is it fundamental?

❖ Need to define models of interest. Most popular are additional EW singlet, 2HDM, NMSSM, composite Higgs, etc.

❖ All allow for SM-like light Higgs phenomenology with smaller or larger coupling modifications.

❖ Most predict additional (heavier) states in the scalar sector.

ROADMAP

Explore the 125 GeV Higgs

- ❖ Production rates (ggH, WH, ZH, VBF, ttH, HH, tH, bbH)
- ❖ Decay widths ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, $\mu\mu$, $Z\gamma$, etc.)
- ❖ Couplings to SM particles
- ❖ Spin and parity
- ❖ LFV, $H \rightarrow \alpha\alpha$, $H \rightarrow \text{inv}$, $\gamma + \cancel{E}$, etc.
- ❖ Are these consistent with SM?

Explicit search for BSM objects

- ❖ Heavy neutral CP-even and CP-odd states ($\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, HH, HZ, tt)
- ❖ Heavy charged Higgs ($\tau\nu$, tb, WZ, cs, etc.)
- ❖ Any deviations from SM backgrounds?

How much of the BSM scenarios can current data exclude?

Note: heavily model dependent!

Explore the 125 GeV Higgs

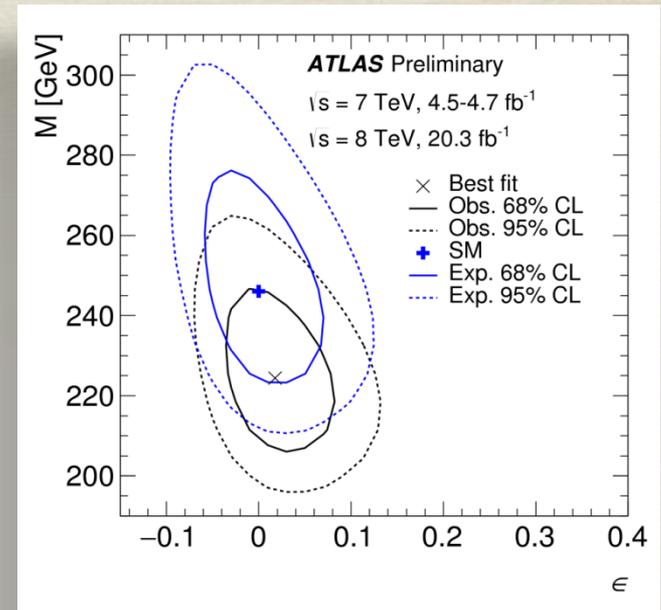
Mass scaling of Higgs Boson Couplings

- ❖ Same production & decay modes as in the SM
- ❖ Test the coupling strength and mass dependence at the same time.
- ❖ Fairly model independent approach.

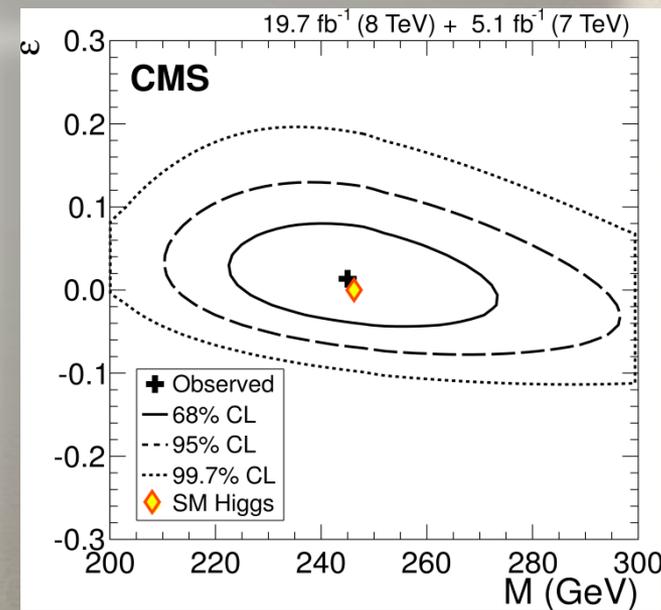
$$K_{f,i} = v \frac{m_{f,i}^\epsilon}{M^{1+\epsilon}}$$

$$K_{V,j} = v \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}},$$

- M is the „vev parameter“ (where $v = 246 \text{ GeV}$)
- ϵ is the „mass scaling parameter“
- **SM:** $\epsilon=0, M=v \Rightarrow K_f = K_V = 1$



ATLAS: arXiv:1509.00672



CMS: arXiv:1412.8662

Additional Electroweak Singlet

NEW

- ❖ The simplest extension to the SM Higgs sector involving the addition of one scalar EW singlet field to the doublet Higgs field of the SM, both of which acquire non-zero vacuum expectation values.
- ❖ Mixing between the singlet state and the surviving state of the doublet field results in two CP-even Higgs bosons, where h (H) is the lighter (heavier) of the pair.

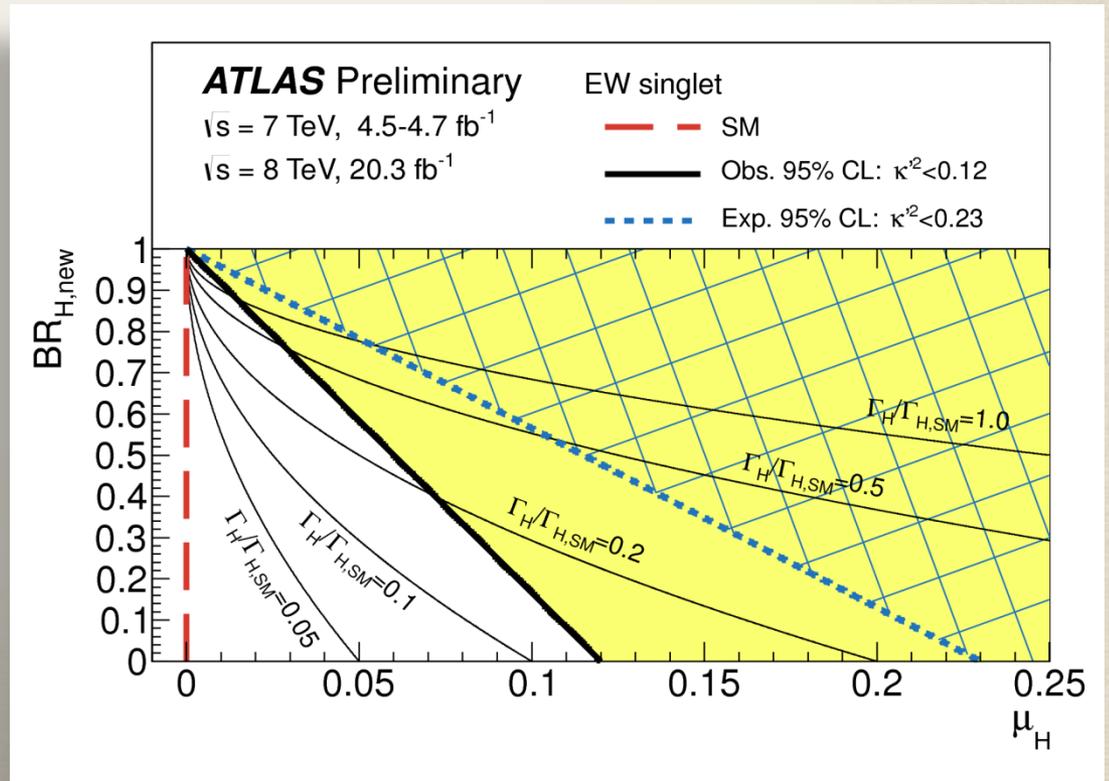
$$\kappa^2 + \kappa'^2 = 1$$

$$\sigma_h = \kappa^2 \times \sigma_{h,SM}$$

$$\mu_H = \kappa'^2 (1 - BR_{H,new})$$

$\kappa'^2 < 0.12$ @ 95 CL
Exp: 0.23

ATLAS:
[arXiv:1509.00672](https://arxiv.org/abs/1509.00672)



ATLAS:

arXiv:1509.00672

2HDM Models



❖ Generic class implementing a second Higgs doublet.

Type I: One doublet couples to vector bosons, the other couples to fermions.

Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „MSSM-like”

Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II.

Flipped: couplings to quarks as in the Type II model and to leptons as in Type I.

$$\tan \beta \equiv v_2/v_1$$

$$v_1^2 + v_2^2 = \bar{v}^2 \approx (246 \text{ GeV})^2$$

$$g_{hVV}^{2\text{HDM}} / g_{hVV}^{\text{SM}} = \sin(\beta - \alpha)$$

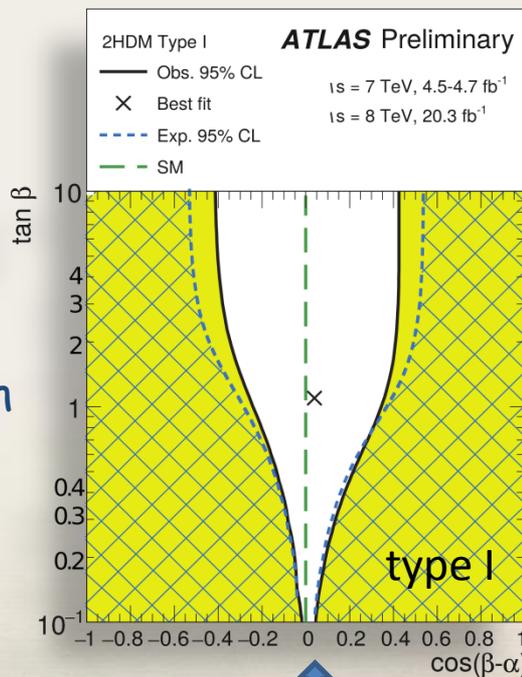
$$g_{HVV}^{2\text{HDM}} / g_{HVV}^{\text{SM}} = \cos(\beta - \alpha)$$

❖ „Decoupling”: A, H^0, H^\pm much heavier than the light h .

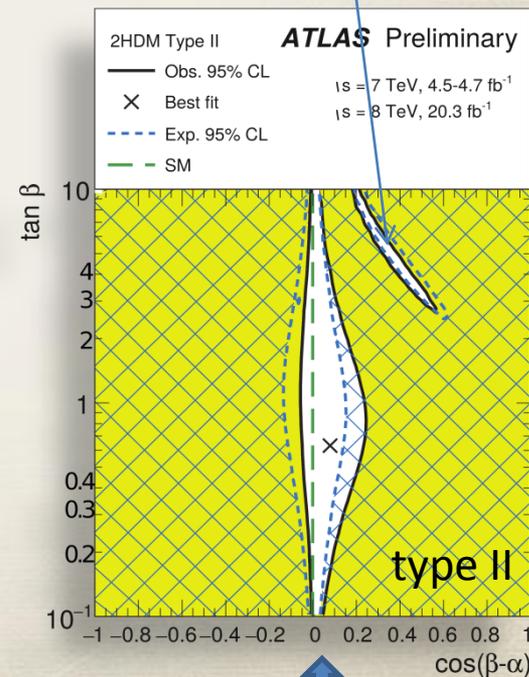
❖ Decoupling is not necessary.

$\cos(\beta - \alpha) \rightarrow 0$ recovers properties of the SM Higgs,

„Alignment”



Inverted coupling to down-type fermions (τ, b)



Simplified hMSSM

ATLAS:
arXiv:1509.00672

- ❖ The dominant top and stop radiative corrections to h mass are used to infer effective couplings to h of the mass **125 GeV** in the hMSSM model.
- ❖ The couplings depend exclusively on the m_A and $\tan(\beta)$ parameters and follow from the diagonalization of the light and heavy CP-even Higgs mass matrix:

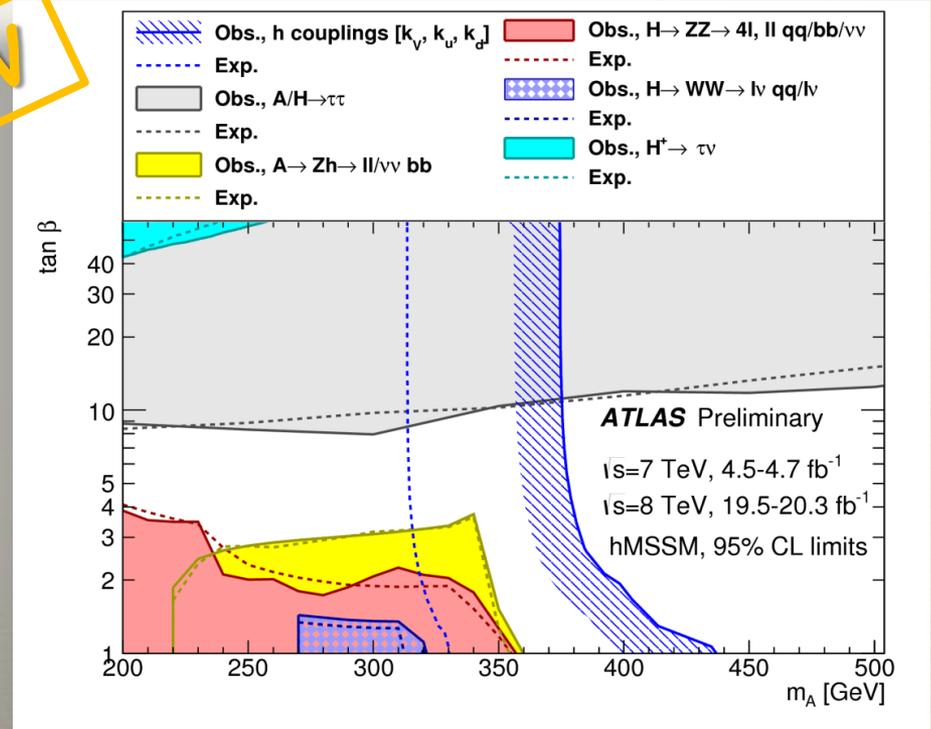
$$\kappa_V = \frac{s_d(m_A, \tan\beta) + \tan\beta s_u(m_A, \tan\beta)}{\sqrt{1 + \tan^2\beta}}$$

$$\kappa_u = s_u(m_A, \tan\beta) \frac{\sqrt{1 + \tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A, \tan\beta) \sqrt{1 + \tan^2\beta} \quad ,$$

NEW

- ❖ Results overlaid with various exclusions from direct searches.
 - ❖ Able to constrain uniformly in wide range of $\tan(\beta)$.
- $m_A > 370$ GeV obs. (310 GeV exp.)



Composite Higgs

theory talk:
Cedric Delaunay

❖ Minimal Composite Higgs Models (MCHM) represent a possible explanation for the scalar naturalness problem, wherein the Higgs boson is a composite, pseudo-Nambu-Goldstone boson rather than an elementary particle.

❖ Two variants explored:

1) MCHM4

$$K = K_V = K_F = \sqrt{1 - \xi}$$

2) MCHM5

$$K_V = \sqrt{1 - \xi}$$

$$K_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

with

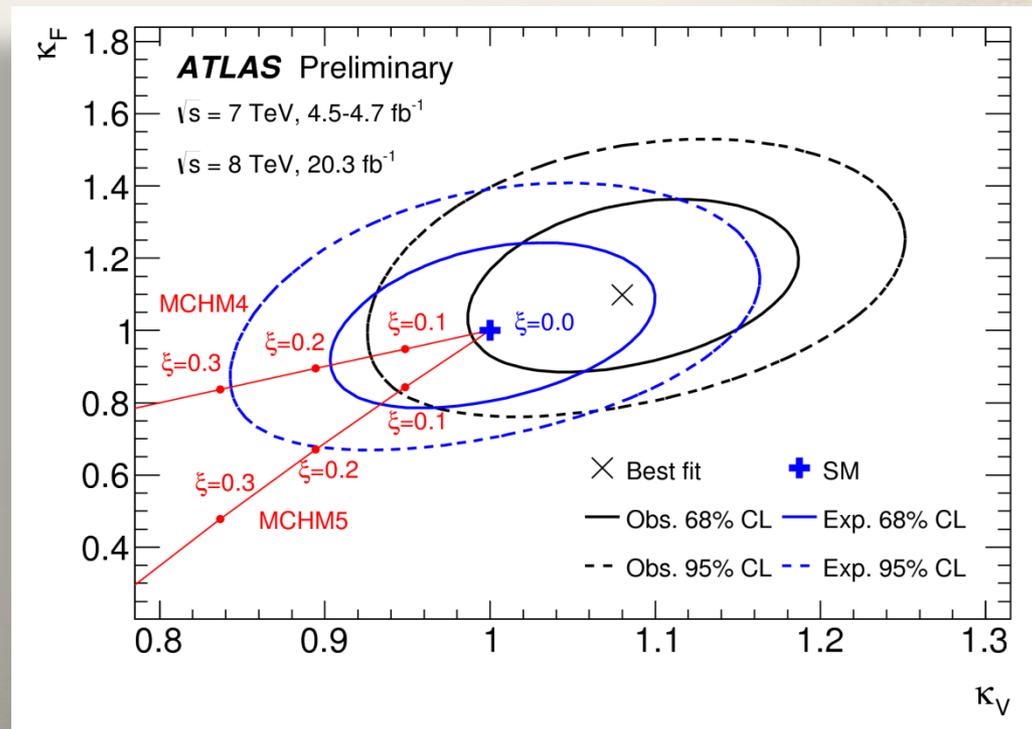
$$\xi = v^2 / f^2$$

❖ SM corresponds to $f \rightarrow \infty$

ATLAS:

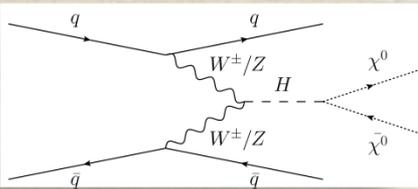
arXiv:1509.00672

NEW



Invisible Higgs Decays

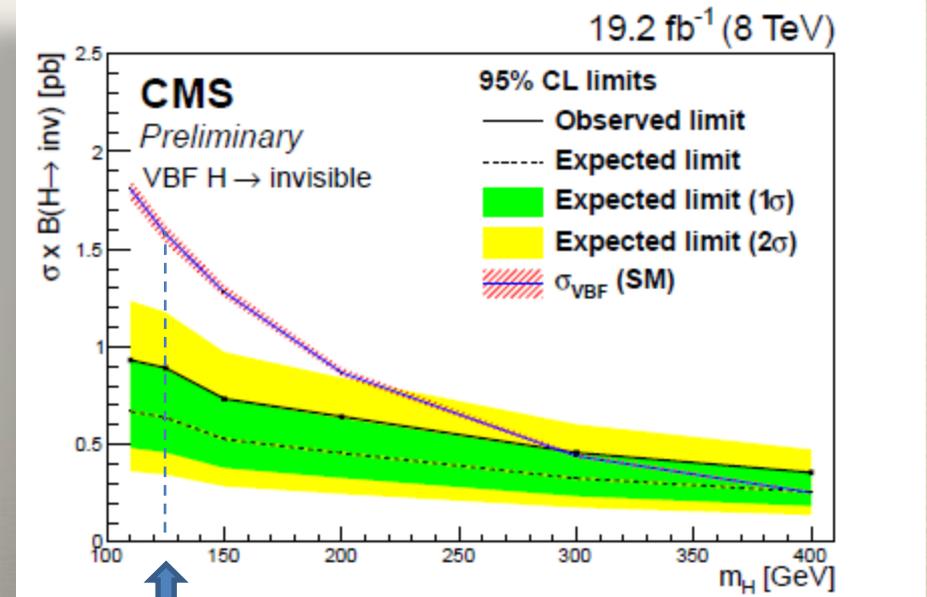
dedicated talk:
Andrew White



- 1) VBF Higgs production with Higgs decaying invisibly. Signature: Two jets with a large pseudorapidity gap and a large invariant dijet mass, together with large E_{miss}^T . [CMS: [CMS-PAS-HIG-14-038](#), ATLAS: [arXiv:1508.07869](#)]
- 2) ZH associated production, with $Z \rightarrow ll$ and $Z \rightarrow bb$ with $H \rightarrow inv$. Signature: OSSF leptons (electrons or muons) forming a Z with large E_{miss}^T . [CMS: [Eur.Phys.J. C74 \(2014\)](#), ATLAS: [Eur.Phys.J. C74 \(2014\)](#)]
- 3) VH (W or Z), where $V \rightarrow jj$ and $H \rightarrow inv$. Signature: m_{jj} consistent with the V mass, together with large E_{miss}^T . [ATLAS: [Eur. Phys. J. C \(2015\) 75:337](#)].

@ 125 GeV:

- ❑ **CMS:** The direct limit from VBF: $BR_{inv} < 0.5$ @ 95 CL (0.40 exp.)
- ❑ When combined with ZH analysis: $BR_{inv} < 0.47$ @ 95 CL (0.35 exp.)
- ❑ **ATLAS:** The combined direct limit: $BR_{inv} < 0.25$ @ 95 CL (0.27 exp.)
- ❑ When combined with the visible modes ($\gamma\gamma, ZZ^*, WW^*, Z\gamma, \tau\tau, \mu\mu, bb$): $BR_{inv} < 0.23$ @ 95 CL (0.24 exp.)



dedicated talks:
 Mariangela Lisanti
 Andrew White

Higgs Portal to DM

NEW

CMS: [Eur.Phys.J. C74 \(2014\)](#)

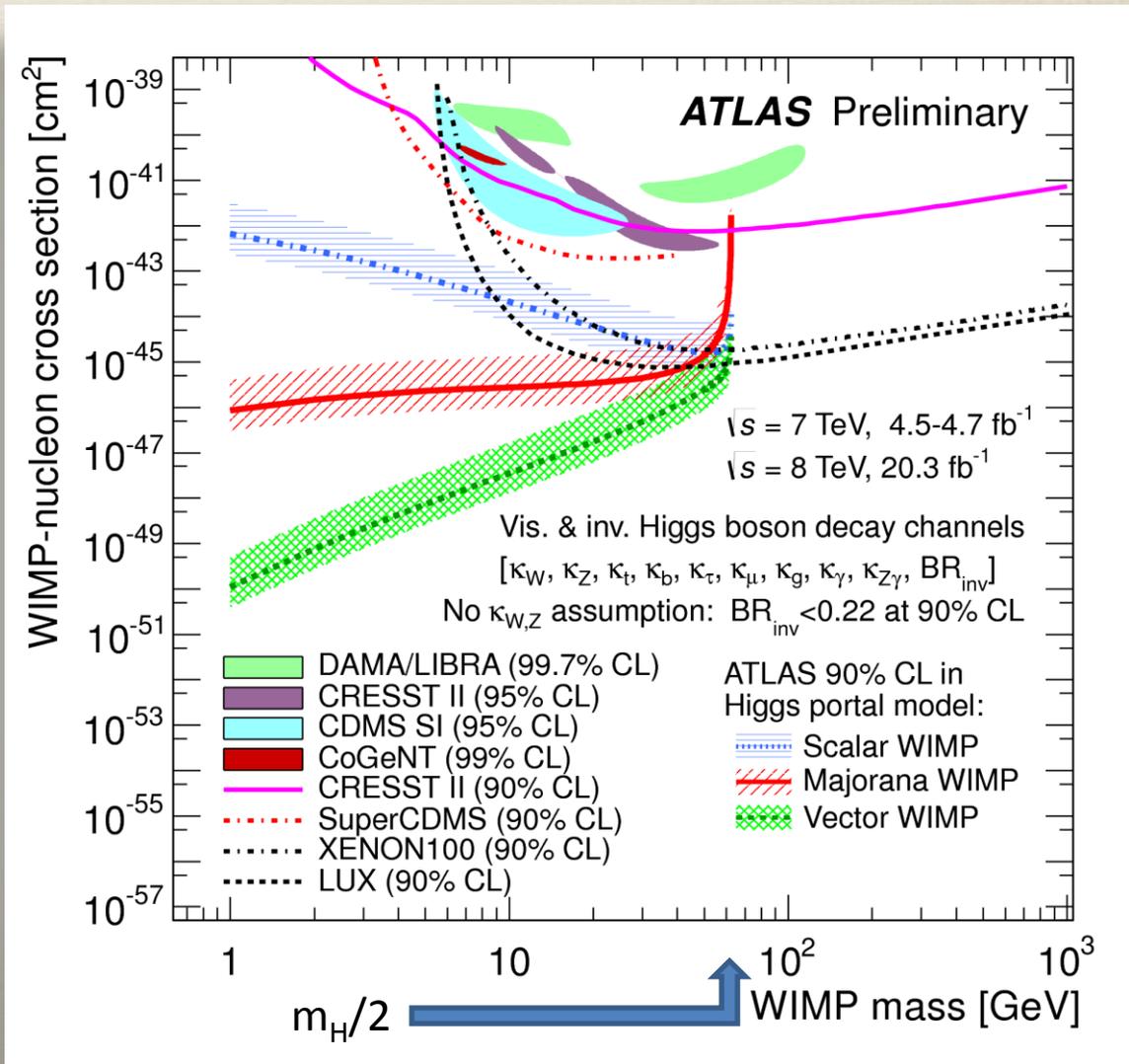
ATLAS: [arXiv:1509.00672](#)

ATLAS: combined limit
 ($BR_{inv} < 0.22$ @ 90% CL)
 is converted to couplings to
 WIMP for either scalar,
 Majorana fermion or vector
 particle.

❖ These are then used to
 calculate the cross-section
 for WIMP-nucleon
 scattering, to be directly
 compared with direct DM
 search experiments.

❖ The main assumption is
 that Higgs is the only
 mediator.

❖ Obvious limit: $2m_{WIMP} < m_H$



CMS: PAS HIG-14-005

ATLAS: arXiv:1508.03372

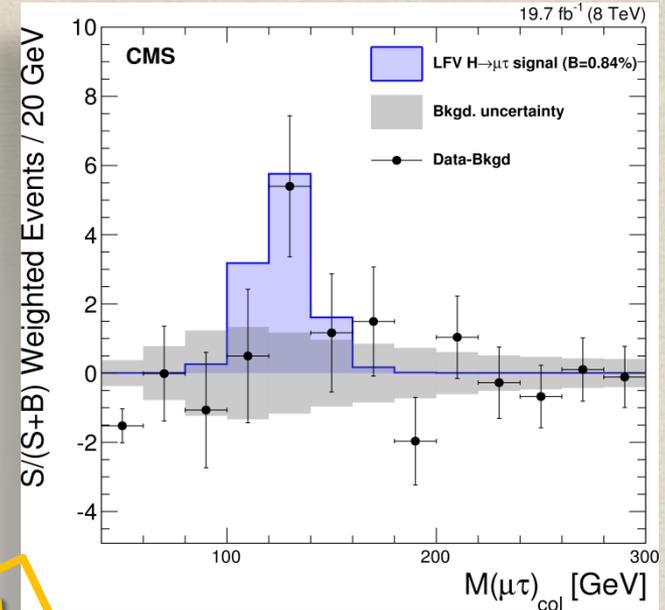
LFV Higgs decays

- ❖ LFV highly suppressed in SM due to renormalizability requirement.
- ❖ Possibility of sizable LFV predicted in various BSM models (2HDM, composite Higgs, RS, etc.)
- ❖ Indirect limits on $BR(H \rightarrow \tau\mu)$ from searches for $\tau \rightarrow \mu\gamma$ weak $O(10\%)$.

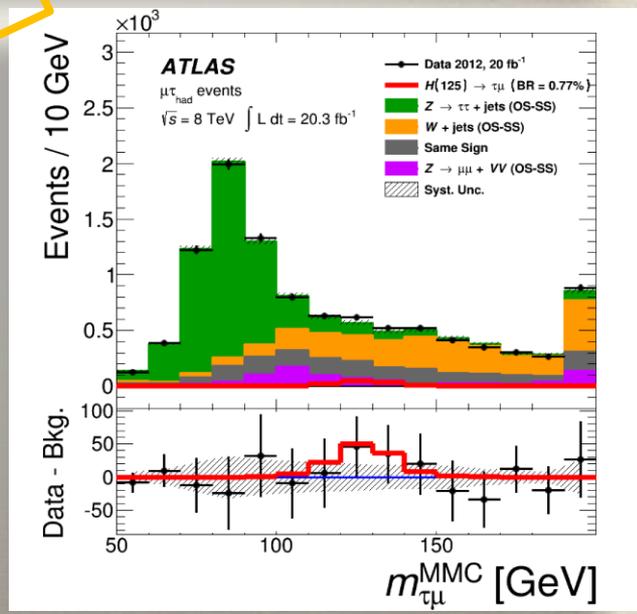
Best fit branching fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_{had}$	$0.72^{+1.18}_{-1.15}$	$0.03^{+1.07}_{-1.12}$	$1.24^{+1.09}_{-0.88}$
$\mu\tau$		$0.89^{+0.40}_{-0.37}$	

- ❖ CMS reports an excess of 2.5σ .
- ❖ ATLAS (only $\tau_{had}\mu$ channel):
 $BR(H \rightarrow \tau\mu) < 1.85\% @ 95 CL$
 (Best fit: $BR(H \rightarrow \tau\mu) = (0.77 \pm 0.62)\%$)
- ❖ Run 2 has to follow-up!

dedicated talk:
Yuta Takahashi

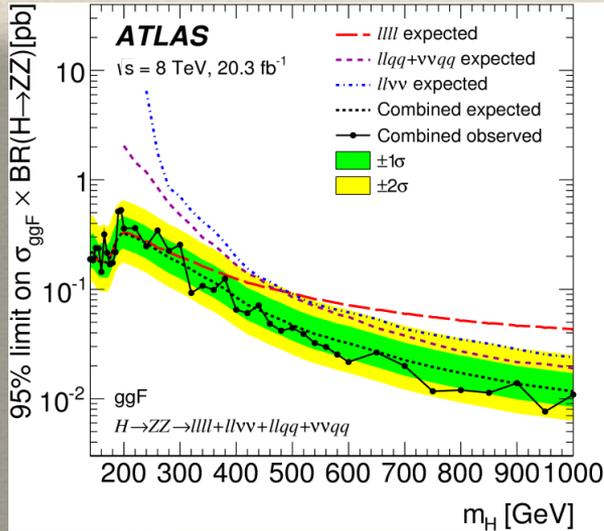


NEW



Explicit search for BSM objects

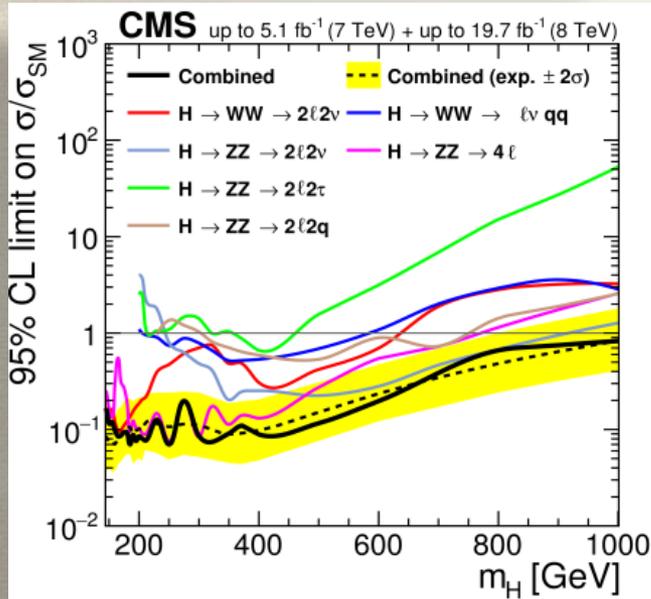
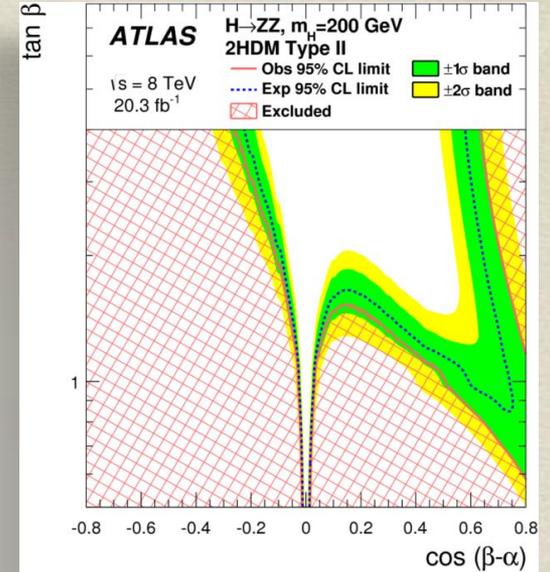
Heavy $H \rightarrow ZZ/WW$



ATLAS: [arXiv:1507.05930](https://arxiv.org/abs/1507.05930)

$H \rightarrow ZZ$

4l, 2l2v, 2l2q final states
Limits on $\sigma \times \text{BR}(H \rightarrow ZZ)$ for
ggf and VBF production.
Limits in the context of
2HDM type II

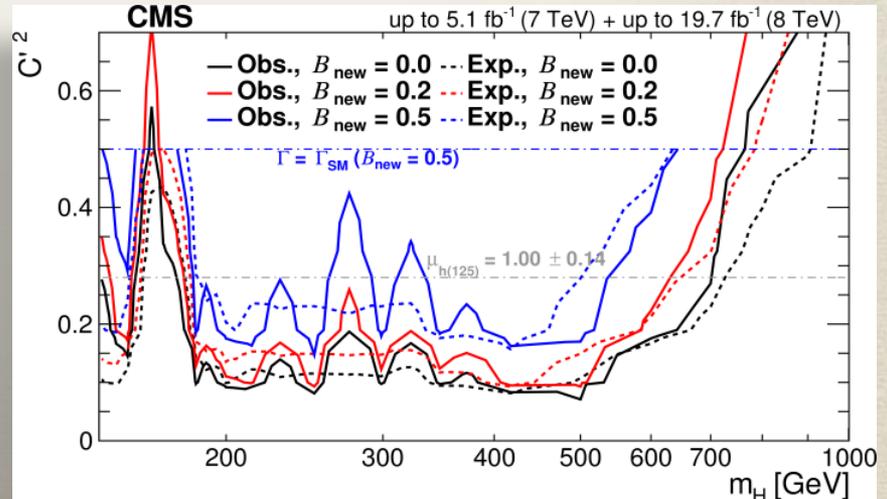


CMS: [arXiv:1504.00936](https://arxiv.org/abs/1504.00936)

$H \rightarrow WW, ZZ$ $WW \rightarrow lvlv, lvqq, ZZ \rightarrow 2l2l, 2l2q, 2l2v$

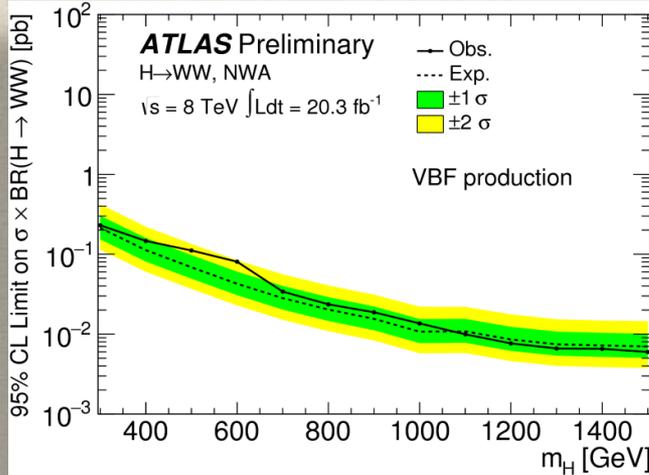


EW singlet Higgs

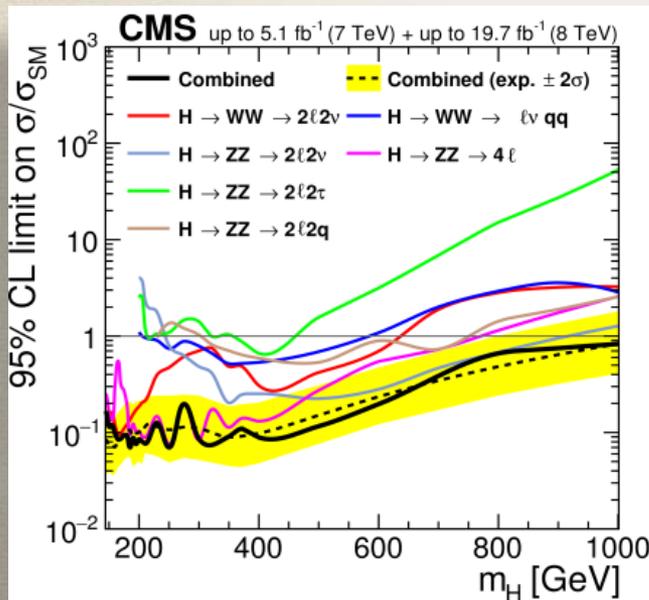
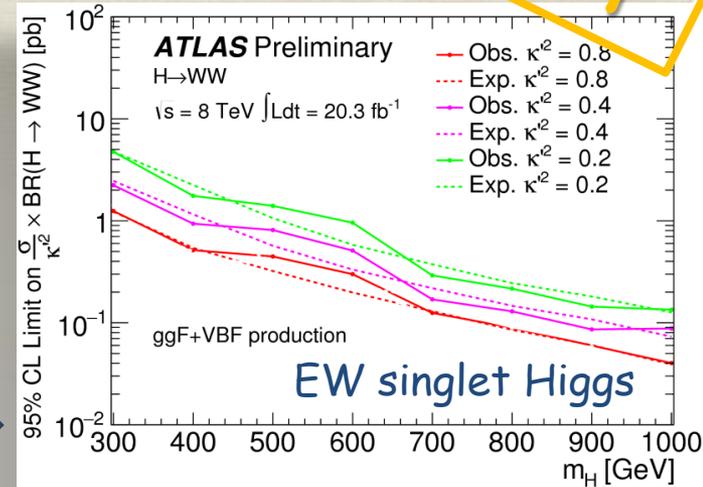


Heavy $H \rightarrow ZZ/WW$

HOT



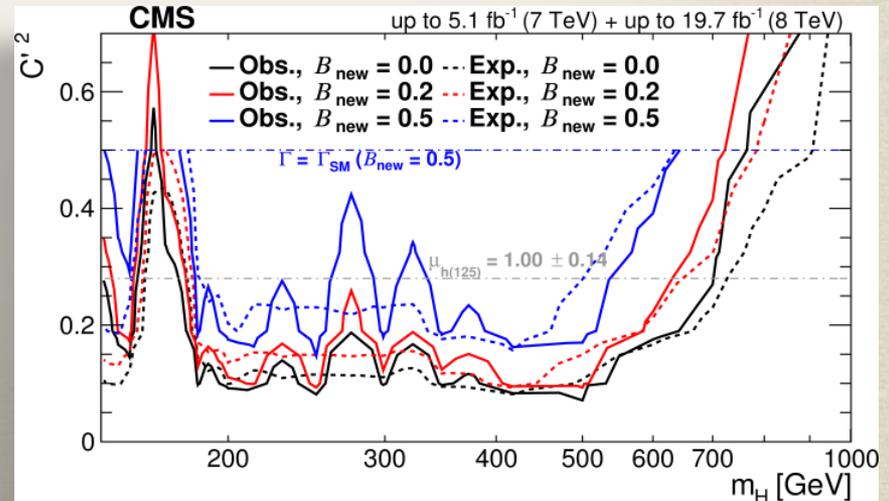
ATLAS: [arXiv:1509.00389](https://arxiv.org/abs/1509.00389)
 $H \rightarrow WW, \ell\nu\ell\nu, \ell\nu qq$
 Range 200 - 1500 GeV
 Limits in the context
 of EW singlet Higgs



CMS: [arXiv:1504.00936](https://arxiv.org/abs/1504.00936)

$H \rightarrow WW, ZZ$ $WW \rightarrow \ell\nu\ell\nu, \ell\nu qq$, $ZZ \rightarrow 2\ell 2\ell, 2\ell 2q, 2\ell 2\nu$

EW singlet Higgs



dedicated talk:
Song-Ming Wang

$X \rightarrow \gamma\gamma, bb$

ATLAS: [PRL 113, 171801 \(2014\)](#)

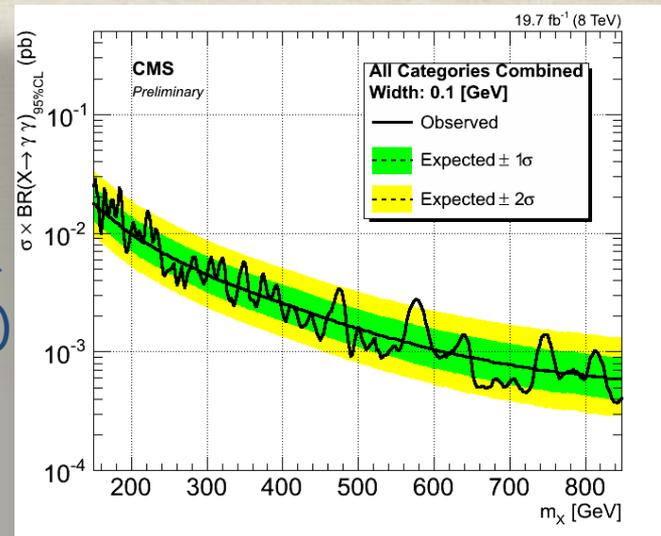
CMS: [arXiv:1506.02301](#)

$X \rightarrow \gamma\gamma$

- ❖ Generic search for $\gamma\gamma$ resonance across a wide range of masses: $m_{\gamma\gamma} < 850$ GeV
- ❖ Both narrow and wide resonances considered

Spin 0 narrow hypothesis \rightarrow (spin 2 very similar)

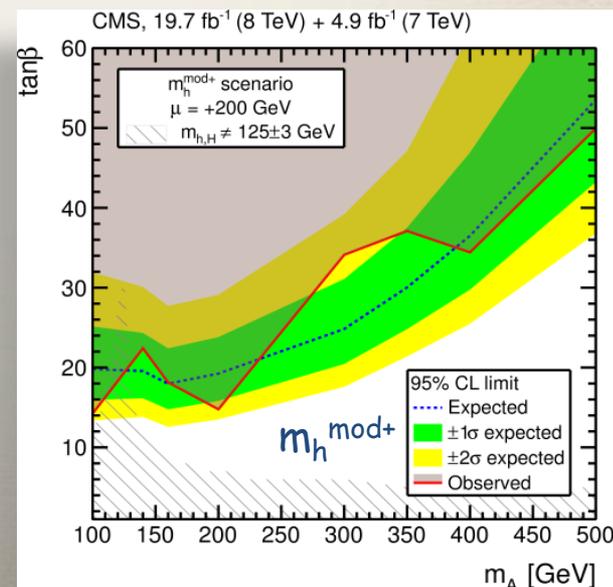
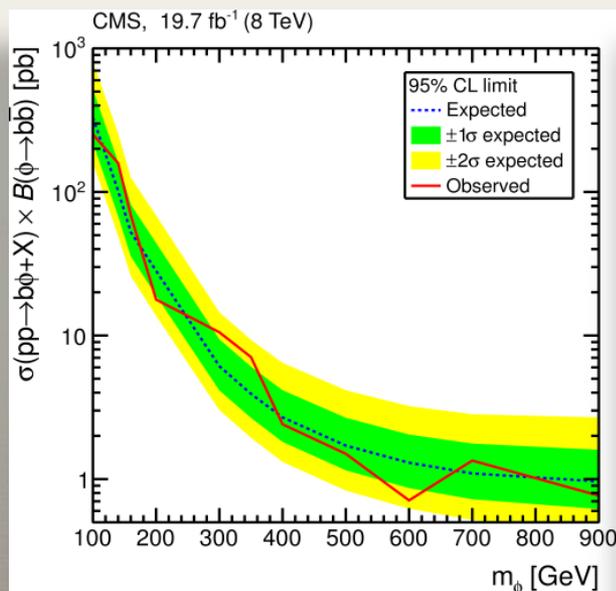
NEW



$\phi \rightarrow b\bar{b}$

CMS: [arXiv:1506.08329](#)

Heavy Higgs produced in association with a b quark

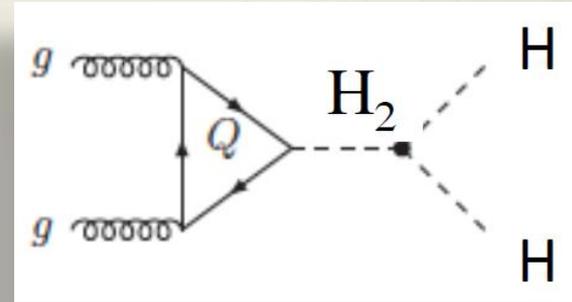


HH or HZ production

dedicated talk:
Andrea Rizzi

- ❖ Higgs self coupling already in the SM: $V=aH^2+bH^3+cH^4$
- ❖ **HH** Cross-section largely enhanced in BSM models:

- Composite: factor <3 ,
- Singlet models: factor up to 15,
- 2HDM models: factor up to 50 !



- ❖ Current experimental limits still far from SM expected rates.
- ❖ **$A \rightarrow ZH$** (or $H \rightarrow ZA$) with H being either the heavier or the lighter CP-even state a powerful probe of 2HDM models.
- ❖ For $m_A < 2m_{\text{top}}$ this may be the dominant decay mode of the CP-odd A .

ATLAS combination on hh production

HOT

- ❖ Both resonant and non-resonant hh production
- ❖ Decay channels: $bbbb, bb\tau, bb\gamma\gamma, WW\gamma\gamma$
- ❖ Limits set for resonant $H \rightarrow hh$: $\sigma(gg \rightarrow H) \times BR(H \rightarrow hh)$ assuming H is narrow ($< 1.5\%$).
- ❖ Limits on MSSM scenarios on $m_A - \tan(\beta)$ inferred. Here hMSSM exmpl.

ATLAS: HIGG-2013-33

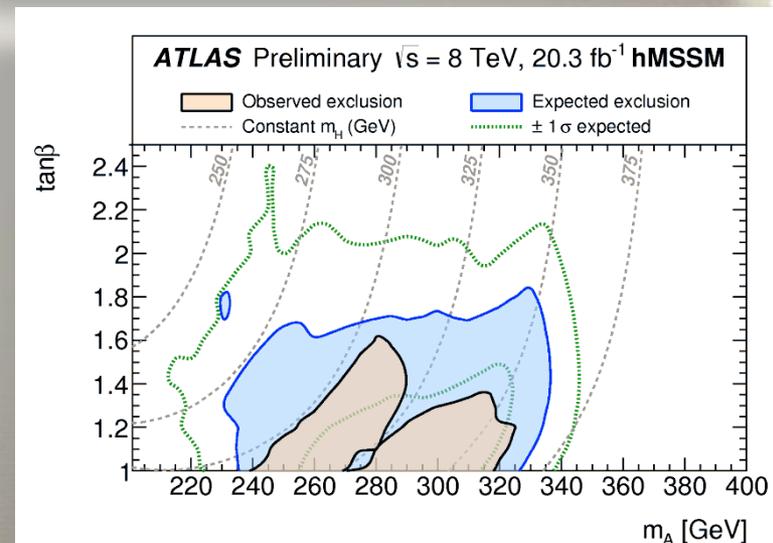
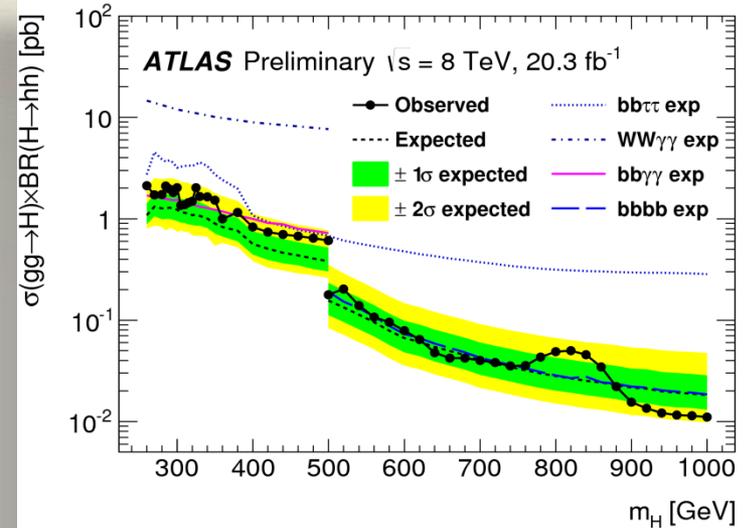
SM prediction @ 125 GeV: 9.9 ± 1.3 fb

non-resonant limits on x-section [pb]:

	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Exp.	1.0	6.7	1.3	0.62	0.47
Obs.	2.2	11	1.6	0.62	0.69

$X \rightarrow HH \rightarrow bbbb$ CMS: [arXiv:1503.04114](https://arxiv.org/abs/1503.04114)

$X \rightarrow HH \rightarrow \gamma\gamma bb$ CMS: [CMS-PAS-HIG-13-032](https://arxiv.org/abs/1303.032)



$A \rightarrow Zh, H/A \rightarrow A/H + Z$

$A \rightarrow Zh$ ($Z \rightarrow ll, \nu\nu, h \rightarrow bb, \tau\tau$)

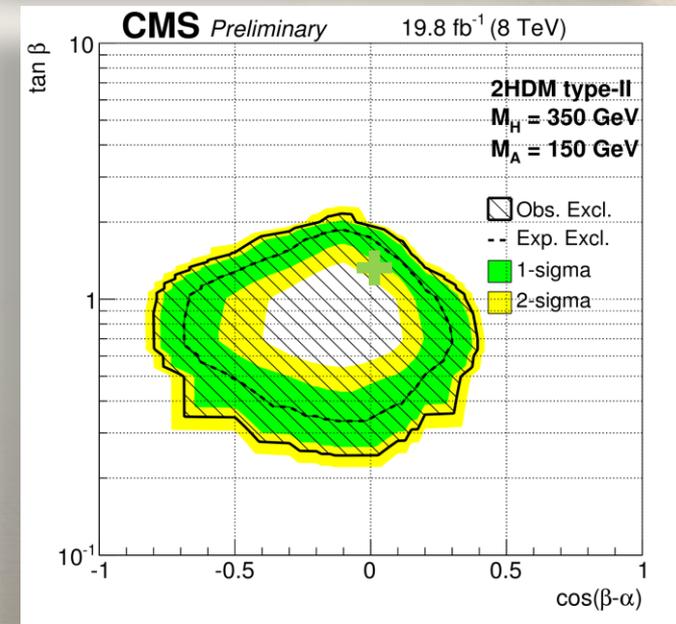
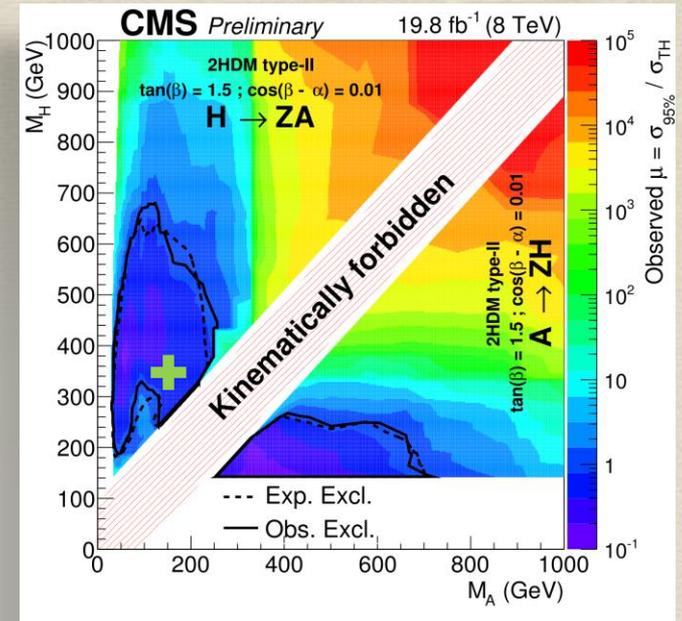
ATLAS: *Phys. Lett. B* 744 (2015) 163-183

CMS: [arXiv:1504.04710](https://arxiv.org/abs/1504.04710)

CMS:

[arXiv:1503.04114](https://arxiv.org/abs/1503.04114)

- ❖ A generic search for 2HDM
- ❖ Expected irrespective of „alignment“
- ❖ $H/A \rightarrow A/H + Z, Z \rightarrow ll, A/H \rightarrow bb, \tau\tau$
- ❖ All combinations of τ_l and τ_{had} .
- ❖ Sensitivity drops rapidly when the $t\bar{t}$ decay channel for the lighter Higgs state opens.
- ❖ Highly boosted topologies suffer from reconstruction inefficiencies.
- ❖ Interesting exclusions on the $\cos(\beta-\alpha)$ - $\tan(\beta)$ plane possible under given mass assumptions.



HOT

MSSM Higgs $\rightarrow \tau\tau$

CMS: **CMS PAS HIG-14-029**

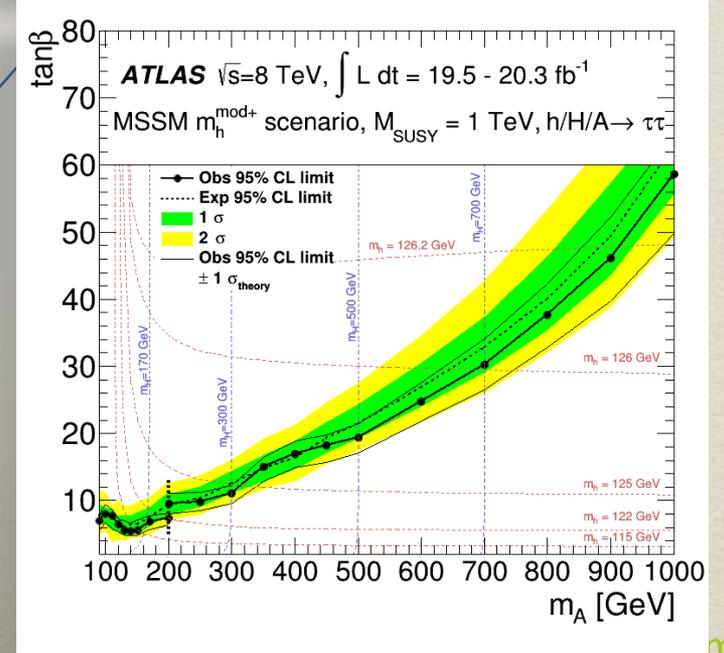
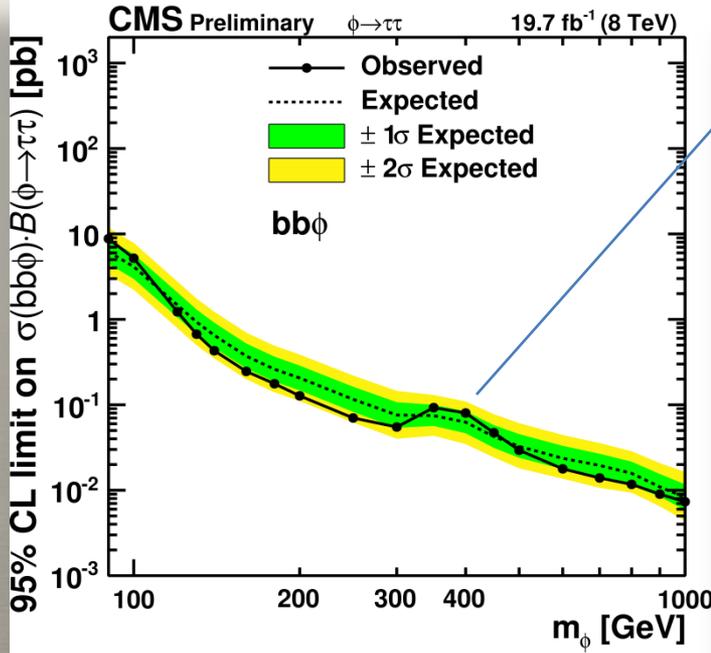
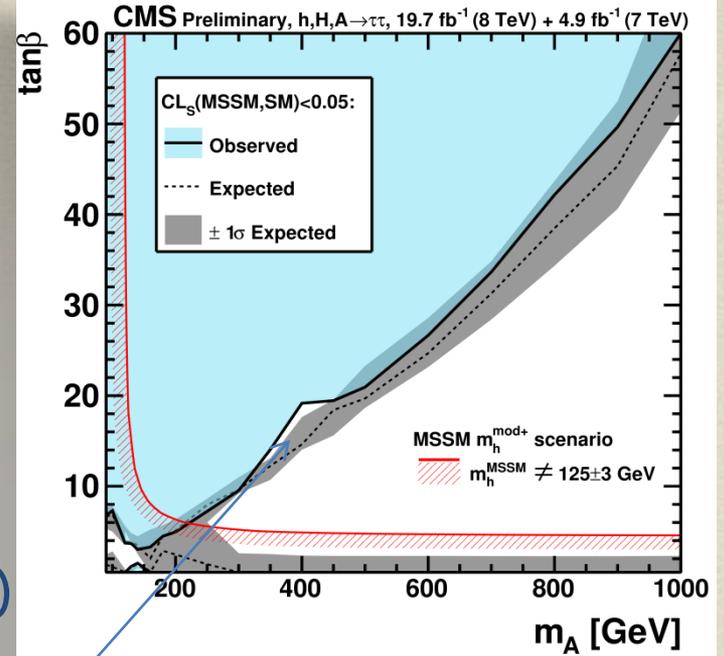
ATLAS: **JHEP 1411 (2014) 056**

❖ ATLAS & CMS

❖ Channels searched:

- $h/H/A \rightarrow \tau_e \tau_\mu$ (+ $\tau_\mu \tau_\mu$ CMS)
- $h/H/A \rightarrow \tau_{lep} \tau_{had}$
- $h/H/A \rightarrow \tau_{had} \tau_{had}$

❖ MSSM Higgs couplings to down type quarks and leptons enhanced for large $\tan(\beta)$

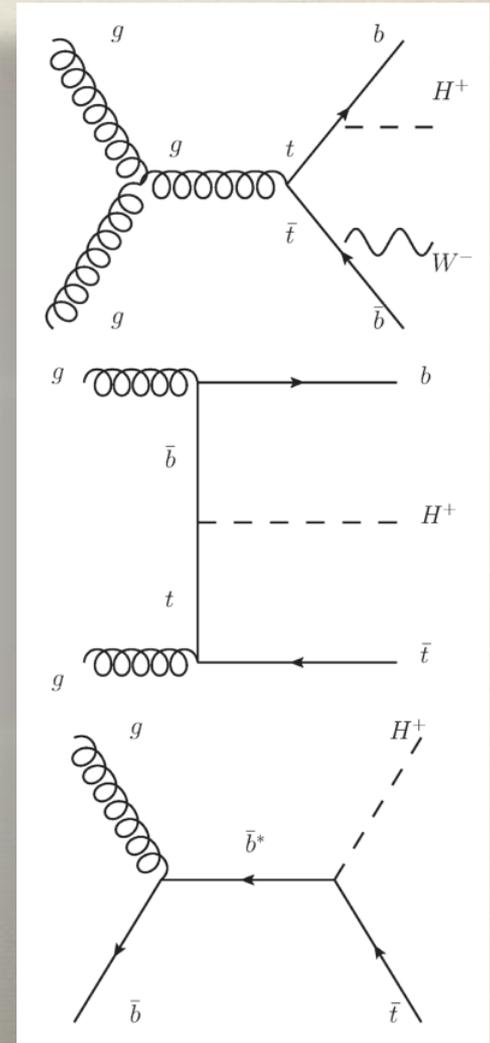


dedicated talk:
Matthias Schröder

Charged Higgs

dedicated talk:
Pietro Vischia

- ❖ A charged Higgs particle would spectacularly sign BSM. Needed with more than one HD (notably SUSY).
- ❖ Within MSSM $BR(H^+ \rightarrow \tau\nu)$ remains significant in large range of masses for high $\tan(\beta)$.
- ❖ For low $\tan(\beta)$ $H^+ \rightarrow tb$ dominates for $m_H > m_+$
- ❖ $H^+ \rightarrow \tau\nu$ saturates the decay for $m_H < m_+$
- ❖ Channels searched
 - $H^+ \rightarrow \tau_{had}\nu$ (ATLAS, CMS)
 - $H^+ \rightarrow tb, \tau_l\nu$ ($t \rightarrow l\nu b$) (CMS)
 - $H^+ \rightarrow cs$ (ATLAS, CMS)
 - $H^+ \rightarrow WZ$ (ATLAS)
- ❖ Except for WZ search, H^+ tagged together with the accompanying top.



Charged $H^+ \rightarrow \tau\nu$ (had)

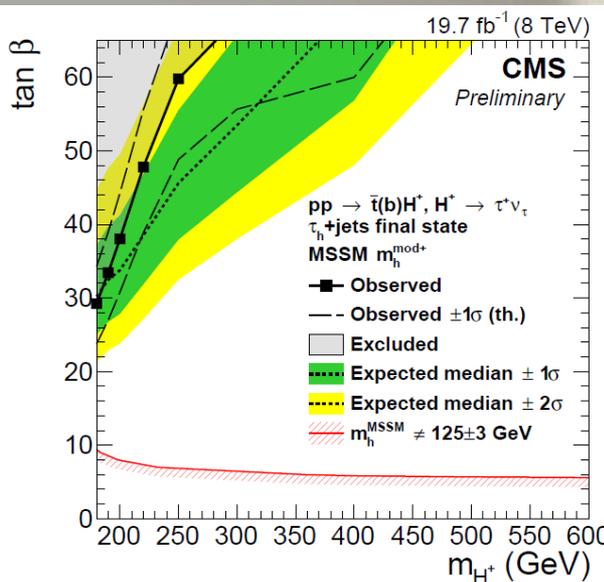
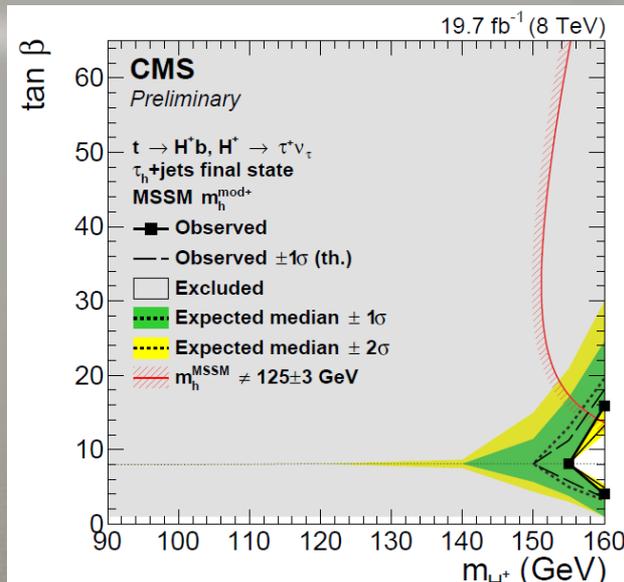
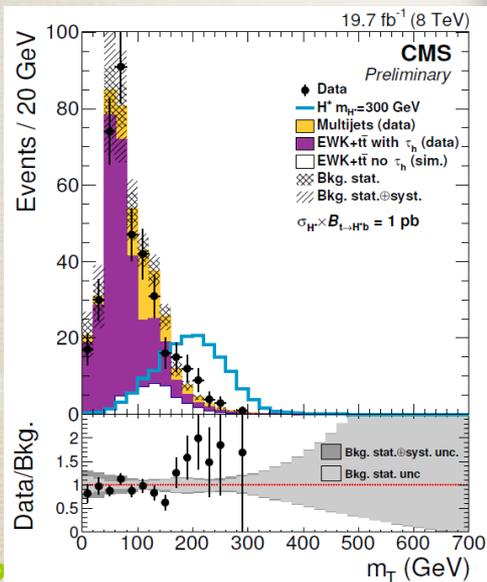
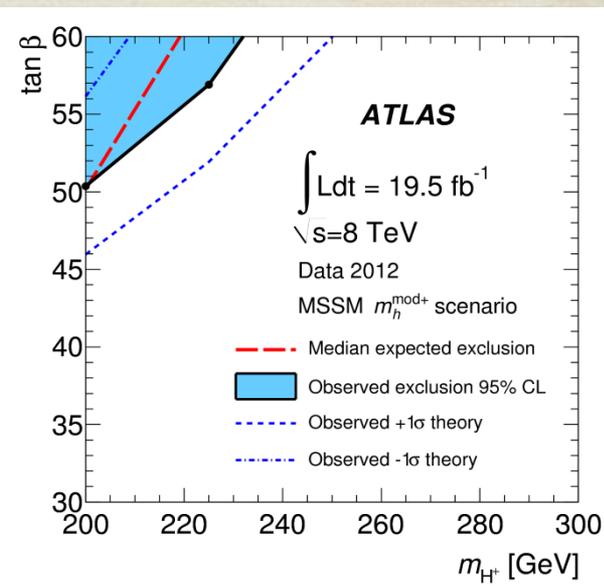
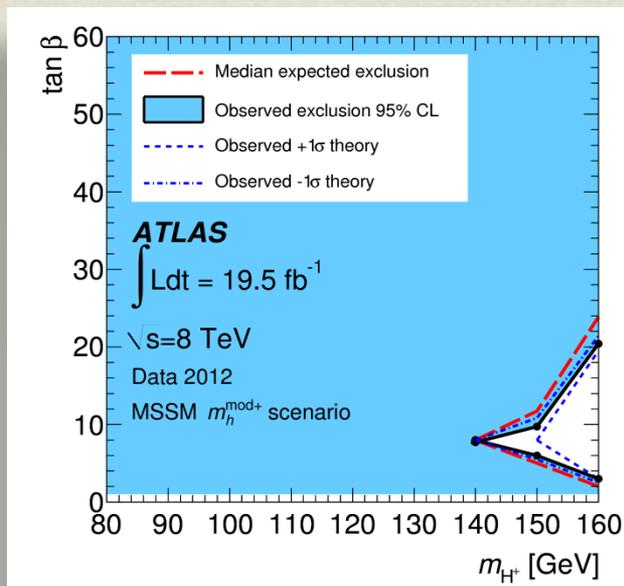
ATLAS: [JHEP 1503 \(2015\), p. 088](#)

CMS: [CMS PAS HIG-14-020](#)

❖ Exclusion limits given in various flavours of 2HDM models:

- ❖ MSSM m_h^{hmax}
- ❖ MSSM $m_h^{mod+/-}$
- ❖ MSSM light stau
- ❖ τ -phobic Higgs
- ❖ Low- M_H

❖ Here m_h^{mod+} exp.



Charged $H^+ \rightarrow \tau\nu$ (had)

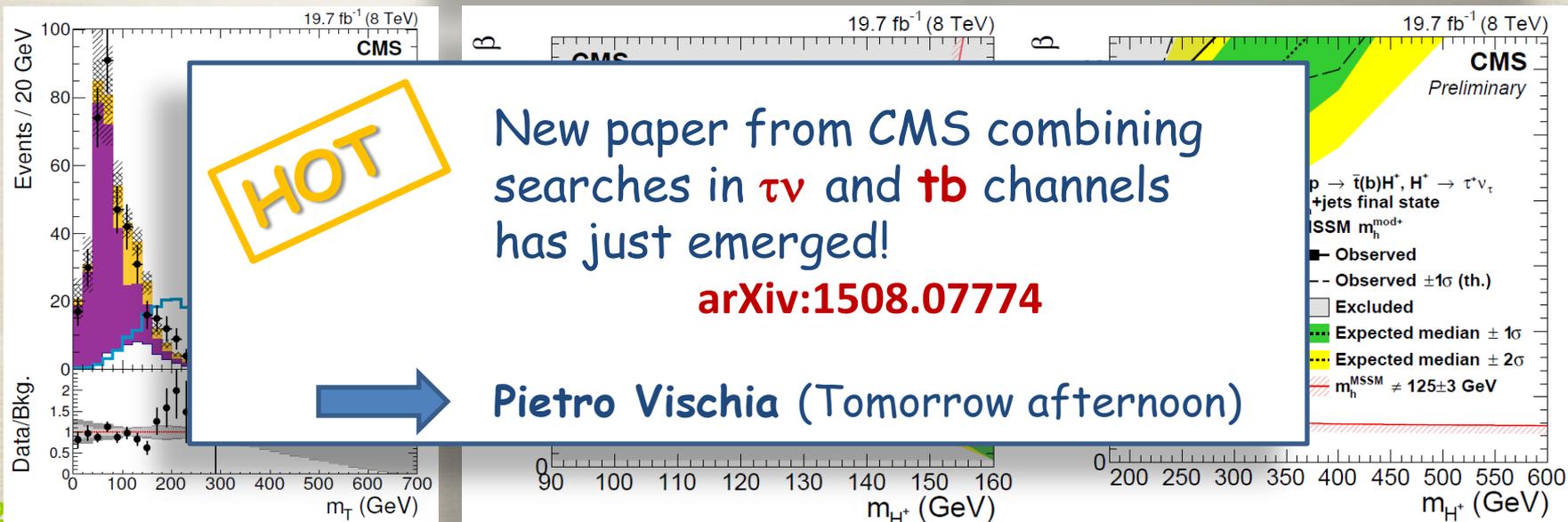
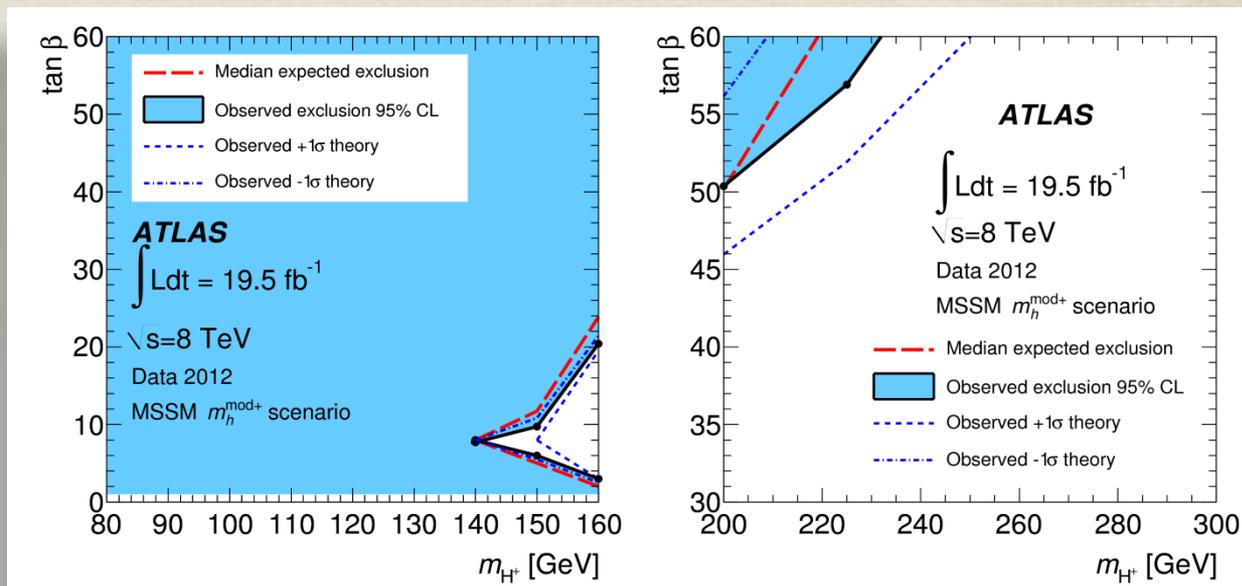
ATLAS: **JHEP 1503 (2015), p. 088**

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❖ Exclusion limits given in various flavours of 2HDM models:

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- ❖ τ -phobic Higgs
- ❖ Low- M_H

❖ Here m_h^{mod+} exmp.



HOT

New paper from CMS combining searches in $\tau\nu$ and $t\bar{b}$ channels has just emerged!

arXiv:1508.07774

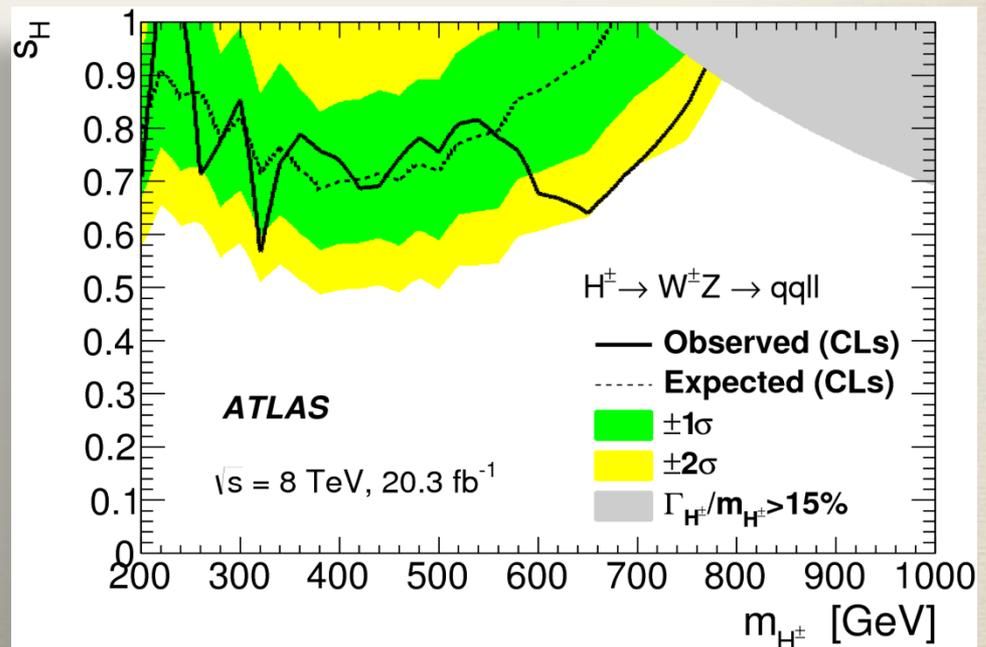
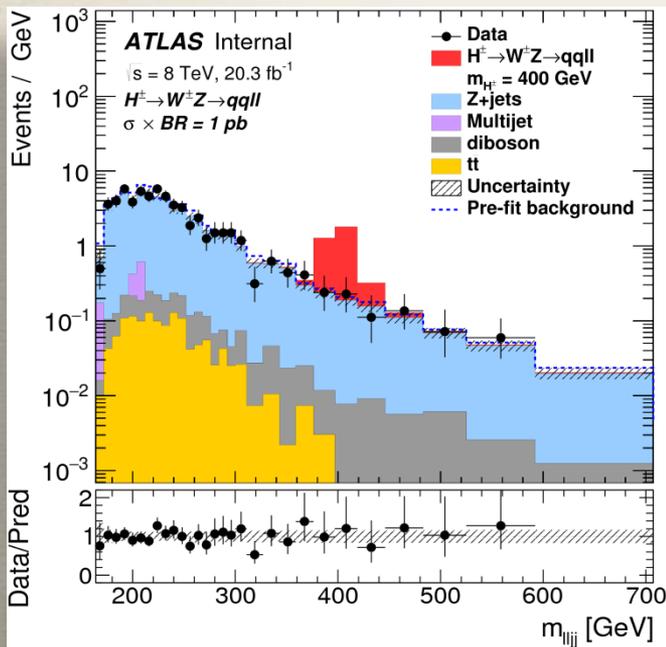
Pietro Vischia (Tomorrow afternoon)

NEW

Charged $H^+ \rightarrow W^\pm Z$

ATLAS:
arXiv:1503.04233

- ❖ Probing for the Georgi-Machacek Higgs Triplet Model (GMHTM) where H^+ couples to ZW at tree level.
- ❖ VBF production of H^+ with subsequent decay into a ZW ($llqq$) is searched for.
- ❖ $240 < m_{H^\pm} < 700$ GeV exclusion is placed for $S_H=1$ and $BR(H^\pm \rightarrow WZ)=100\%$



NMSSM

Introduces an additional Higgs singlet relaxes the constraints resulting from the mass of h^0 being much larger than m_Z (radiative corrections, $m_h^{\text{mod+}}$ scenarios)

ATLAS:

EXOT-2013-24

NEW

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

Signature: ≥ 3 isolated γ
Search for di-photon resonance (m_{23}).

$h_{125} \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ $300 < m_H < 600$
Search for $m_a < 250$ GeV

Limits on:

$$\sigma/\sigma_{SM} \times BR(h \rightarrow aa) \times BR(a \rightarrow \gamma\gamma)^2$$

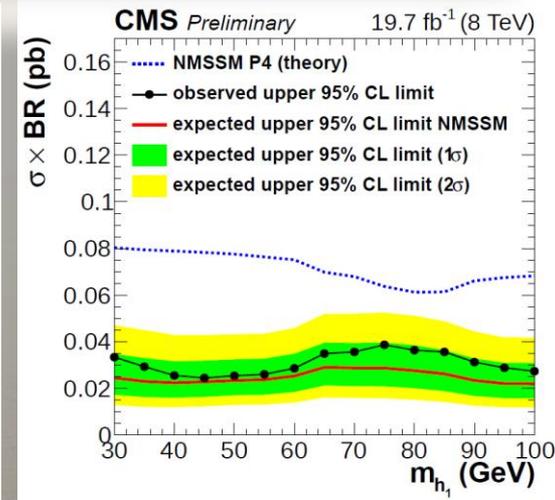
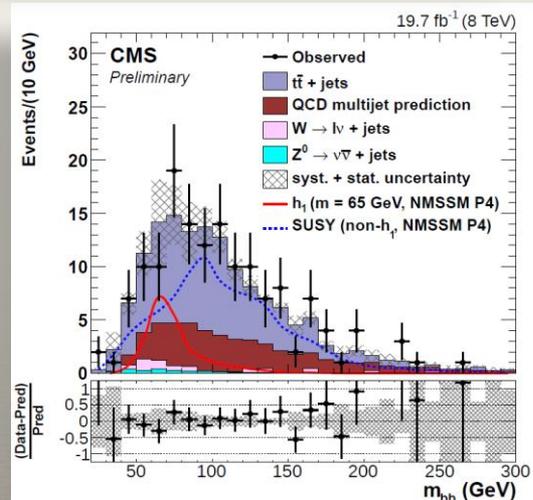
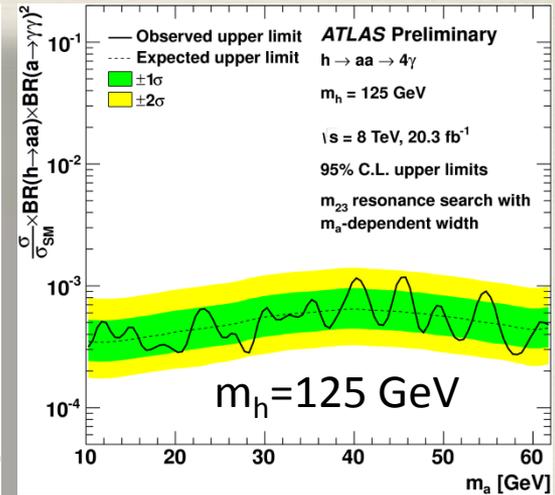
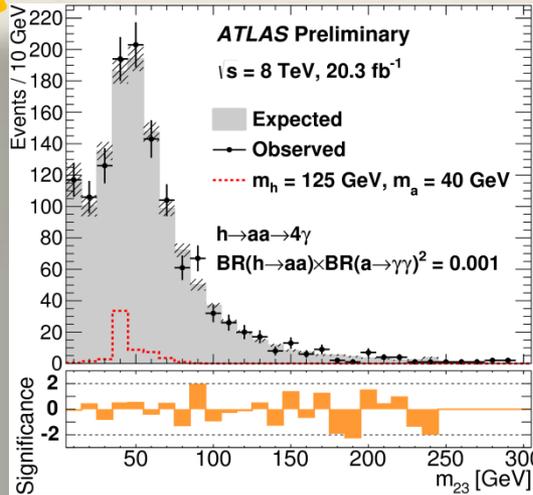
CMS:

CMS PAS HIG-14-030

$a \rightarrow bb$

SUSY cascade tagged by $E_{T, \text{miss}} > 200$ GeV and large H_T plus two b-tagged jets.

Limits within the coloured SUSY mass scale of 1 TeV.



dedicated talk:
Matthias Schröder



EXECUTIVE SUMMARY

No BSM excitement in the scalar sector
... yet

CONCLUSIONS

- ❖ The 125 GeV Higgs looks very SM-like.
- ❖ No evidence for BSM phenomena in the scalar sector.
- ❖ Large variety of analyses managed to place exclusion limits on various BSM scenarios.
- ❖ 8- \rightarrow 13 TeV marks an increase of σ_H by more than factor two.
- ❖ VH, ttH, HH production waiting to be fully explored.
- ❖ X-section for production of heavier states increased @13 TeV extending the discovery potential.
- ❖ For HL-LHC prospects see: Aleandro NISATI & Jeff RICHMAN

	$\sigma(\text{pb})$ at 13 TeV	$\sigma(\text{pb})$ at 8 TeV
Gluon Fusion	43.9	19.27
Vector Boson Fusion	3.748	1.578
WH	1.38	.70
ZH	.87	.42
ttH	.51	.13
HH	.034	.008

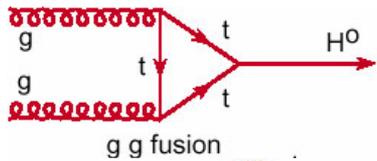
Run 2 is ongoing. Stay tuned!

THANK YOU.

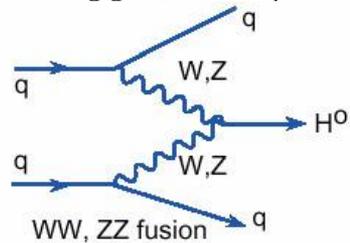
BONUS MATERIAL

SM Higgs production @ LHC

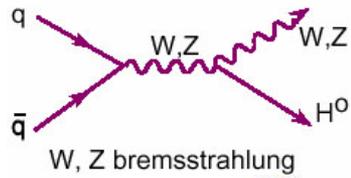
($\sim 25 \text{ fb}^{-1}/\text{exp}$ has been collected till LS1)



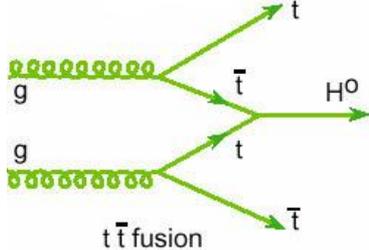
$\sim 19 \text{ pb}$
(0.95 pb)



$\sim 1.5 \text{ pb}$
(0.07 pb)

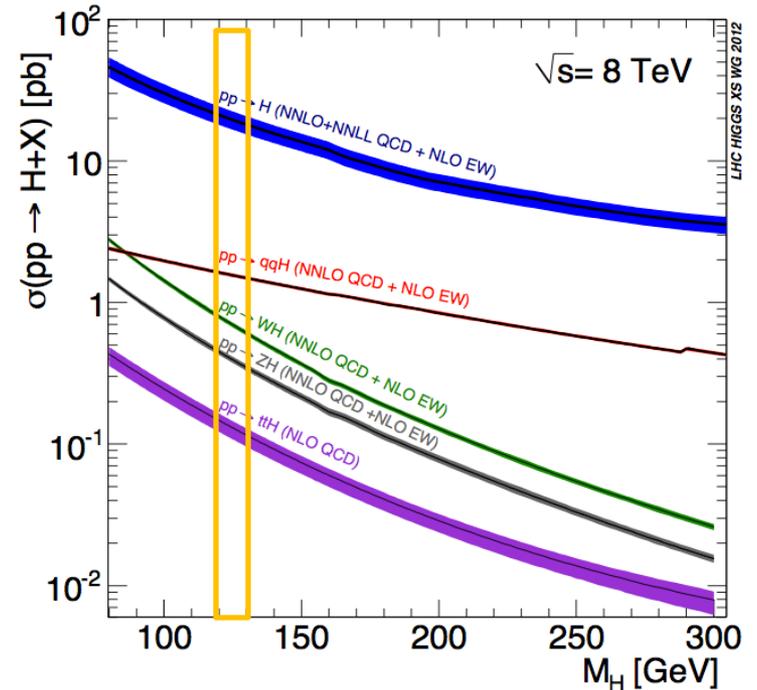


$\sim 1.0 \text{ pb}$
(0.21 pb)

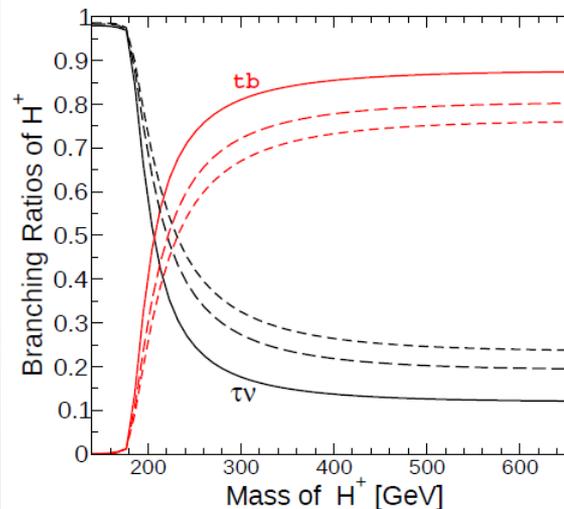
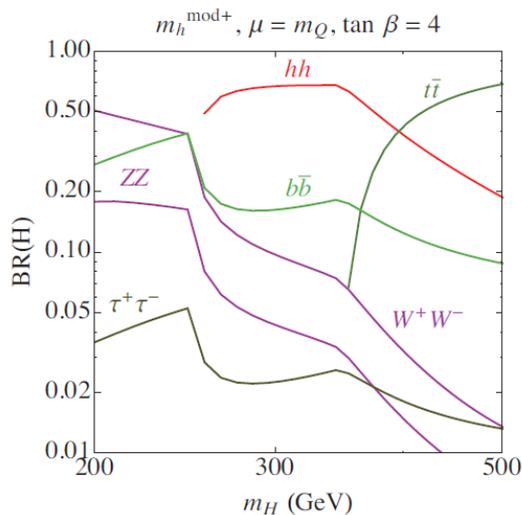
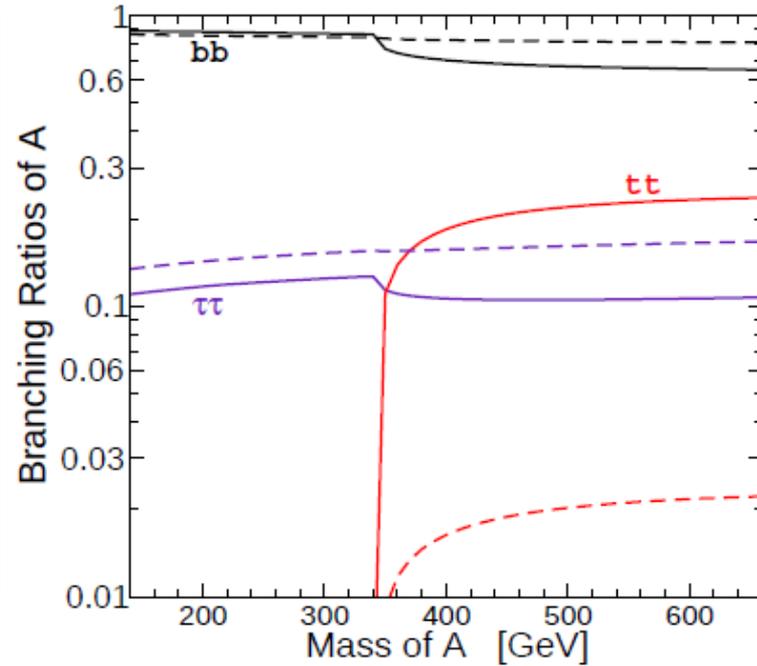
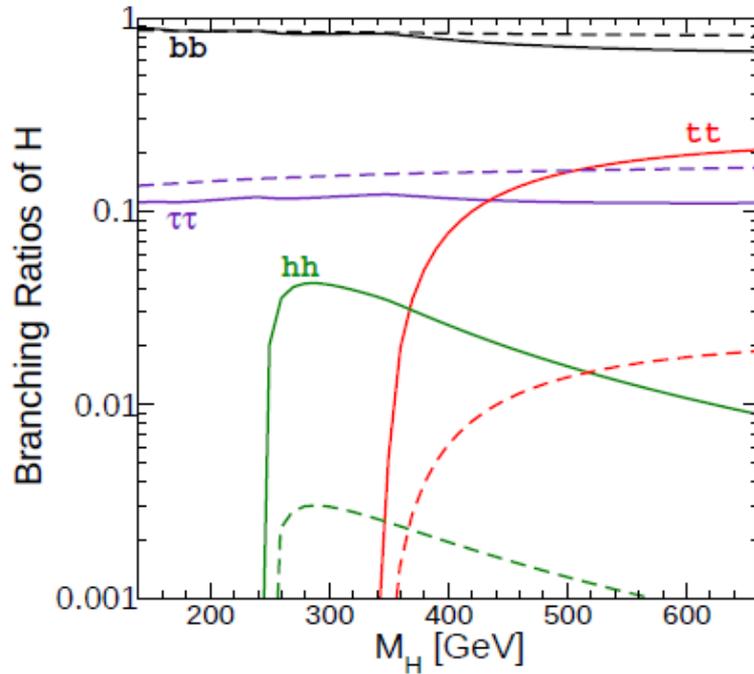


$\sim 0.1 \text{ pb}$
(0.004 pb)

Tevatron



Solid: $\tan \beta = 10$, dashed: $\tan \beta = 20$.



Solid: $\tan \beta = 10$,
long dashed: $\tan \beta = 20$,
short dashed: $\tan \beta = 30$.

Higher $\tan \beta$ gives
more $\tau\nu$.

Extensive coupling studies

dedicated talks:
Marco Pieri, Wouter Verkerke

arXiv:1412.8662

$$\mu = \sigma / \sigma_{SM}, \quad \kappa_H^2 = \Gamma_{tot} / \Gamma_{SM}$$

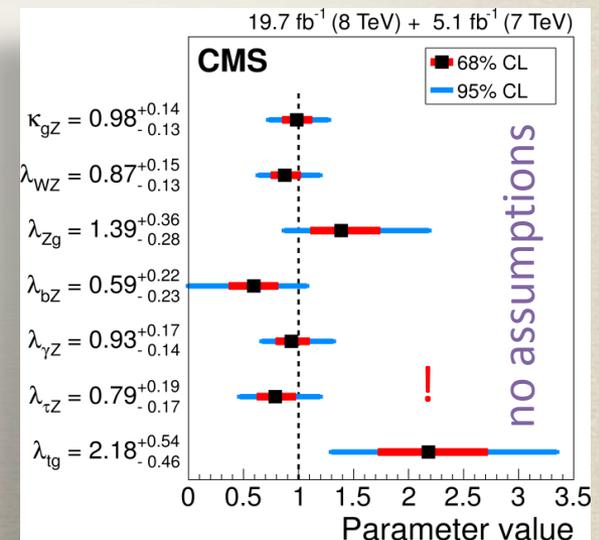
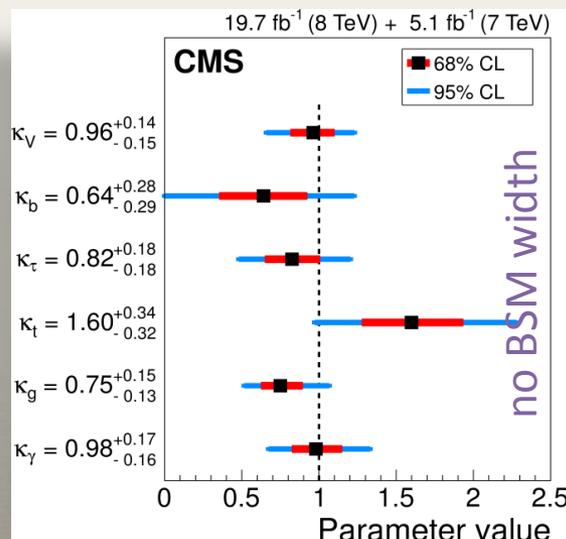
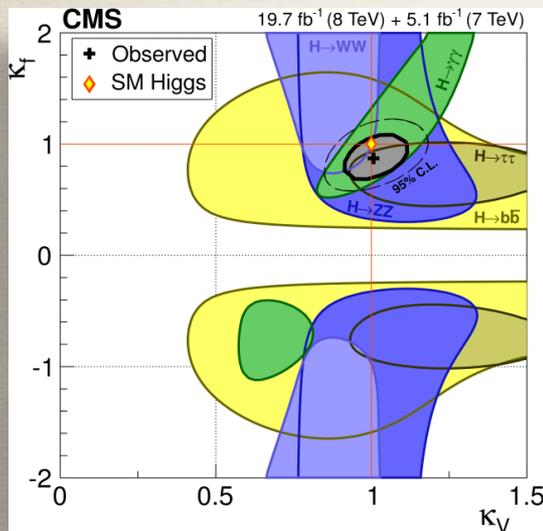
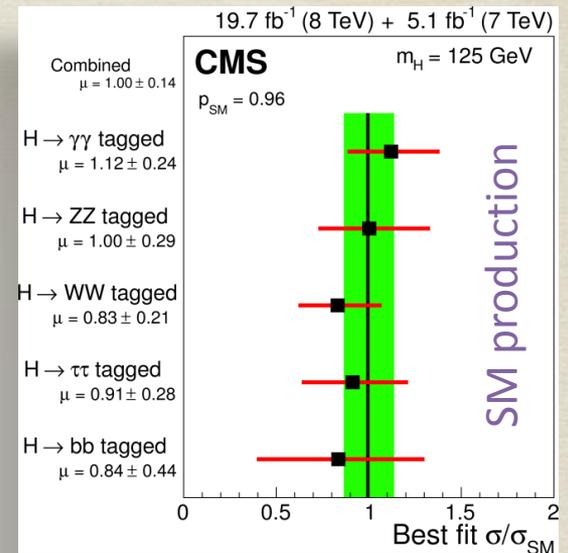
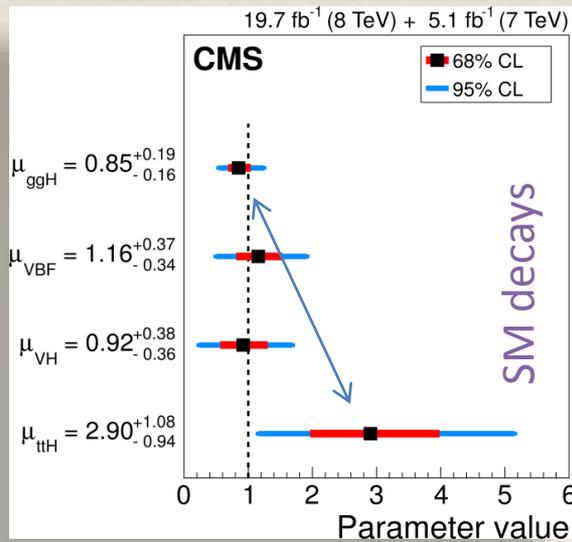
$$\kappa_p^2 = \sigma / \sigma_{SM}, \quad \kappa_d^2 = \Gamma / \Gamma_{SM}$$

$$\lambda_{ab} = \kappa_a / \kappa_b, \quad \kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$$

❖ κ_V, κ_f common factors for couplings to vector bosons and fermions, respectively.

❖ Assumption of no BSM loops/width, except for λ

❖ Interferences allow to resolve signs!



ATLAS J^{CP}:

arXiv:1506.05669

CMS J^{CP}:

Phys. Rev. D 92, 012004

Testing for alternative J^{CP} scenarios using decay kinematics.

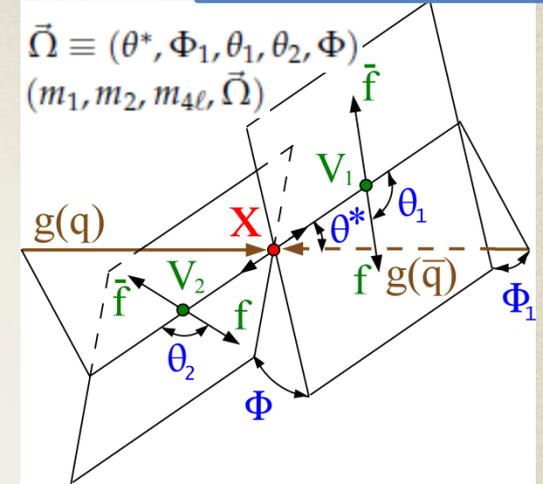
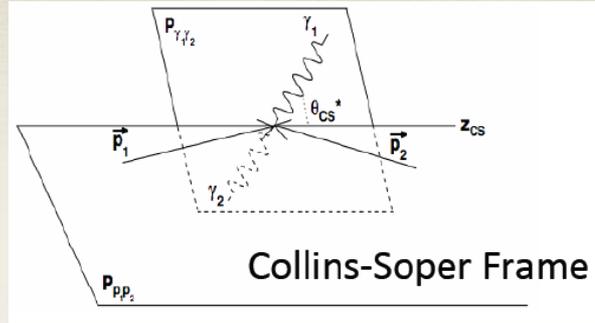
ZZ: full kinematics available

WW: $m^{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\phi^{\ell\ell}$ and m_T

$\gamma\gamma$: $\cos(\Theta_{CS}^*)$, $p_T^{\gamma\gamma}$

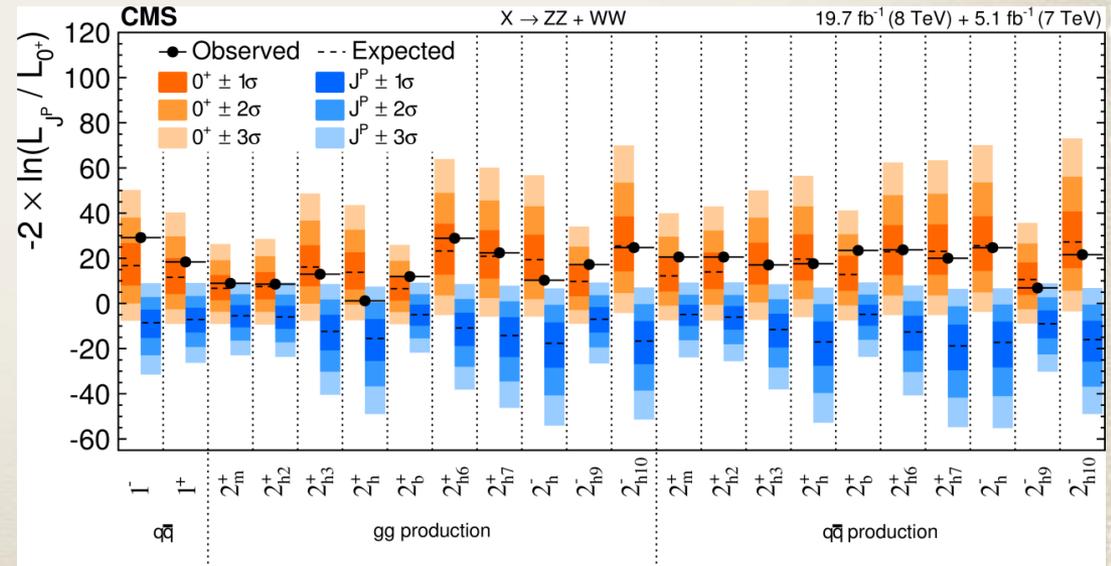
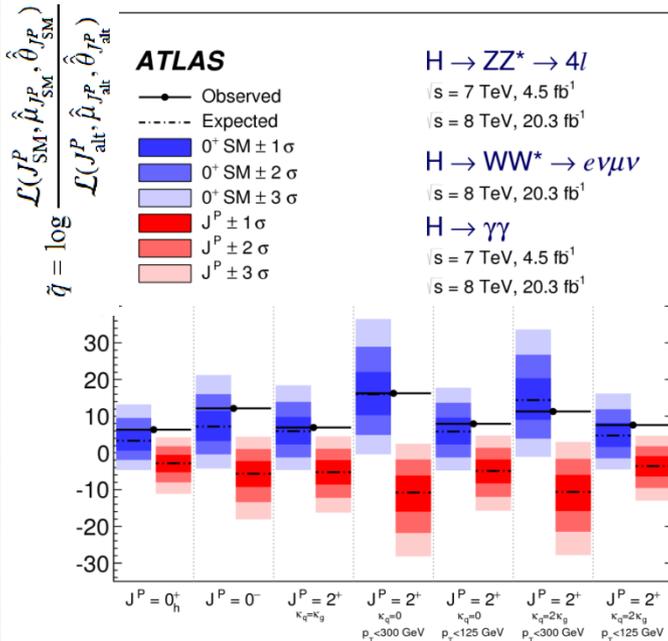
J^{CP} of the 125 GeV Higgs

dedicated talks:
Manuela Venturi,
Kerstin Tackmann



Exclusions @ 99% CL or better

Note: Landau-Yang theorem precludes J=1 hypothesis in the presence of H->γγ



Higgs $d\sigma_H/dx$

ATLAS:

arXiv:1508.02507

- ❖ Constraints on Wilson coefficients for anomalous CP-even and CP-odd int. in the EFT (operators $\geq \text{dim}6$)
- ❖ Use $H \rightarrow \gamma\gamma$. $d\sigma/dx$:

$$p_T^{\gamma\gamma}, N_{\text{jets}}, m_{jj}, \Delta\phi_{jj}, p_T^{j1}$$

CMS:

CMS-PAS-HIG-14-028

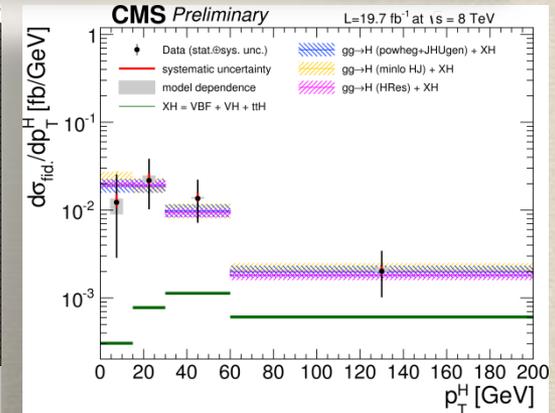
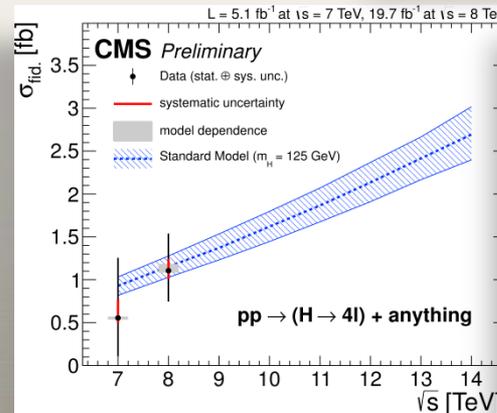
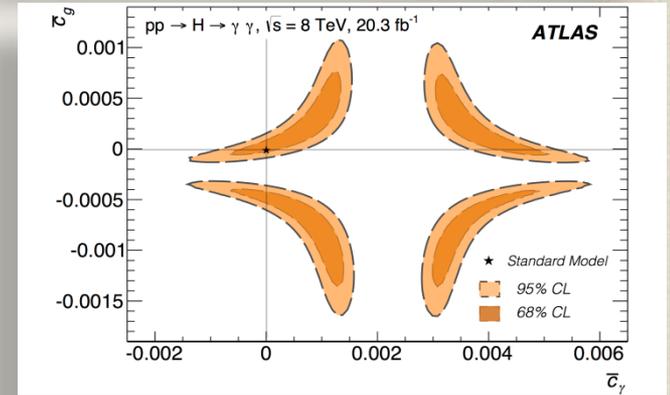
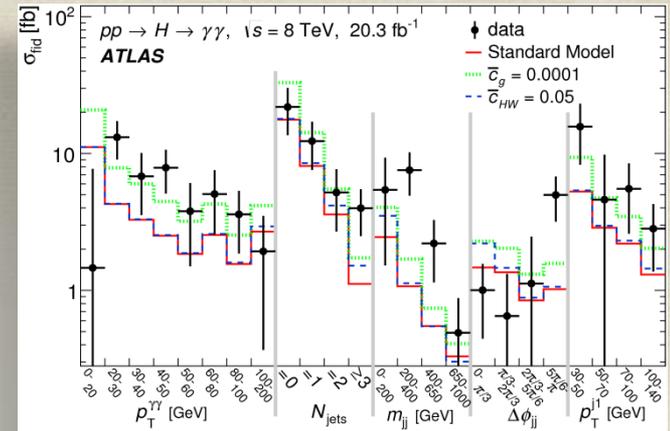
- ❖ Study of the $H \rightarrow ZZ \rightarrow 4l$ channel
- ❖ Extract fiducial x-sections both inclusive and differential.
- ❖ $d\sigma/dx$:

$$p_T^H, y^H, N_{\text{jets}}, p_T^{j1}, \Delta y_{Hj1}$$

Fiducial cross section $H \rightarrow 4l$ at 7 TeV	
Measured	$0.56^{+0.67}_{-0.44}$ (stat.) $^{+0.21}_{-0.06}$ (sys.) $^{+0.02}_{-0.02}$ (model) fb
$gg \rightarrow H(\text{HRES}) + XH$	$0.93^{+0.10}_{-0.11}$ fb
Fiducial cross section $H \rightarrow 4l$ at 8 TeV	
Measured	$1.11^{+0.41}_{-0.35}$ (stat.) $^{+0.14}_{-0.10}$ (sys.) $^{+0.08}_{-0.02}$ (model) fb
$gg \rightarrow H(\text{HRES}) + XH$	$1.15^{+0.12}_{-0.13}$ fb
Ratio of fiducial cross sections of $H \rightarrow 4l$ at 7 and 8 TeV	
Measured	$0.51^{+0.71}_{-0.40}$ (stat.) $^{+0.13}_{-0.05}$ (sys.) $^{+0.00}_{-0.03}$ (model)
$gg \rightarrow H(\text{HRES}) + XH$	$0.805^{+0.003}_{-0.010}$

HOT

dedicated talk:
Kerstin Tackmann



2HDM Models

❖ Generic class implementing a second Higgs doublet.

Type I: One doublet couples to vector bosons, the other couples to fermions.

Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „**MSSM -like**”

Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II.

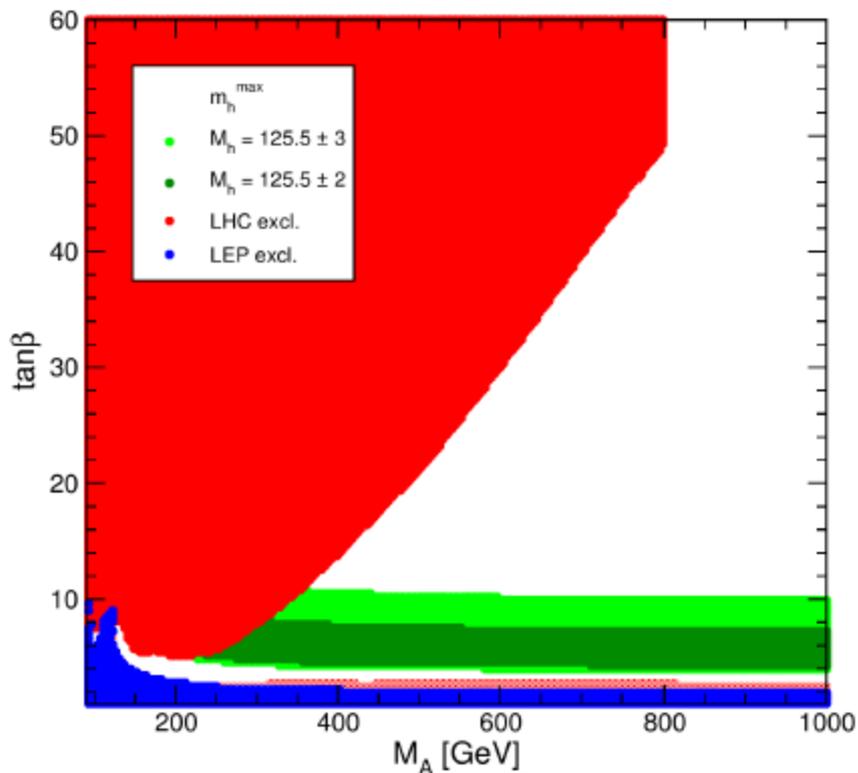
Flipped: couplings to quarks as in the Type II model and to leptons as in Type I.

$$\tan \beta \equiv v_2/v_1 \qquad g_{hVV}^{2\text{HDM}}/g_{hVV}^{\text{SM}} = \sin(\beta - \alpha)$$

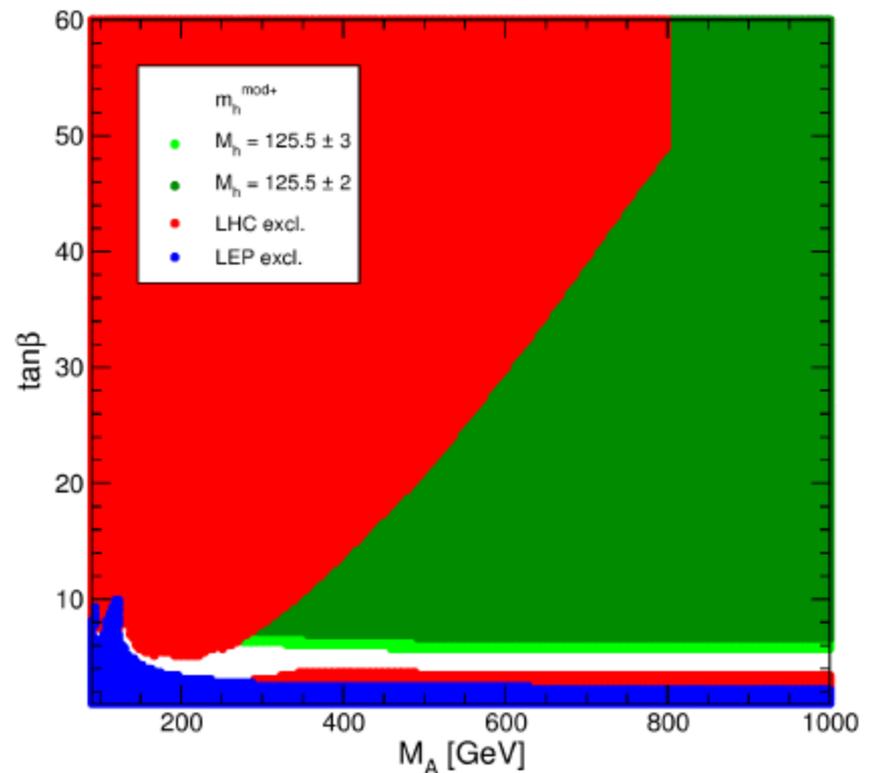
$$v_1^2 + v_2^2 = v^2 \approx (246 \text{ GeV})^2 \qquad g_{HVV}^{2\text{HDM}}/g_{HVV}^{\text{SM}} = \cos(\beta - \alpha)$$

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

m_h^{\max} : maximize M_h by choosing A_t , with other parameters fixed.



$m_h^{\text{mod}+}$: make $M_h = 125$ GeV by choosing A_t , with other parameters fixed.



CMS: Search for $X \rightarrow HH$

$X \rightarrow HH \rightarrow bbbb$

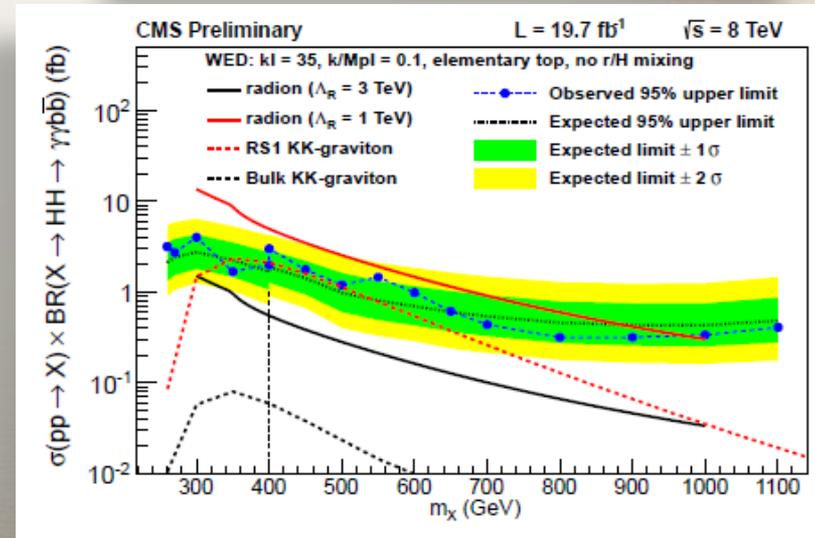
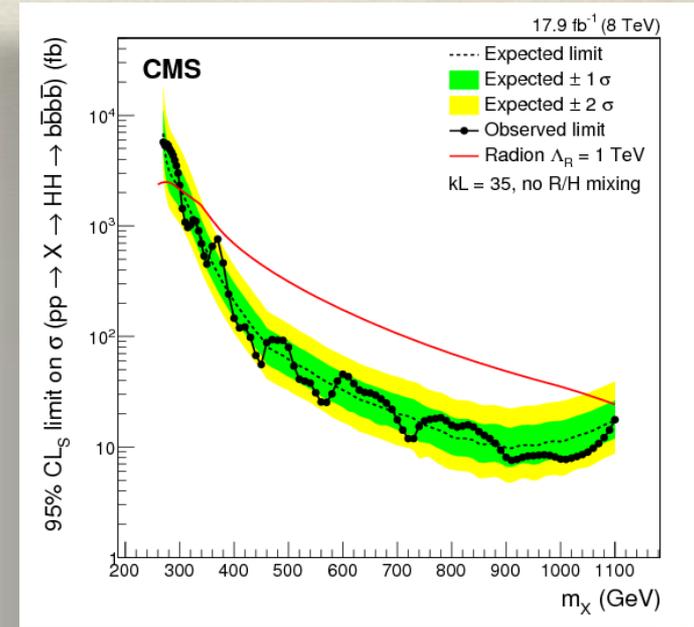
arXiv:1503.04114

- ❖ Model independent search
- ❖ Using four b-tagged jets.
- ❖ QCD bkg estimated from data control regions

$X \rightarrow HH \rightarrow \gamma\gamma bb$

CMS-PAS-HIG-13-032

- ❖ Using pairs of b-tagged jets and pairs of photons.
- ❖ Sensitivity in the range of 260-1100 GeV
- ❖ Limits derived for both scalar Radion as well as RS1 G_{KK}^* .



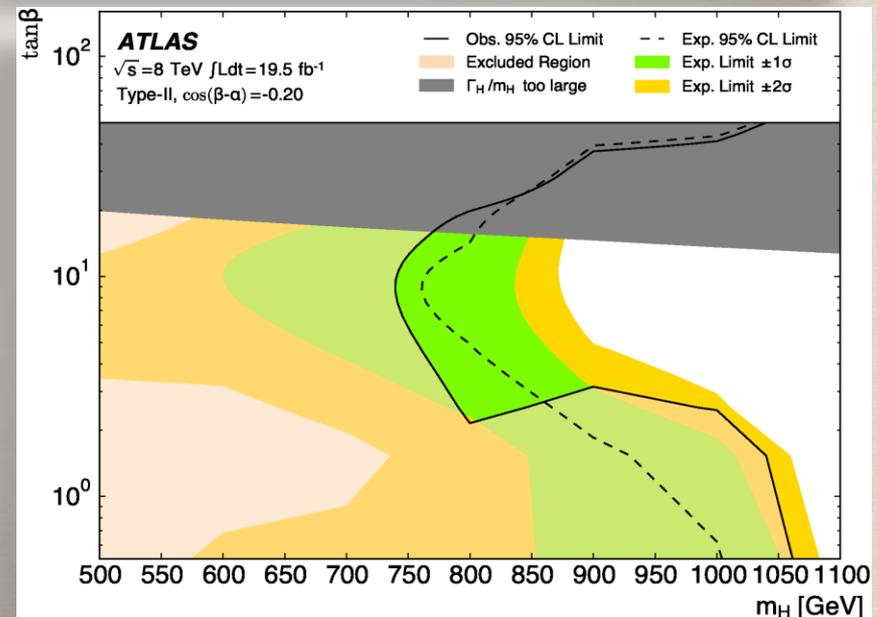
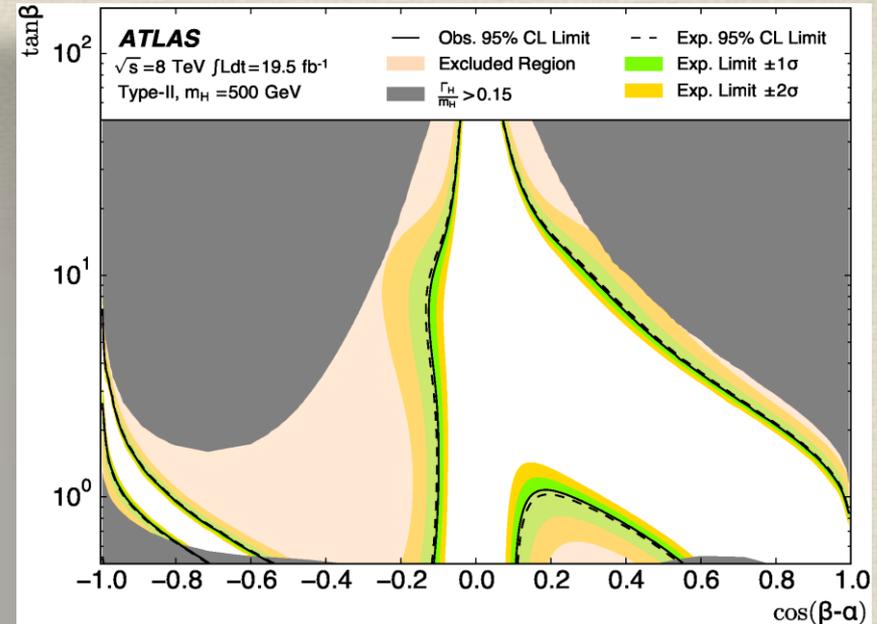
NEW

hh -> bbbb

ATLAS:

arXiv:1506.00285

- ❖ Using both pairs of resolved anti- k_T b-tagged jets and trimmed fat anti- k_T jets with two other b-jets.
- ❖ Sensitivity in the range of 500-2000 GeV
- ❖ Limits derived for both RS G_{KK}^* as well as $H \rightarrow hh$ in the 2HDM models.
- ❖ Here 2HDM type II example shown.
- ❖ Shaded areas do not provide reliable limits as the width becomes too large.

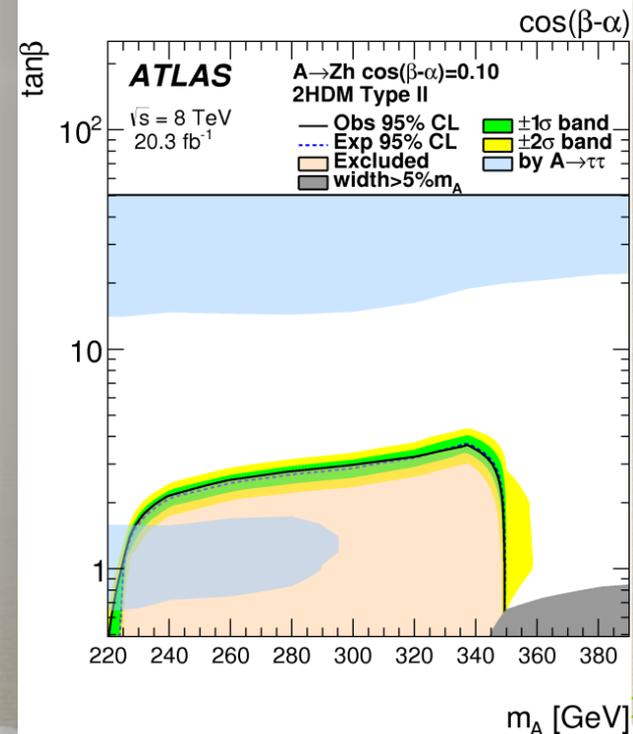
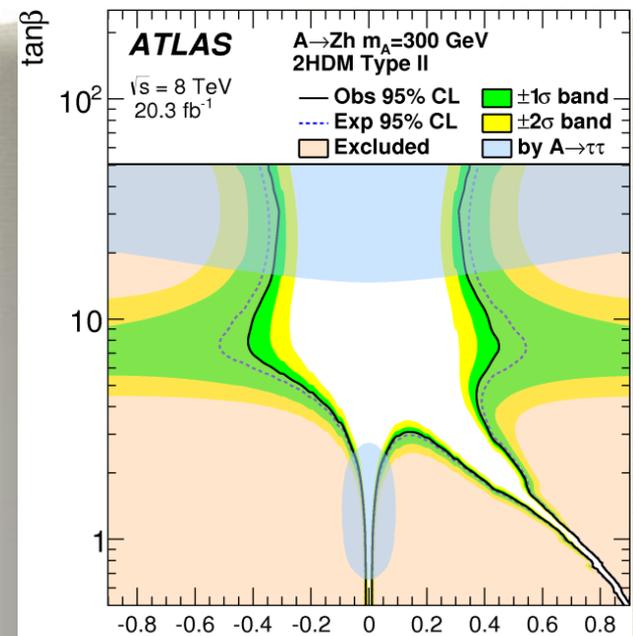


Zh production

ATLAS:

Phys. Lett. B 744 (2015) 163-183

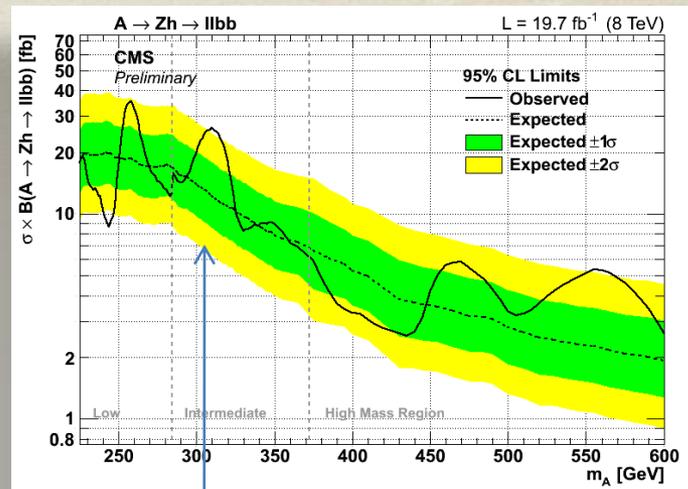
- ❖ $A \rightarrow hZ, Z \rightarrow ll, \nu\nu, h \rightarrow bb, \tau\tau$
 - ❖ h denotes here the observed Higgs with mass of 125 GeV
 - ❖ $m_A \in (220; 1000) \text{ GeV}$
 - ❖ 2HDM (type I & II) limits are given for specific choice of m_A or $\cos(\beta-\alpha)$.
 - ❖ Here example of 2HDM type II with $m_A=300 \text{ GeV}$ or $\cos(\beta-\alpha)=0.10$
 - ❖ Assumptions for calculating the limits:
- $m_A = m_H = m_{H^\pm}, m_h = 125 \text{ GeV}$
 and $m_{12}^2 = m_A^2 \tan\beta / (1 + \tan^2\beta)$
- ❖ Blue shaded areas are excluded by $A \rightarrow \tau\tau$ analysis [JHEP 1411 (2014) 056]



HZ production

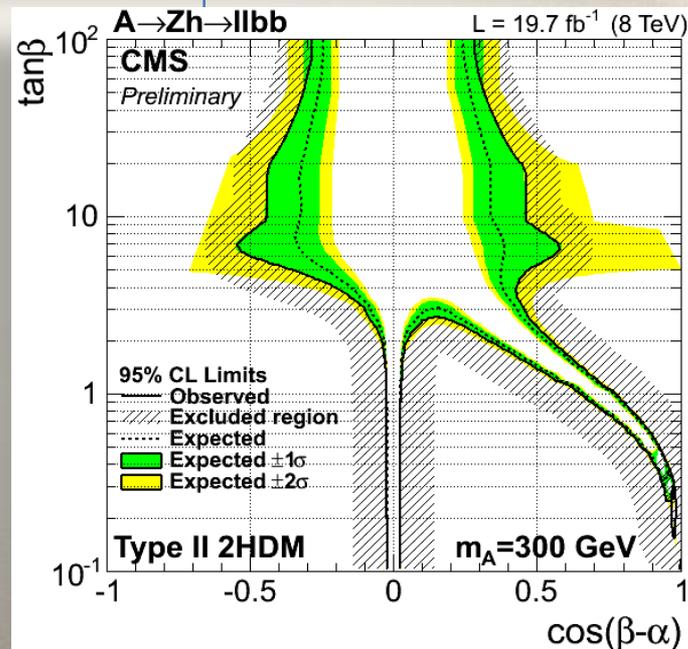
CMS: [arXiv:1504.04710](https://arxiv.org/abs/1504.04710)

- ❖ $A \rightarrow hZ, Z \rightarrow ll, h \rightarrow bb$
- ❖ h denotes here the observed Higgs with mass of 125 GeV
- ❖ 2HDM (type I & II) limits are given for specific choice of m_A .
- ❖ Here example of 2HDM type II with $m_A = 300$ GeV



CMS-PAS-HIG-13-025

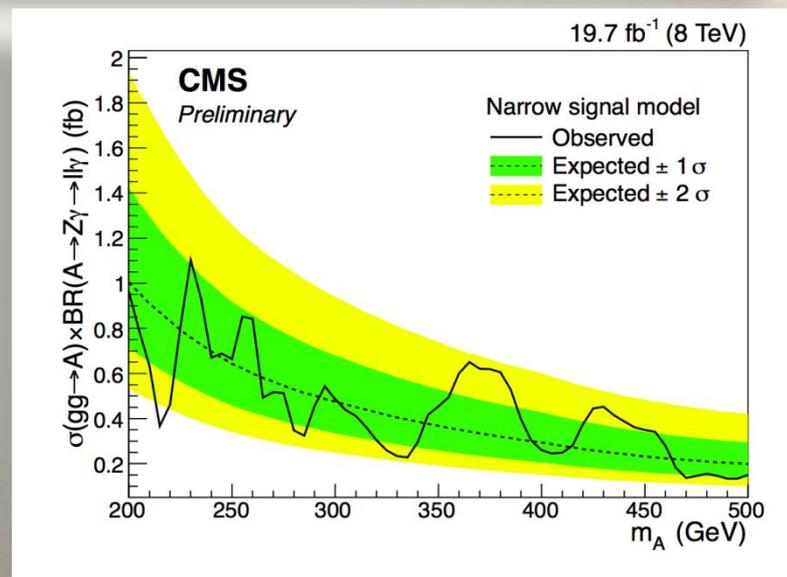
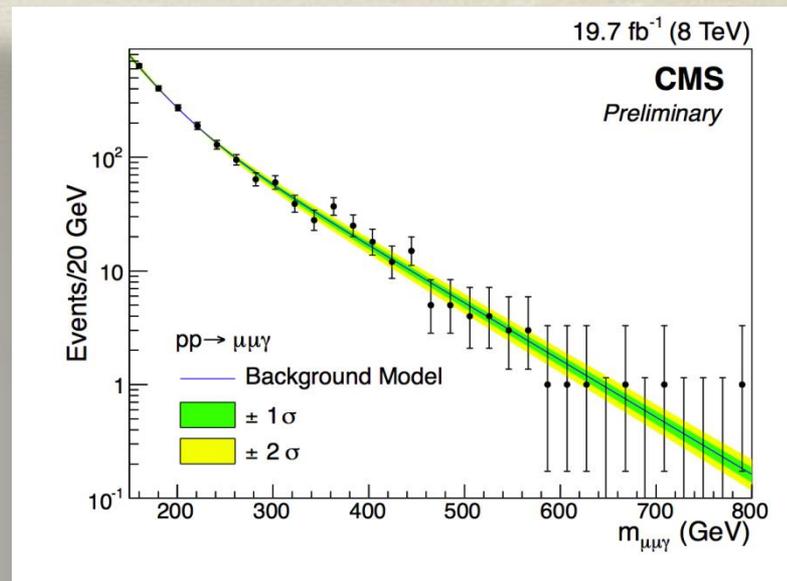
- ❖ $H \rightarrow hh$ & $A \rightarrow Zh$
- ❖ Sensitivity up to 360 GeV
- ❖ Limits derived for 2HDM type I & II.



Search for $A \rightarrow Z\gamma$

CMS PAS HIG-14-031

- ❖ $A \rightarrow Z\gamma, Z \rightarrow ll$ (e or μ)
- ❖ Model independent
- ❖ In particular, probes for composite Higgs models with $SU(4)$ chiral symmetry breaking.
- ❖ Sensitivity up to the $t\bar{t}$ threshold.



NMSSM

ATLAS:

arXiv:1505.01609

$H \rightarrow aa \rightarrow \mu\mu\tau\tau$

The most stringent limit is placed at 3.5% for $m_a = 3.75$ GeV. Upper limits are also placed on the production cross section of $H \rightarrow aa$ from 2.33 pb to 0.72 pb, for fixed $m_a = 5$ GeV with m_H ranging from 100 GeV to 500 GeV.

