Beyond the Standard Model searches in the Higgs sector from ATLAS and CMS

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CERN, 4 July 2012
Ladies and gentlemen, I think we've got it!
Discovery of a Higgs-like particle coupling to gauge bosons

Introduction

$$m_W = \tfrac{1}{2} g_W \upsilon \qquad m_H = \sqrt{2\lambda}\upsilon$$

❖ 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 (~m for fermions, ~m^2 for bosons)

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

The big picture @ 8 TeV

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

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

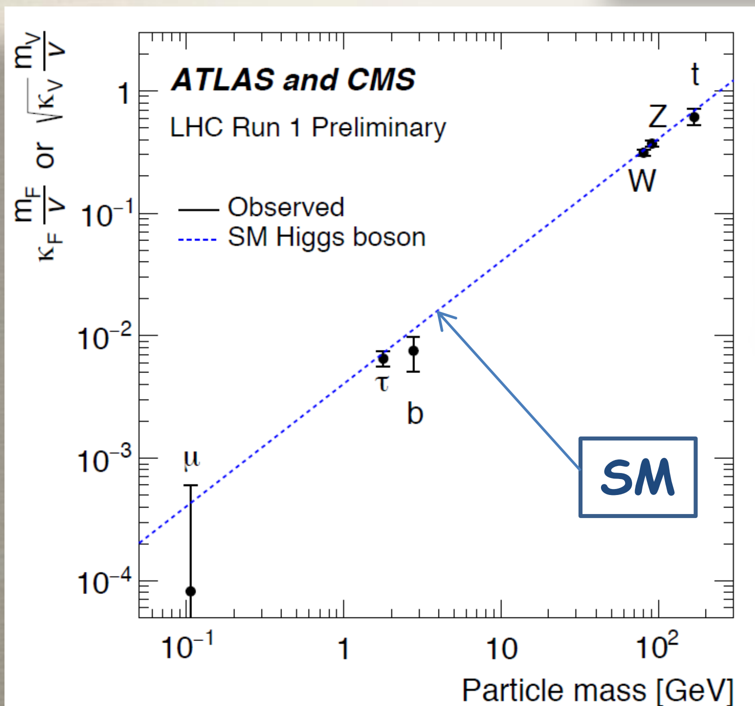
ATLAS J^{CP}: **Eur.Phys.J. C75(2015)476**
CMS J^{CP}: **Phys. Rev. D 92, 012004**

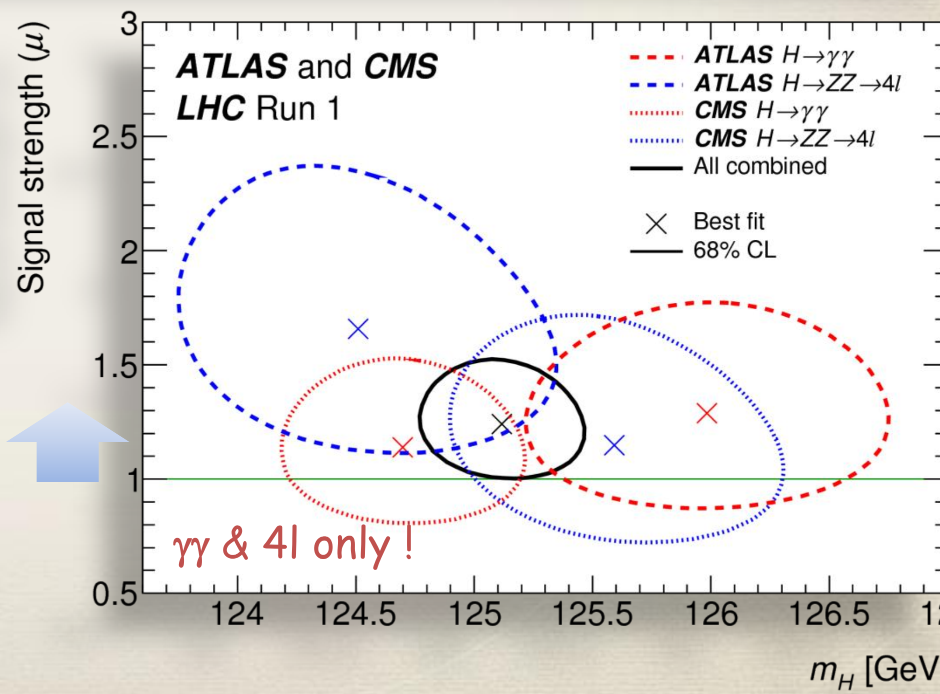
ATLAS $d\sigma/dx$: **Phys.Let. B 753(2016)69**
CMS $d\sigma/dx$: **JHEP 04 (2016) 005**

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$

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

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 ≠ 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, $\tau\tau$, $\mu\mu$, Zγ, etc.)
- Couplings to SM particles
- Spin and parity
- LFV, H->$\alpha\alpha$, H->inv, 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?

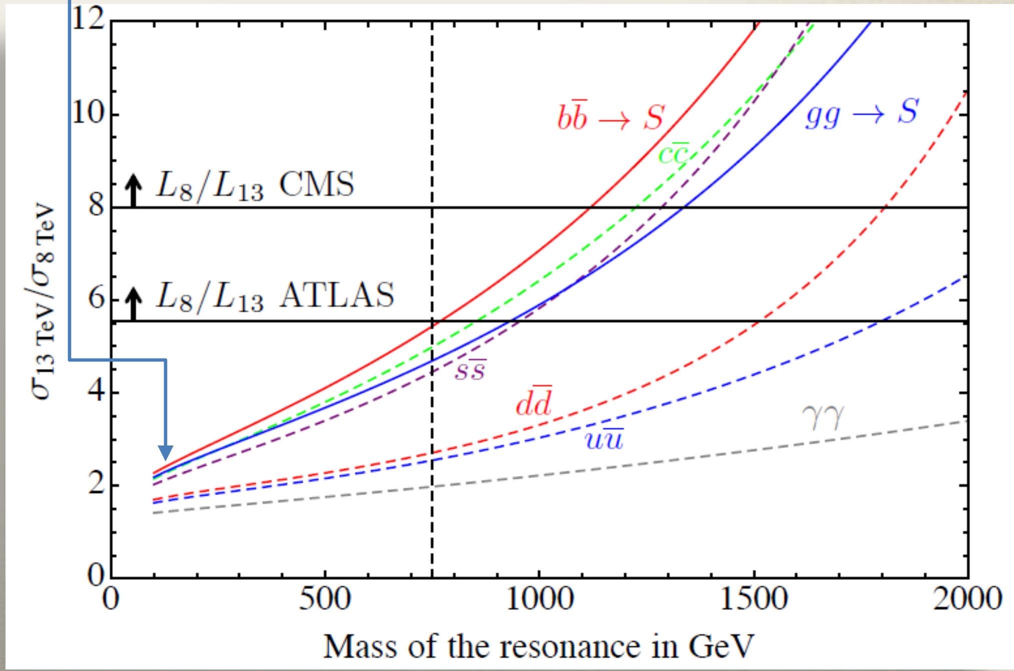
Note: heavily model dependent!

Having collected ~3.2 fb^{-1}/exp @13 TeV

- Limited increase of x-section for 125 GeV Higgs (~ x2)
- Cannot yet compete with 20 fb^{-1}/exp @8 TeV

	σ(pb) at 13 TeV	σ(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

- For various high mass searches we have already increased our reach!



Explore the 125 GeV Higgs @8 TeV

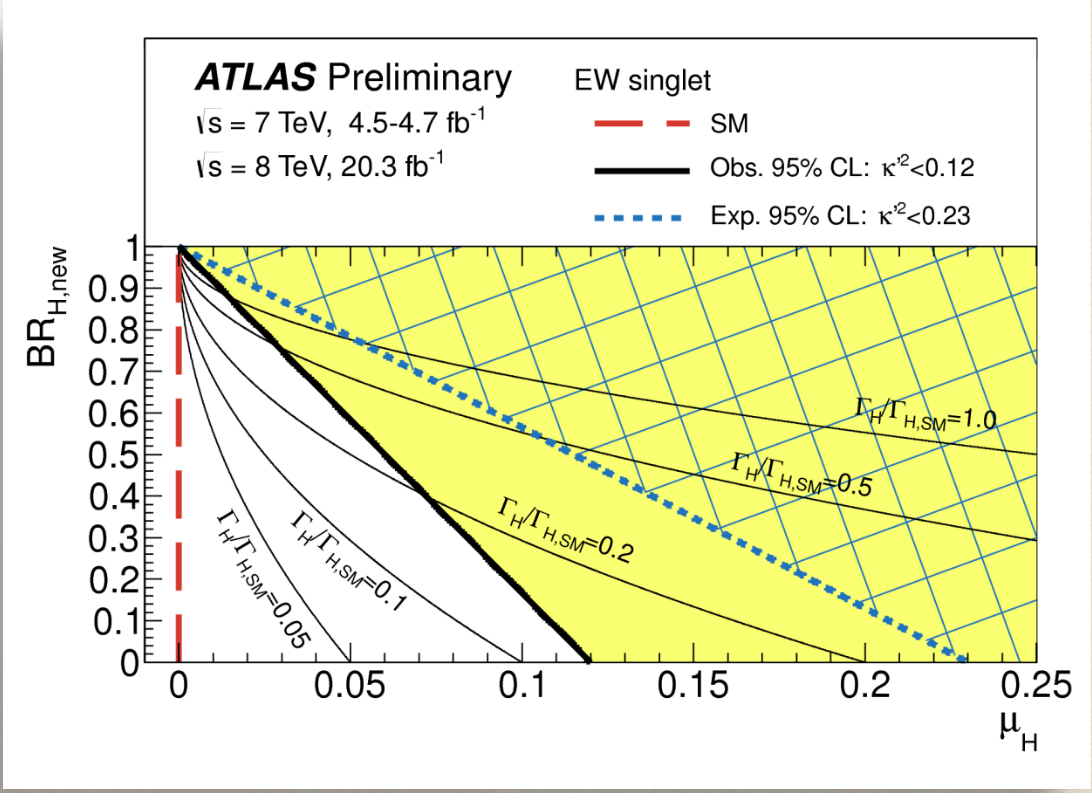
Additional Electroweak Singlet

- 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 **125 GeV** (heavier) of the pair.

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

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

$$\mu_H = \kappa'^2 \left(1 - \mathrm{BR}_{H,\mathrm{new}}\right)$$



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

ATLAS:
JHEP11(2015)206

ATLAS:
JHEP11(2015)206

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.

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

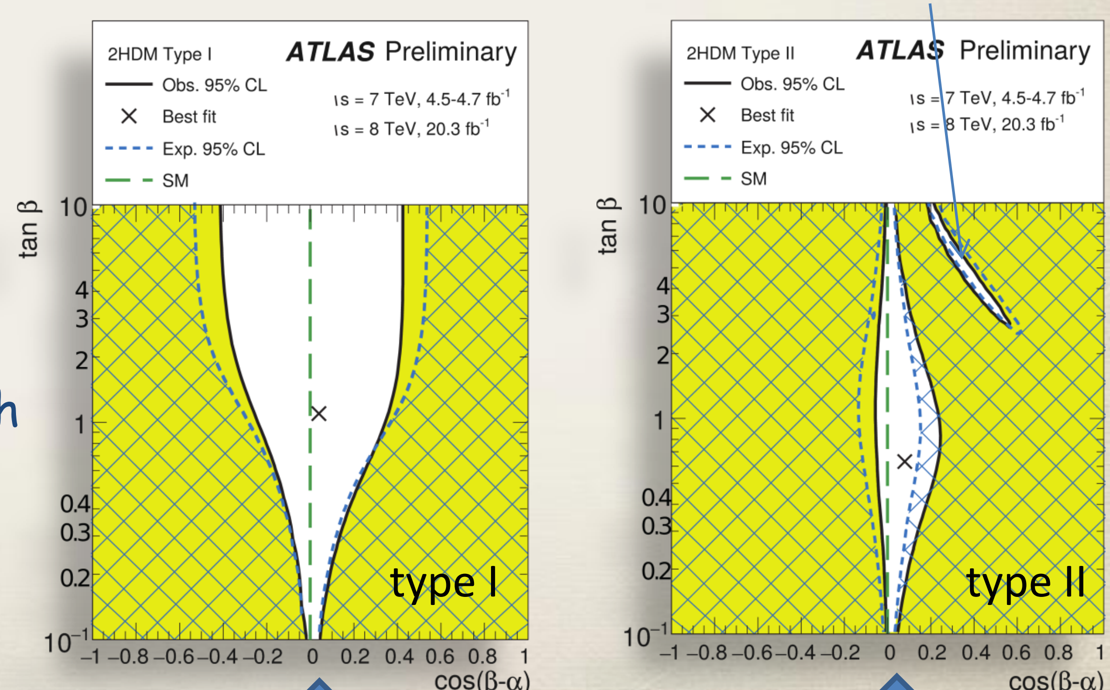
$$v_1^2 + v_2^2 = v^2 \approx (246\ \mathrm{GeV})^2$$

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

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

- „Decoupling": A, H^0, $H^\pm$ much heavier than the light h.
- Decoupling is not necessary. $\cos(\beta-\alpha)\to 0$ recovers properties of the SM Higgs, „Alignment"

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



Simplified hMSSM

ATLAS:
JHEP11(2015)206

❖ 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:

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

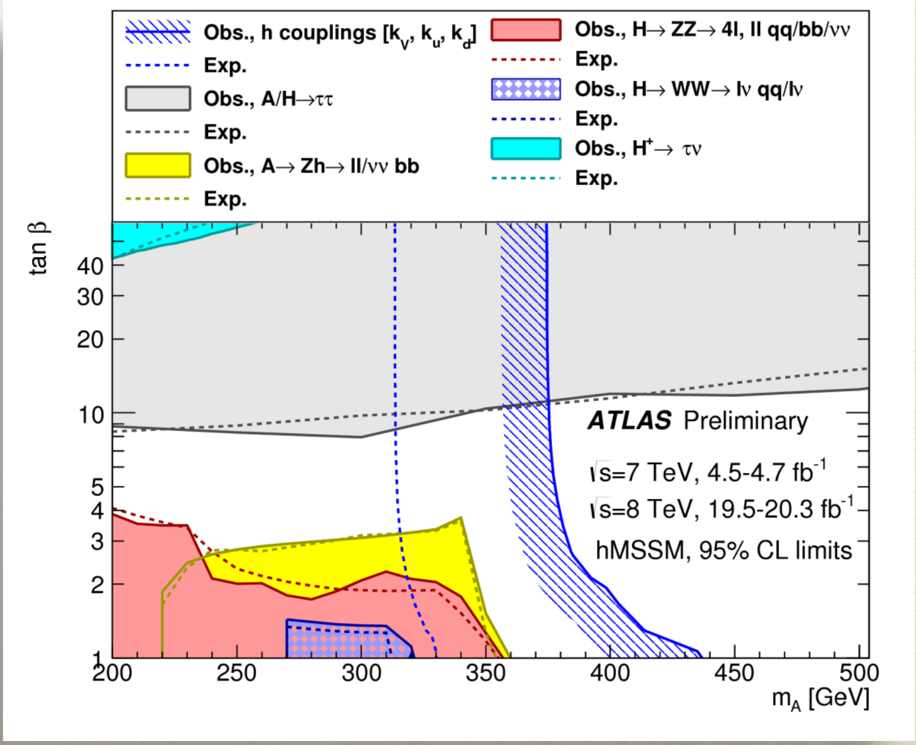
$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

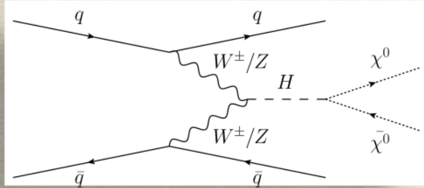
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$

❖ 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.)





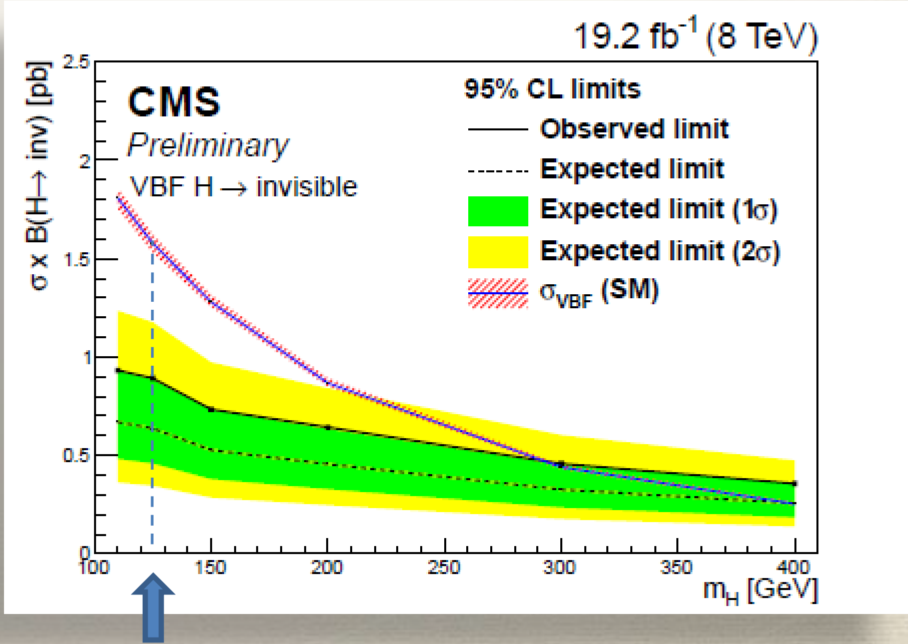
Invisible Higgs Decays

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^T_{miss}. [CMS: **CMS-PAS-HIG-14-038**, ATLAS: **arXiv:1508.07869**]
2) ZH associated production, with Z ->ll and Z->bb with H->inv. Signature: OSSF leptons (electrons or muons) forming a Z with large E^T_{miss}.
   [CMS: **Eur.Phys.J. C74 (2014)**, ATLAS: **Eur.Phys.J. C74 (2014)**]
3) VH (W or Z), where V->jj and H->inv. Signature: m_{jj} consistent with the V mass, together with large E^T_{miss}. [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.)
- Comb: [**CMS-PAS-HIG-15-012**] BR_{inv}<0.36 @ 95 CL (0.30 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.)



Higgs Portal to DM

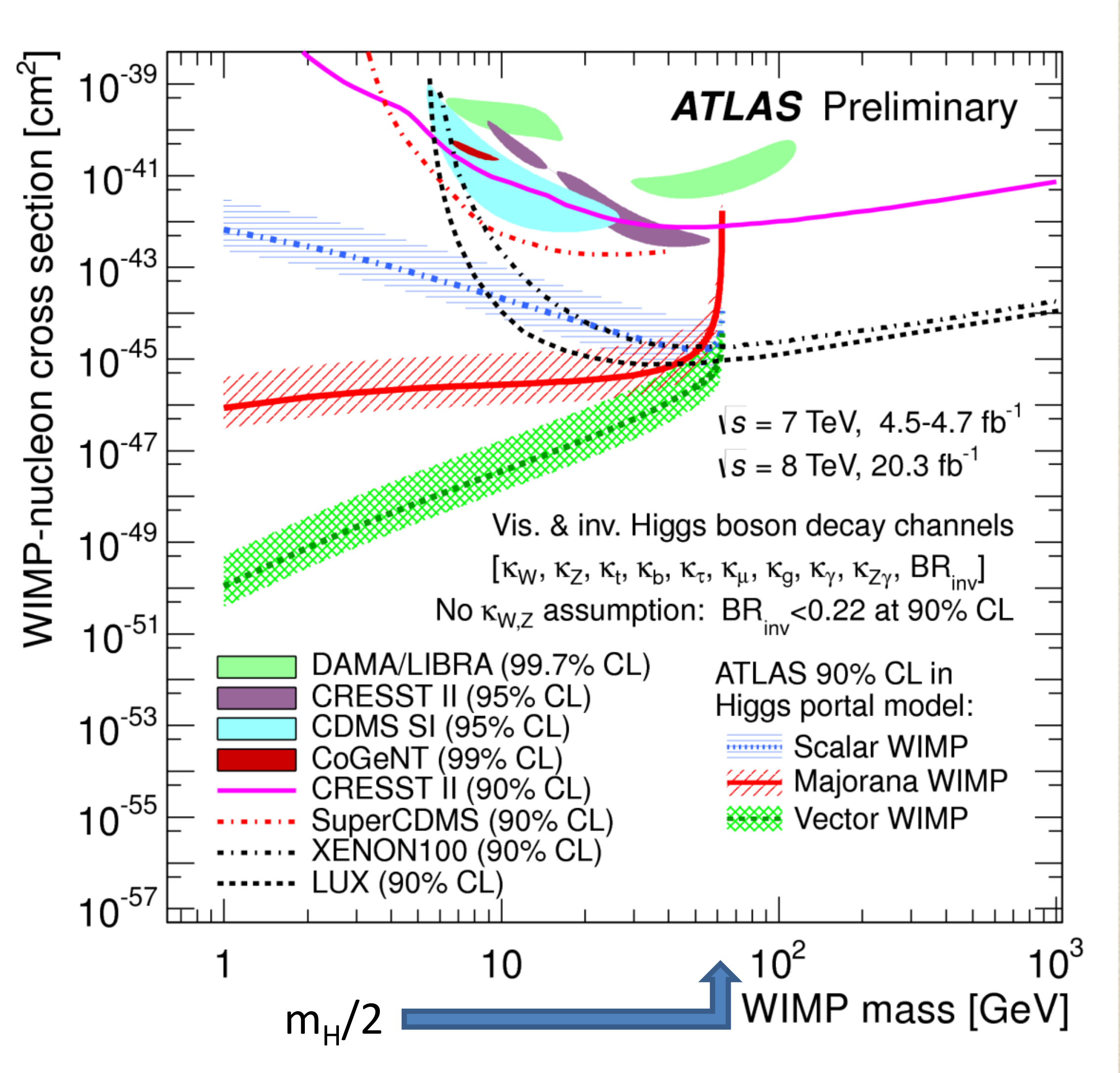
CMS: **Eur.Phys.J. C74 (2014)**
ATLAS: **JHEP11(2015)206**

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:PLB 749 (2015) 337
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.)

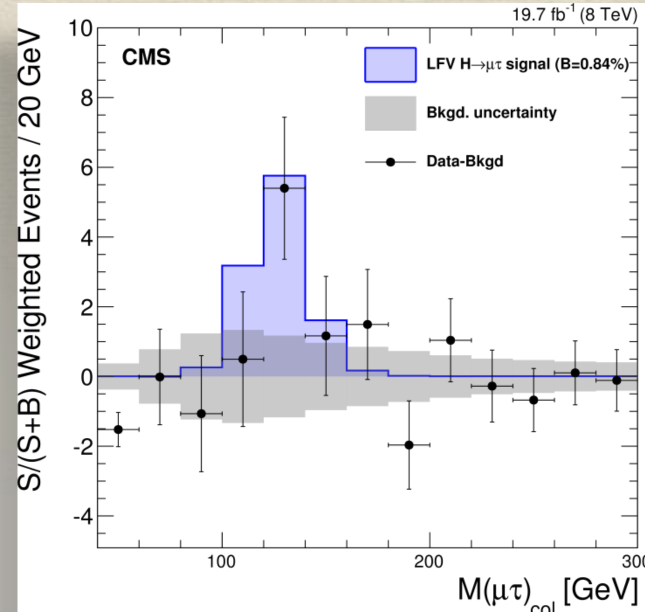
❖ Indirect limits on BR($H\to\tau\mu$) from searches for $\tau\to\mu\gamma$ weak O(10%).

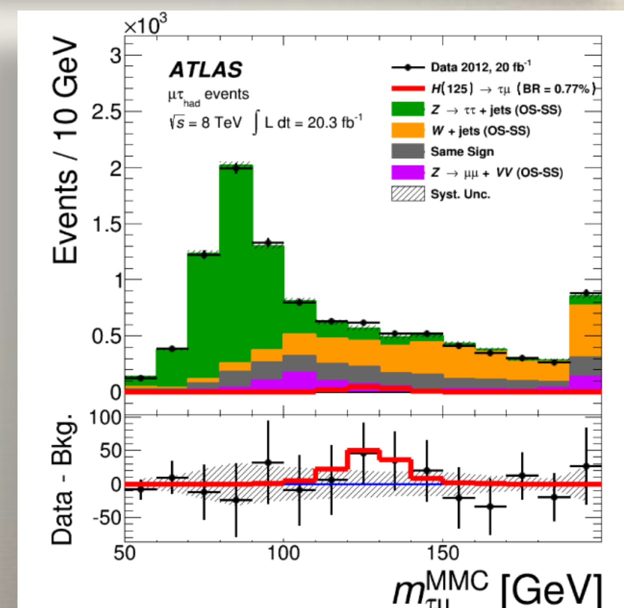
Best fit branching fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_{had}$	$0.72^{+1.18}_{-1.15}$	$0.03^{+1.07}_{-1.12}$	$1.24^{+1.09}_{-0.88}$
$\mu\tau$	$0.89^{+0.40}_{-0.37}$		

❖ CMS reports an excess of 2.5σ.

❖ ATLAS (only $\tau_{had}\mu$ channel):
BR($H\to\tau\mu$)<1.85% @ 95 CL
(Best fit: BR($H\to\tau\mu$)=(0,77 ± 0,62)%)

❖ **Run 2 has to follow-up!**





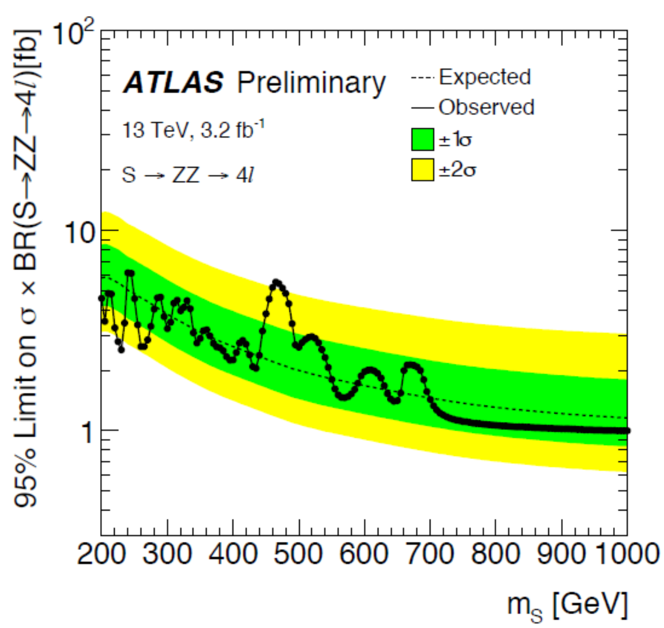
Explicit search for BSM objects @13 TeV

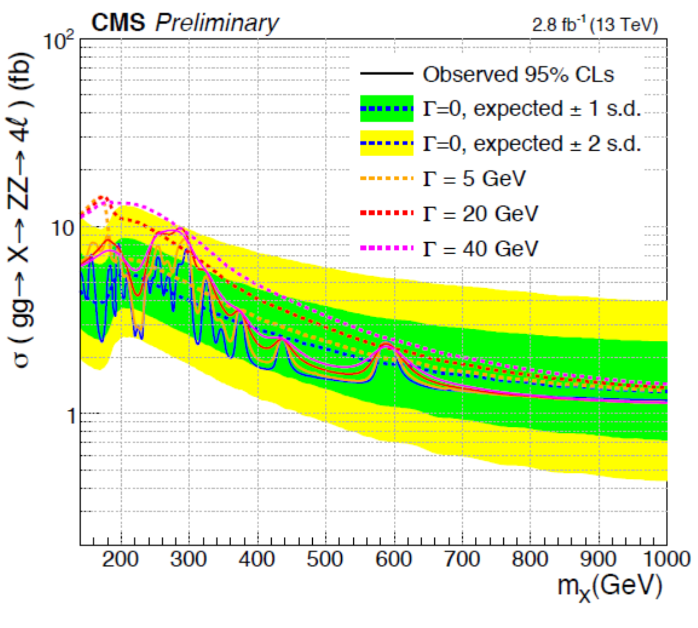
X->ZZ

❖ The search is for a resonance of m_H=140 (200)-1000 GeV for CMS (ATLAS).

❖ Search is based on selection from h(125) ->ZZ->4l analysis.

ATLAS: **ATLAS-CONF-2015-059** CMS: **CMS-PAS-HIG-15-004**





❖ Searched in the llνν channel as well with no signal observed:

ATLAS: **ATLAS-CONF-2016-012** CMS: **CMS-PAS-HIG-16-001**

❖ Searched in the llqq in both boosted and resolved regime:

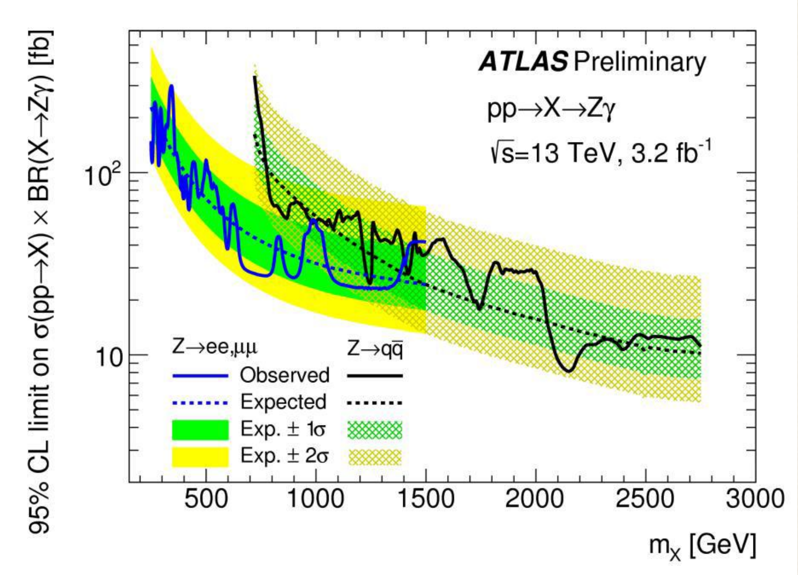
ATLAS: **ATLAS-CONF-2016-016**

X->Zγ

ATLAS: **ATLAS-CONF-2016-010**

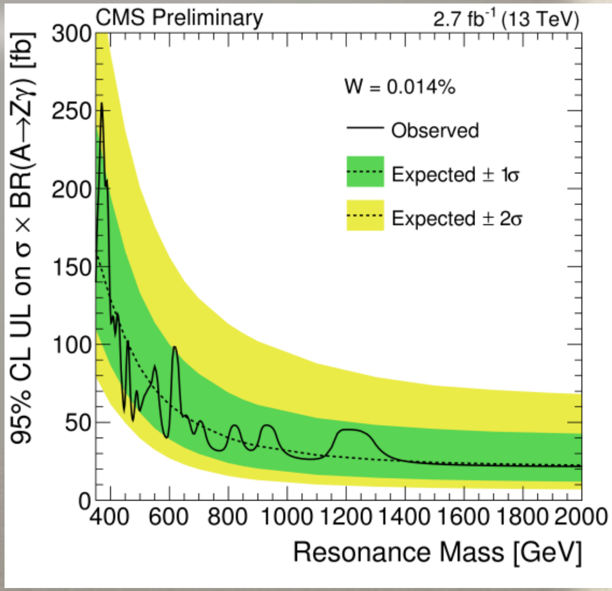
- **Z->ll +γ** (250-1500 GeV):
  ➢ 2 same flavor, **opposite sign leptons** consistent with Z.

- **Z->qq +γ** (720-2750 GeV):
  ➢ Jets reconstructed as a **single large-radius jet** with pT >200 GeV



CMS: **CMS-PAS-EXO-16-019**

- **Z->ll +γ** (400-2000 GeV):
  ➢ Similar sensitivity



A->Z/W+h, H->ZA

❖A→ZH (or H->ZA) with H being either the heavier or the lighter CP-even state a powerful probe of 2HDM models.
❖ For $m_A<2m_{top}$ this may be the dominant decay mode of the CP-odd A.

ATLAS: **ATLAS-CONF-2016-015**

A->Zh->vvbb, llbb

-Resolved/boosted *bb* (p_TZ</>500)

-1/2 b-jets

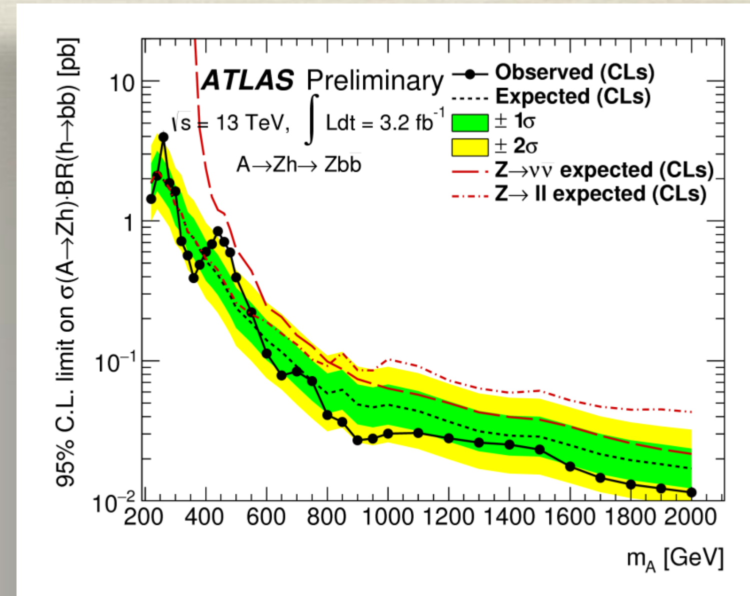
-Limits (200-2000) in ggF or bA/bbA

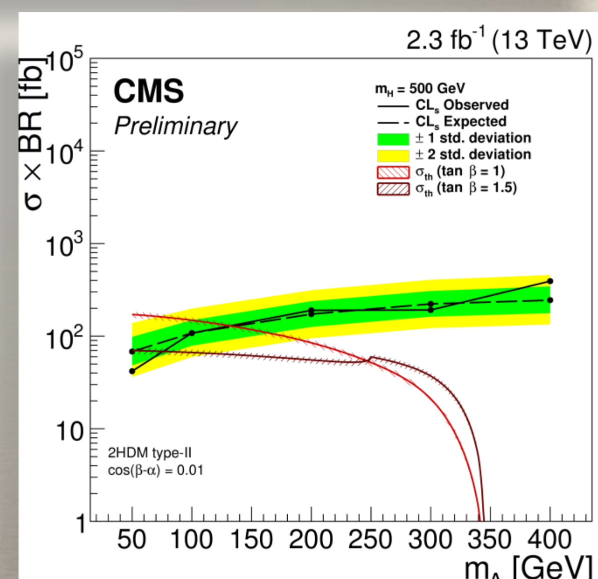
-Dominant backgrounds of Z+jets and ttbar are constrained in CR from data

CMS: **CMS-PAS-HIG-16-010**

H->ZA(llbb)

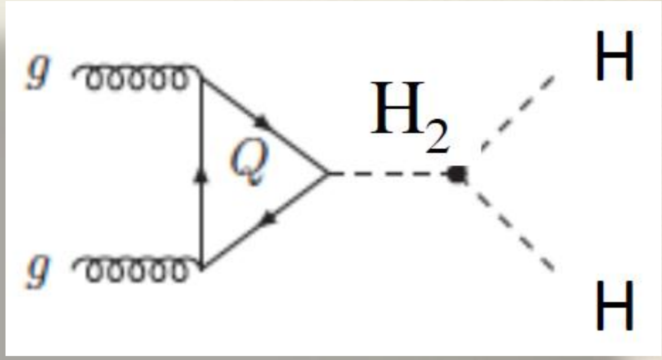
-2HDM with "twisted custodial sym": $m_H > m_A$





HH production

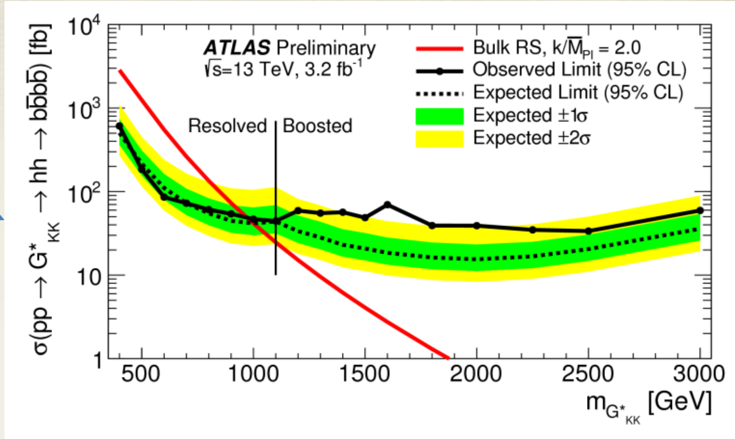
- Higgs self coupling already in the SM: $V = aH^2 + bH^3 + cH^4$
- HH Cross-section largely enhanced in BSM models:
  - Composite: factor <3,
  - Singlet models: factor up to 15,
  - 2HDM models: factor up to 50 !



- Current experimental limits still far from SM expected rates.
- SM prediction @ 125 GeV: 9.9 ± 1.3 fb

HH production

ATLAS: **ATLAS-CONF-2016-017**
hh -> 4b

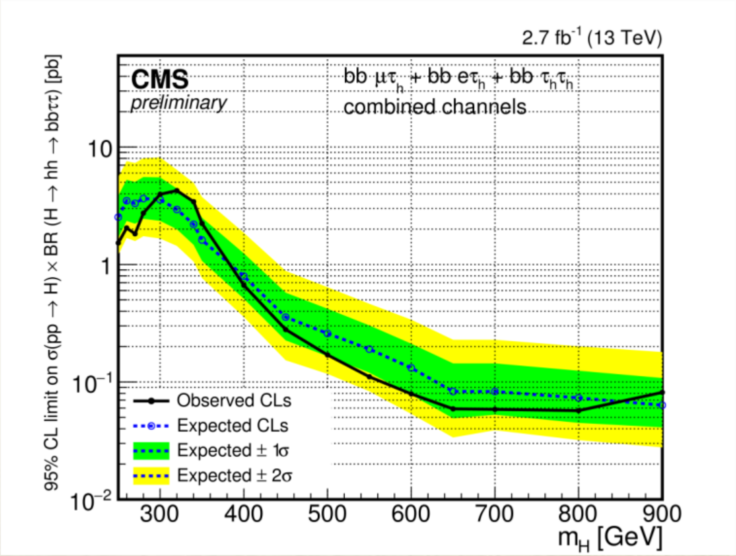


CMS: **CMS-PAS-HIG-16-002**
hh -> 4b

ATLAS: **ATLAS-CONF-2016-017**
hh -> bbγγ

CMS: **CMS-PAS-HIG-16-012**
hh -> bbττ (non-resonant)

CMS: **CMS-PAS-HIG-16-013**
hh -> bbττ (resonant)

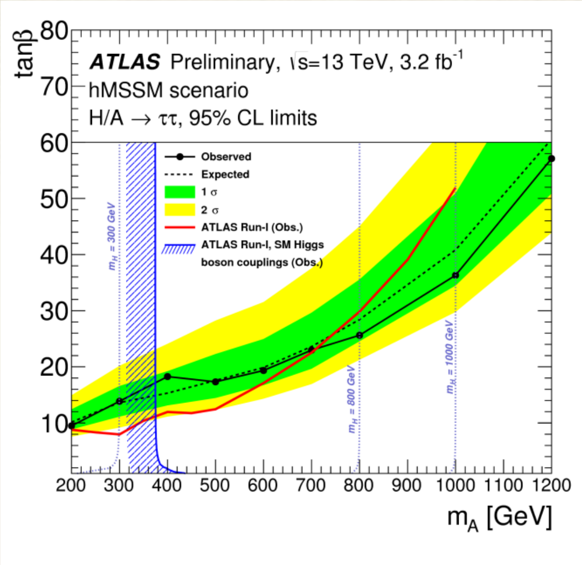


H->τ

ATLAS: **ATLAS-CONF-2015-061**

A/H ->ττ

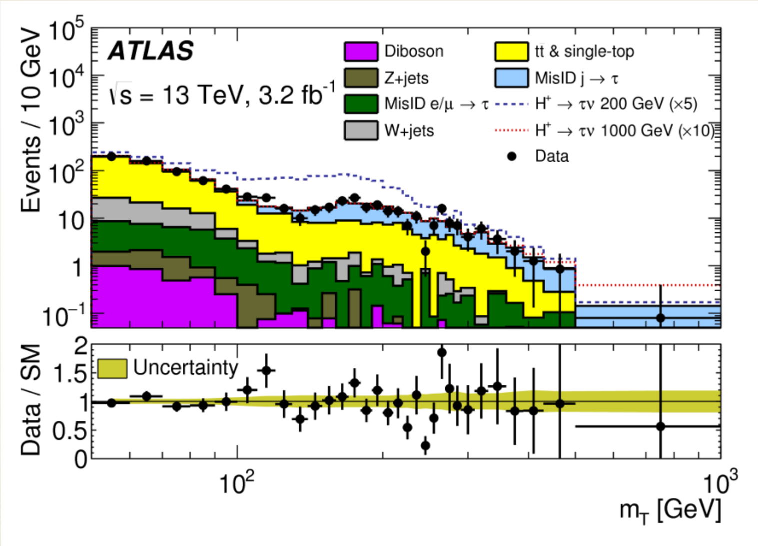
ggF and bA/bbA production

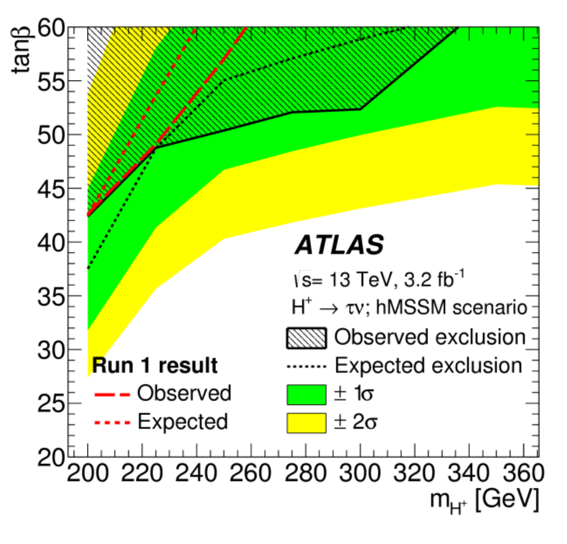


ATLAS: **arXiv:1603.09203**

H^{+}->τν

t-associated production





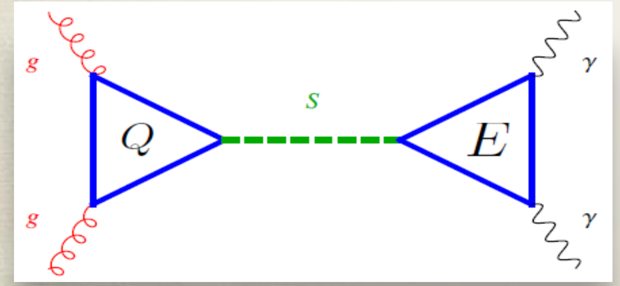
Search for diphoton resonances ($X \to \gamma\gamma$)

1) Clean signal over well determined SM background.
2) High mass resonances decaying to $\gamma\gamma$ predicted in various BSM scenarios.
3) Benchmark models exist on the market.

Spin-0

(e.g. extended Higgs sector)

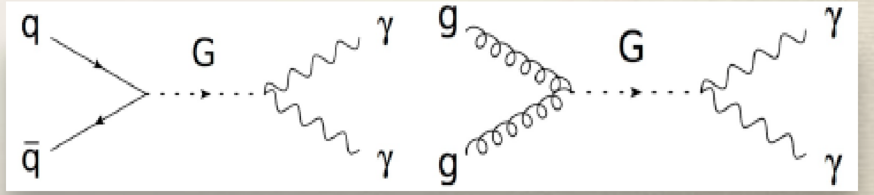
- 2HDM class of models
- h^0, $\boxed{H^0, A^0}$, $H^\pm$
- Loop-induced decays can have sizable branching ratio to photons



Spin-2

(e.g. Randall-Sundrum graviton)

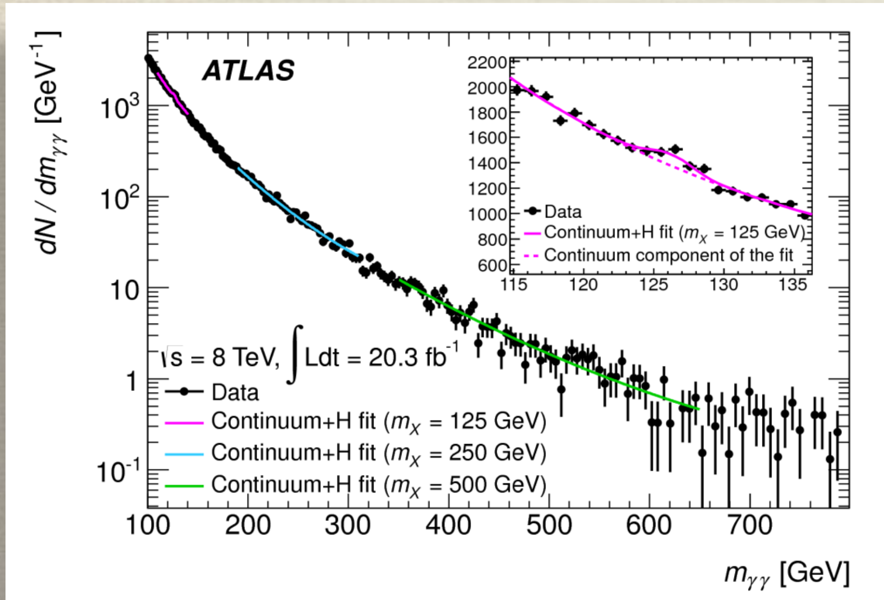
- Kaluza-Klein excited state of the graviton (TeV-scale)
- Tower of states
- Predicts universal couplings to SM fields (κ/M_{Pl})
- m_G, $\Gamma_G \sim (\kappa/M_{Pl})^2$



* Owing to the Landau-Young theorem, vector resonances are excluded

X->γγ - 8 TeV legacy

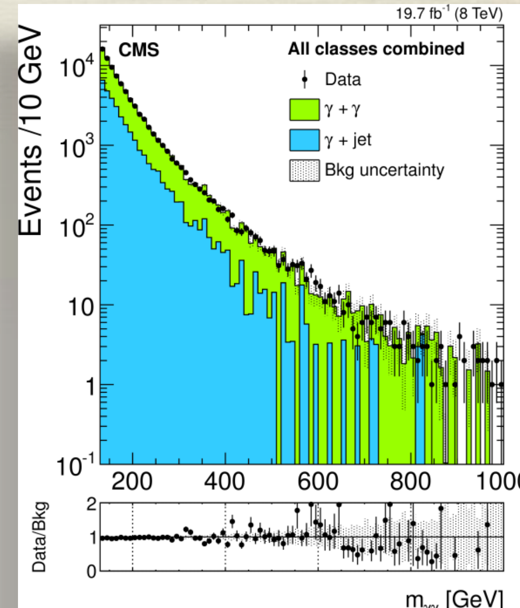
ATLAS: PRL 113, 171801 (2014)



Search for narrow scalar resonances

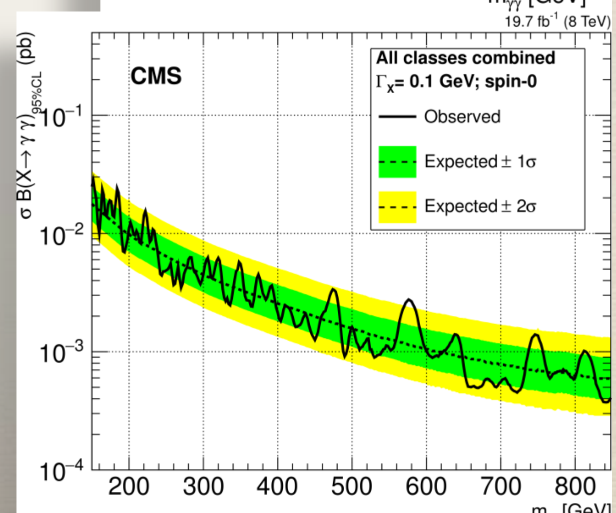
Limit on J=0 reported for 65-600 GeV

CMS: **Phys. Lett. B 750 (2015) 494**



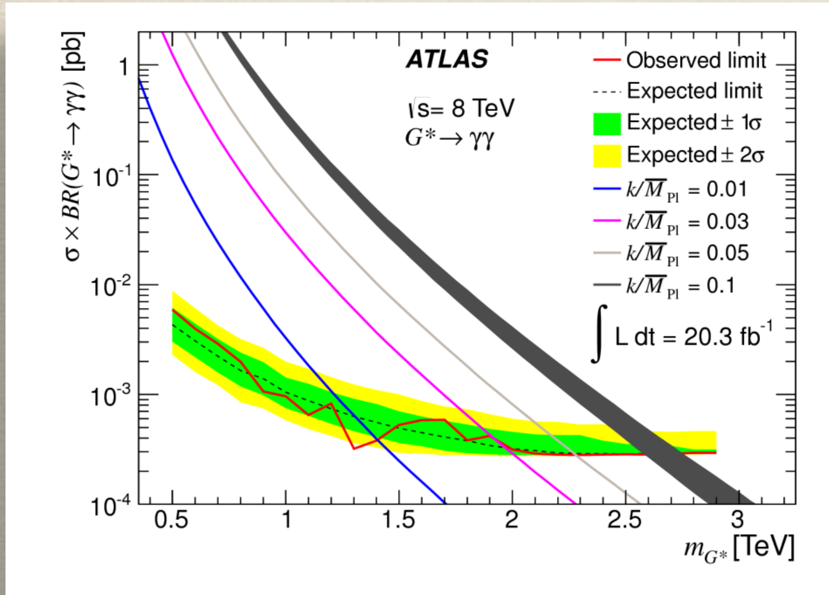
Spin 0 narrow hypothesis
(spin 2 very similar)
wide & narrow tested

Limit ~fb^{-1} @750 GeV



X->γγ - 8 TeV legacy

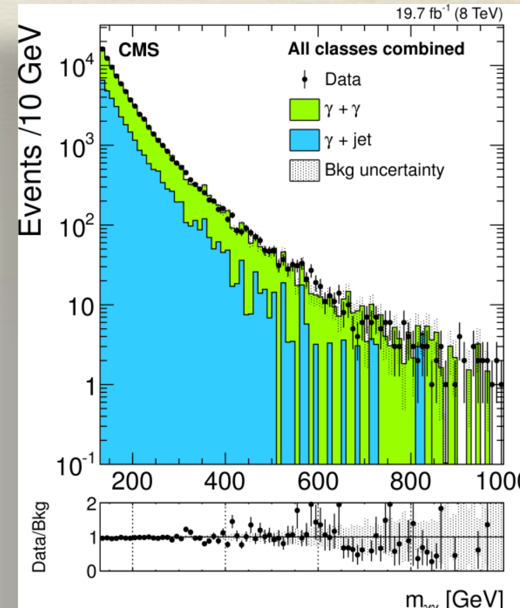
ATLAS: **Phys. Rev. D 92, 032004 (2015)**



Search for narrow J=2 resonances.

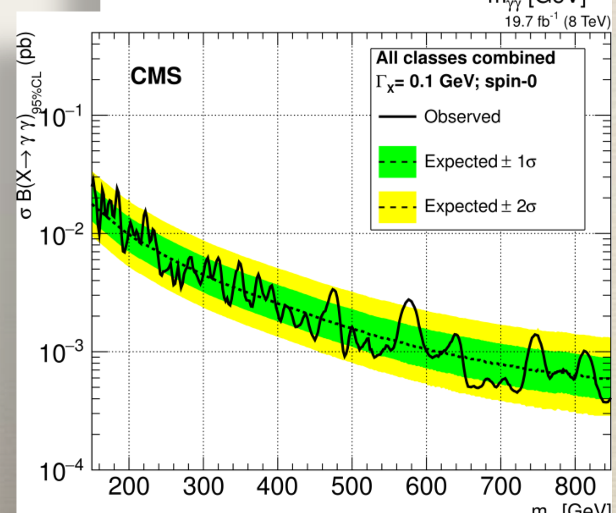
Limit on RS scenario reported for 0.5-2.6 TeV

CMS: **Phys. Lett. B 750 (2015) 494**



Spin 0 narrow hypothesis
(spin 2 very similar)
wide & narrow tested

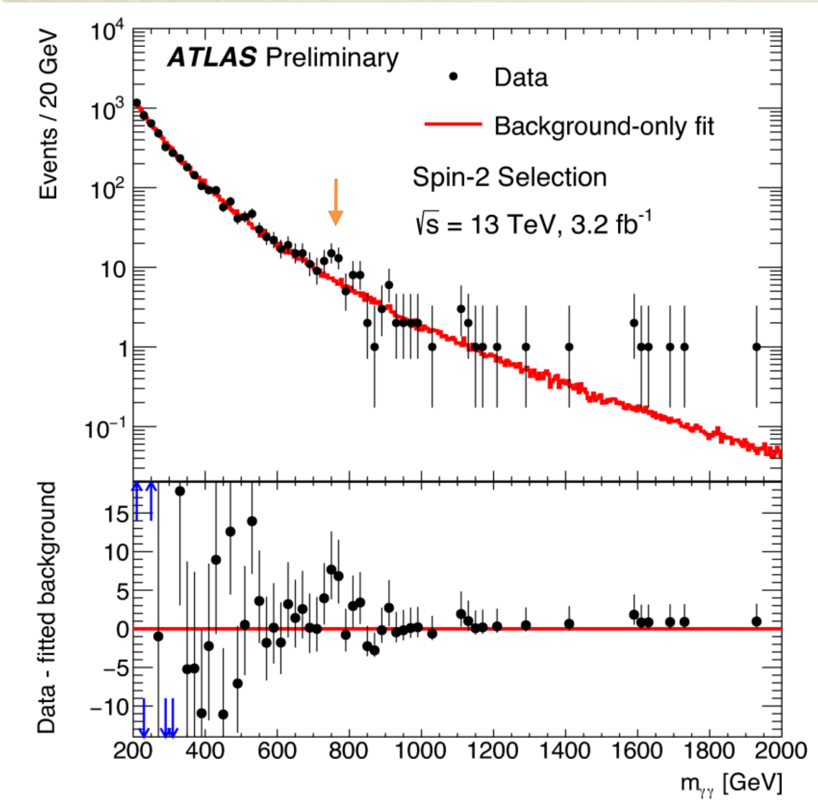
Limit ~fb^{-1} @750 GeV



X->γγ @ 13 TeV

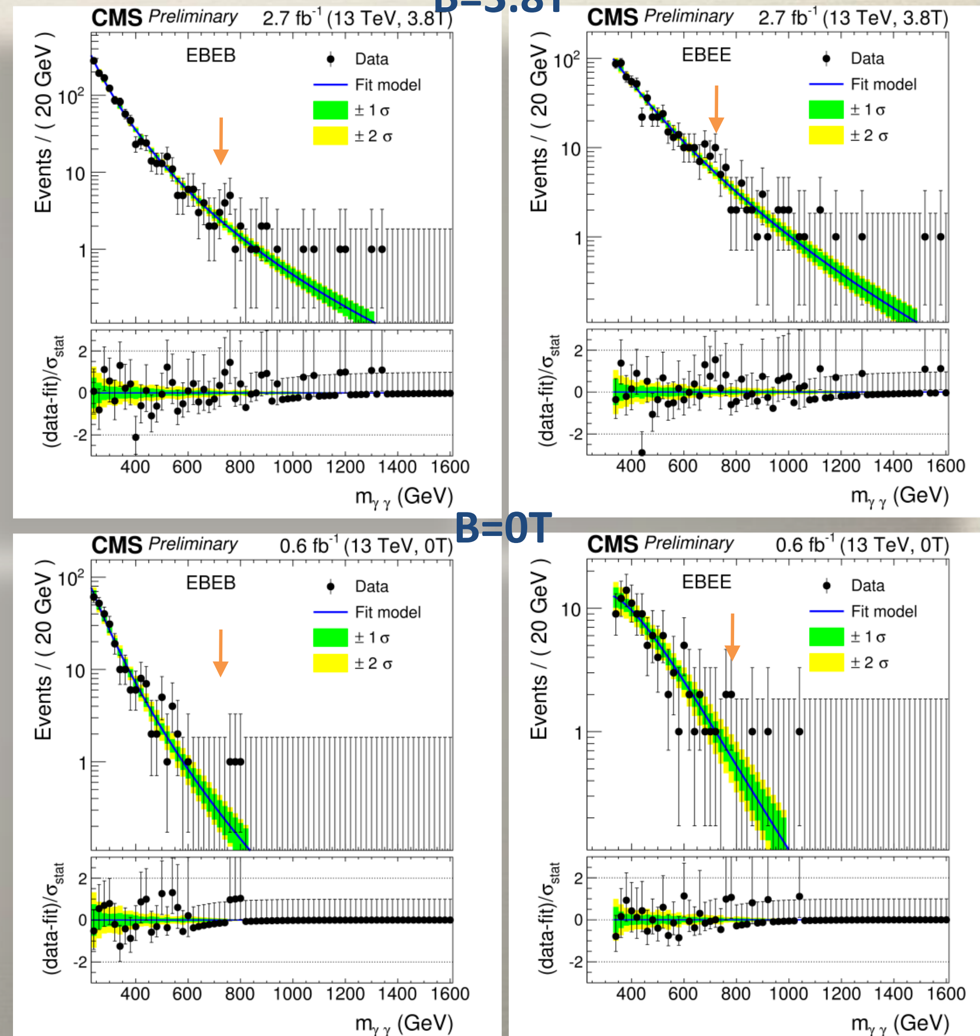
ATLAS: **ATLAS-CONF-2016-018**

CMS: **CMS-PAS-EXO-16-018**



B=3.8T

B=0T



Search for diphoton resonances X->$\gamma\gamma$ (ATLAS)

1) Common pre-selection and photon identification
2) MV regression to calibrate photon cluster (0.6-1.6%, validated with Z->ee)
3) Photon isolation (calorimeter cone + track isolation)

Spin-0

Optimized for Higgs-like signal

❖ $E_T^{\gamma 1} > 0.4\ m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3\ m_{\gamma\gamma}$
Effectively deplete forward regions

❖ Limit on fiducial cross section

❖ Search range:

m_X = [200 GeV – 2 TeV]

Γ_X/m_X = [0% - 10%]

❖ Signal modeled as DSCB (accounting for both natural width and detector resolution)

❖ Bkg: functional fit from sidebands

$$f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b\, x^{\sum_{j=0}^{k} a_j (\log x)^j}$$

$$x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

Spin-2

Targets RS KK graviton benchmark

❖ Loose selection:
$E_T^{\gamma 1} > 55$ GeV, $E_T^{\gamma 2} > 55$ GeV

❖ Search range:

m_G = [500 GeV – 3 TeV]

κ/M_{Pl} = [0.01-0.3]

Γ_G/m_G ~ [0.01% - 11%]

❖ Signal modeled as analytical convolution of RS-prediction and DSCB.

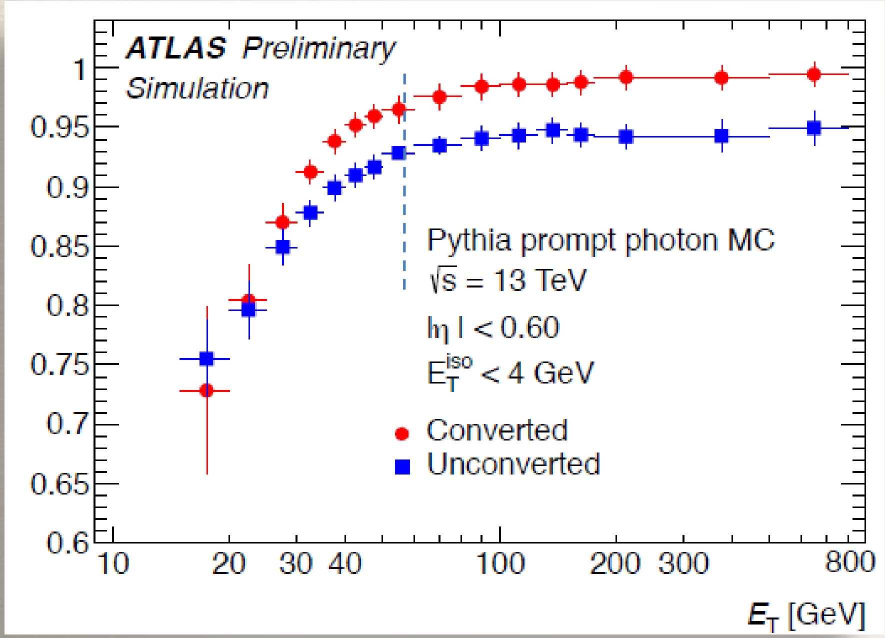
Bkg: MC+data CR -> high mass

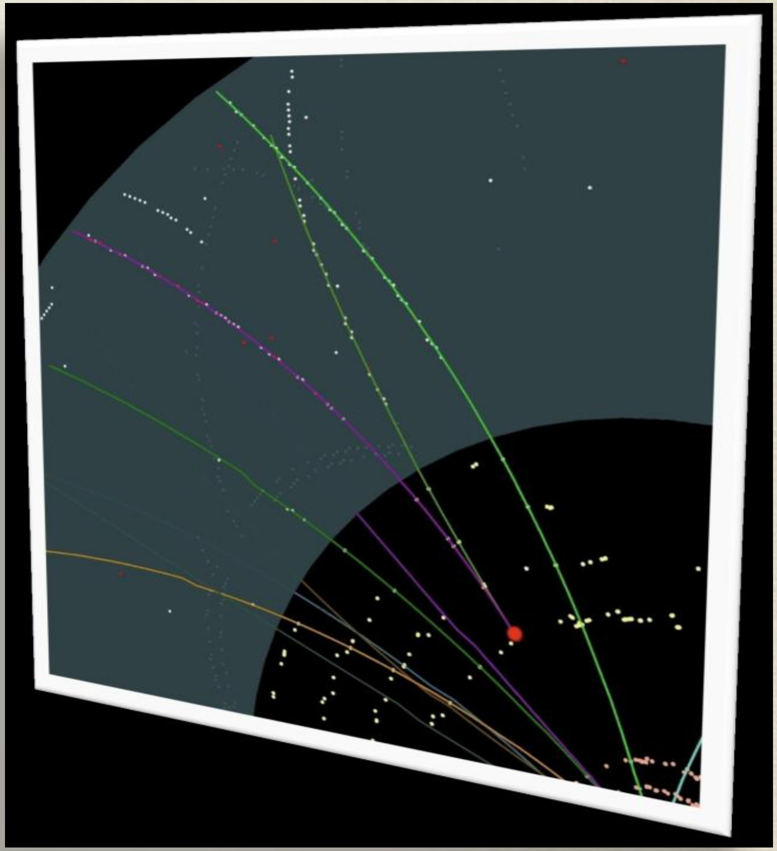
Irreducible ($\gamma\gamma$): SHERPA $\gamma\gamma$ including detector simulation, reweighted to DIPHOX $m_{\gamma\gamma}$

Reducible (γj, jγ, jj): data CR (γ ID)

Search for diphoton resonances X->γγ (ATLAS)

1) High efficiency for both converted and unconverted photons





2) Isolation:

- Calorimeter (ΔR=0.4): $E_T^{iso} < 0.022\, E_T^{\gamma} + 2.45$ GeV
- Track p_T^{iso} (ΔR=0.2) $p_T^{iso} < 0.05\, E_T^{\gamma}$

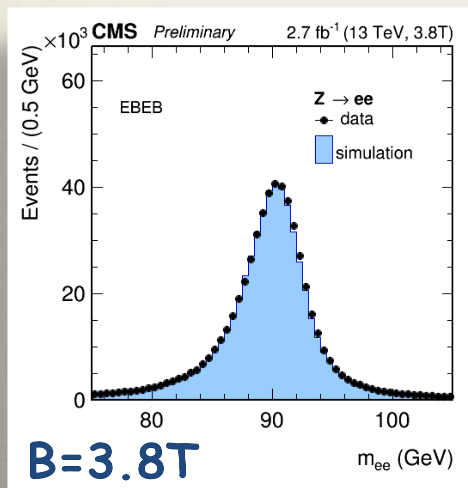
Search for diphoton resonances $X\to\gamma\gamma$ (CMS)

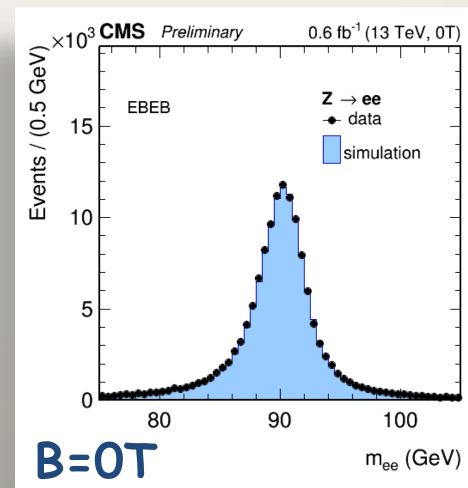
1) Common analysis for spin-0 and spin-2: Two isolated photons with pT above 75GeV. At least one of which in the barrel ($|\eta|<1.44$).

2) Separate for 2.7 fb^{-1} (B=3.8T) and 0.6 fb^{-1} (B=0T)

No information on tracks momenta: Weakens power of isolation requirements Complicates primary vertex selection (based on recoiling tracks). ☹

No energy spread due to brem/conversions: Better intrinsic energy resolution and simpler e/γ extrapolation. Use more information on lateral shower profile. ☺





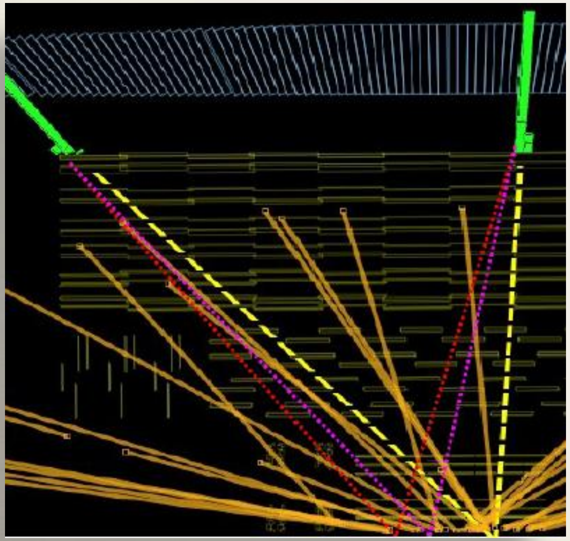
3) Split in barrel-barrel(EBEB) and barrel-endcaps(EBEE) categories.

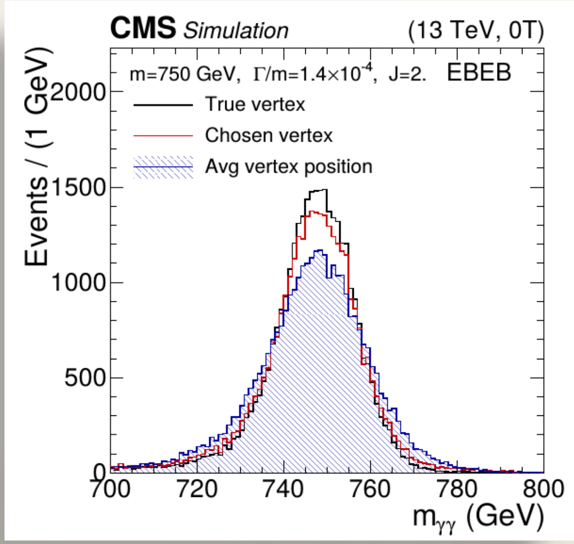
Per-photon efficiency in the barrel: 90(85)% at 3.8(0)T.

Per-photon efficiency in the endcaps: 85(70)% at 3.8(0)T.

Search for diphoton resonances X->$\gamma\gamma$ (CMS)

1) Correct assignment of the primary vertex affects the resolution on the reconstructed $\gamma\gamma$ invariant mass.
2) p_T of the associated tracks are used for 3.8 T data and simpler track counting for the 0 T sample.

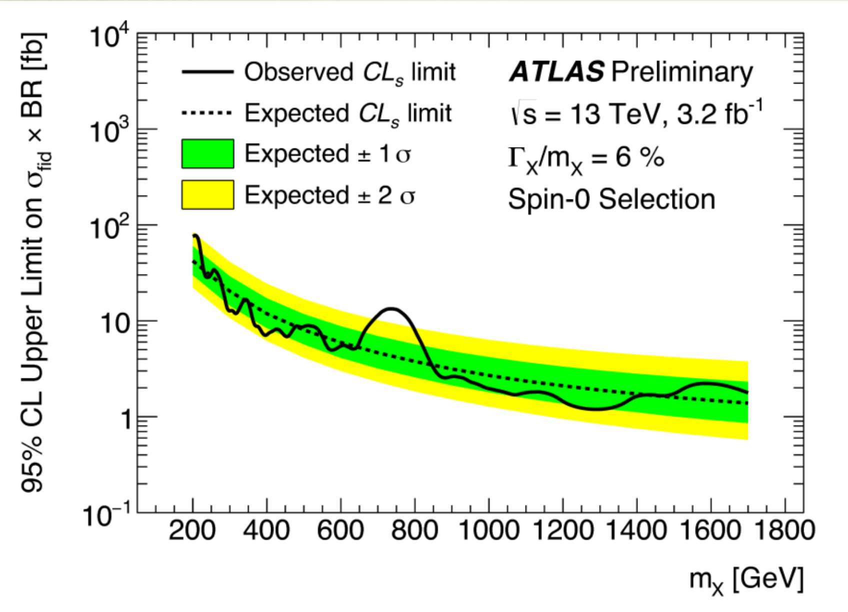




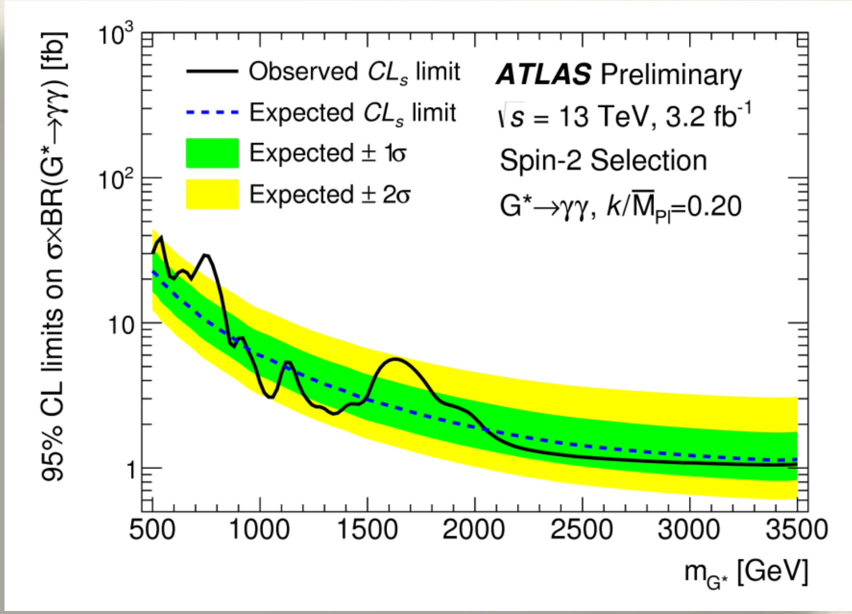
3) Signal model: convolution of line-shape with detector resolution.
4) Bkg model: parametric function of $m_{\gamma\gamma}$, independently for each cathegory.
5) Simultaneous unbinned likelihood fit to $m_{\gamma\gamma}$ in all four analysis categories.
6) Profile likelihood ratio test statistics is used.

Interpretation of the results
X->γγ (ATLAS)

Spin-0



Spin-2



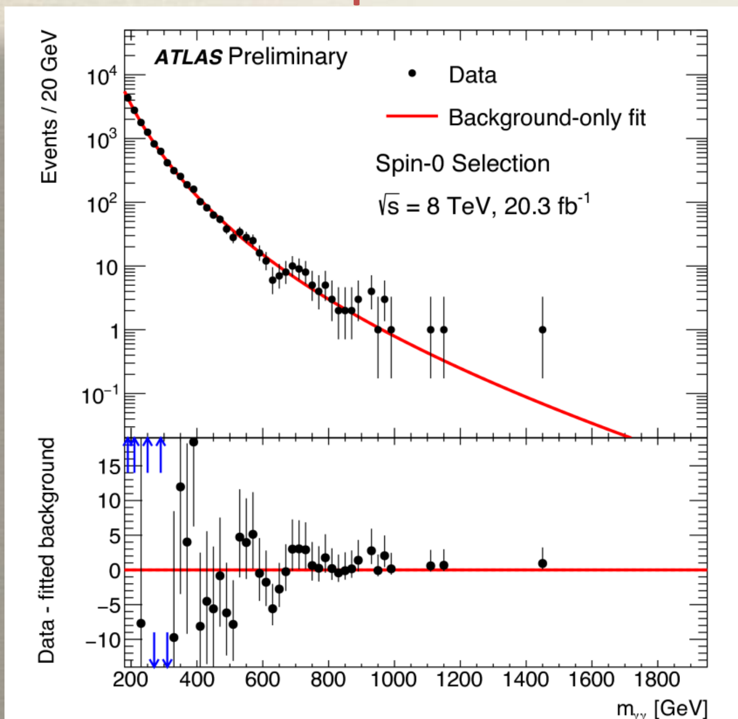
Largest deviation from B-only hypothesis:
- ❑ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
- ❑ Local Sign = **3.9 σ**
- ❑ Global Sign = **2.0 σ**

Largest deviation from B-only hypothesis:
- ❑ m_G ~ 750 GeV, κ/M_{Pl} ~ 0.2 (Γ_G ~ 6% m_G)
- ❑ Local Sign = **3.6 σ**
- ❑ Global Sign = **1.8 σ**

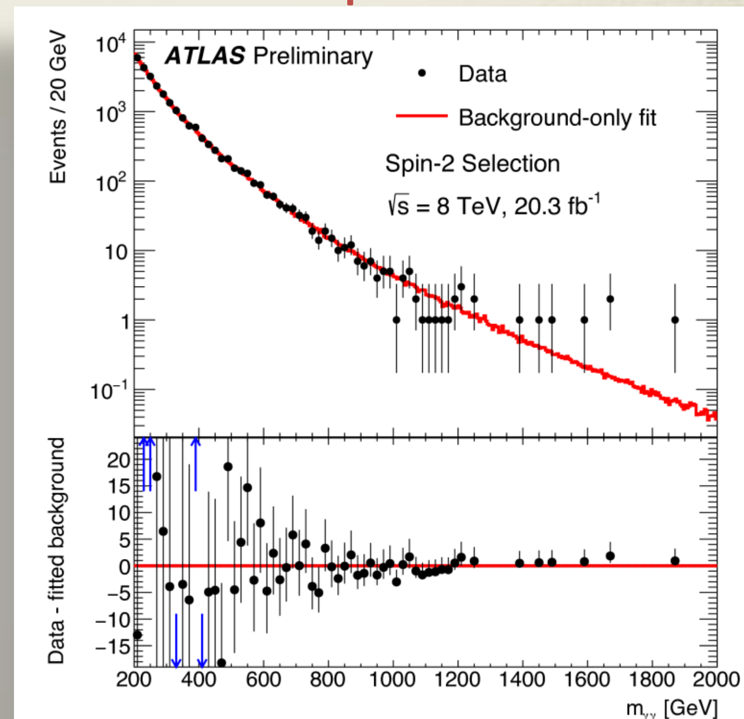
Compatibility with 8 TeV results
X->γγ (ATLAS)

* 8 TeV data re-analyzed: new γ calibration + Run 1 selections + 13 TeV analysis methods

Spin-0



Spin-2



1.9 σ at m_X = 750 GeV , Γ_X/m_X = 6%
Compatibility with 13 TeV scalar:
- gg (scaling: 4.7) -> compatibility: 1.2 σ
- qq (scaling: 2.7) -> compatibility: 2.1 σ

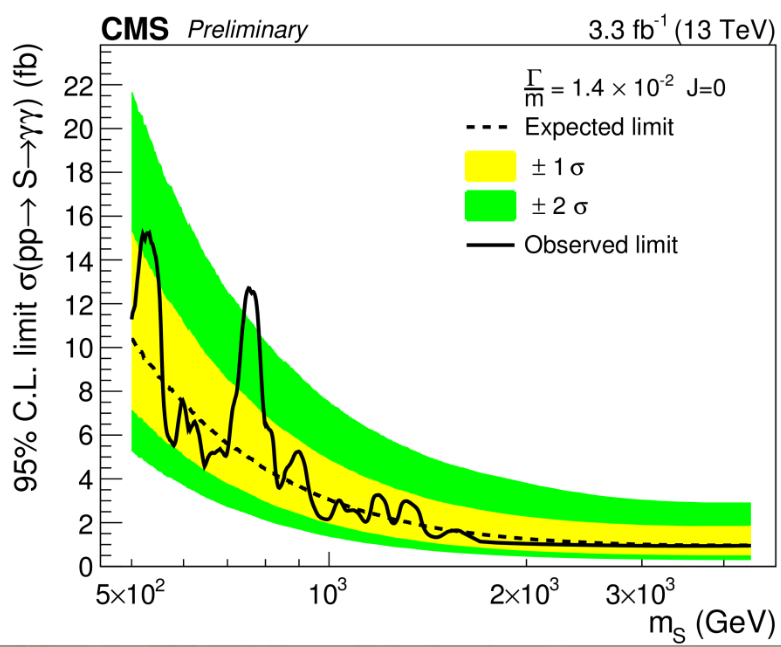
No significant excess
Compatibility with 13 TeV graviton:
- gg -> compatibility: 2.7 σ
- qq -> compatibility: 3.3 σ

Interpretation of the results
X->γγ (CMS)

1) Largest excess observed for m_X = 760GeV and $\Gamma/m = 1.4\text{x}10^{-2}$.
2) Local significance: 2.8-2.9σ depending on the spin hypothesis.
3) "Global" significance < 1σ.

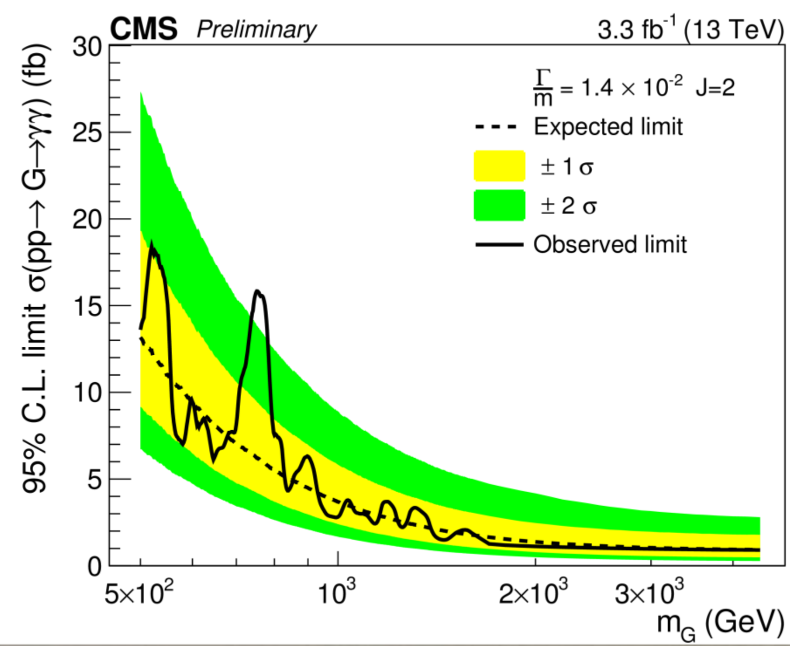
Spin-0

$\Gamma/m = 1.4\text{x}10^{-2}$ J=0



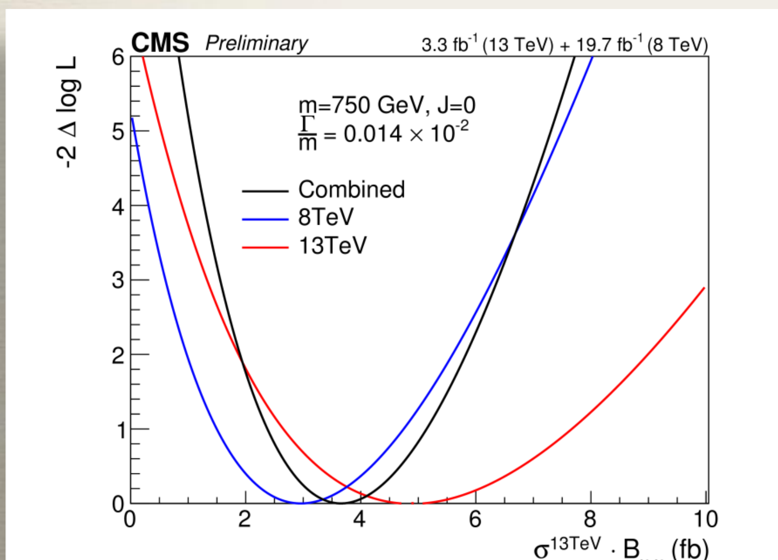
Spin-2

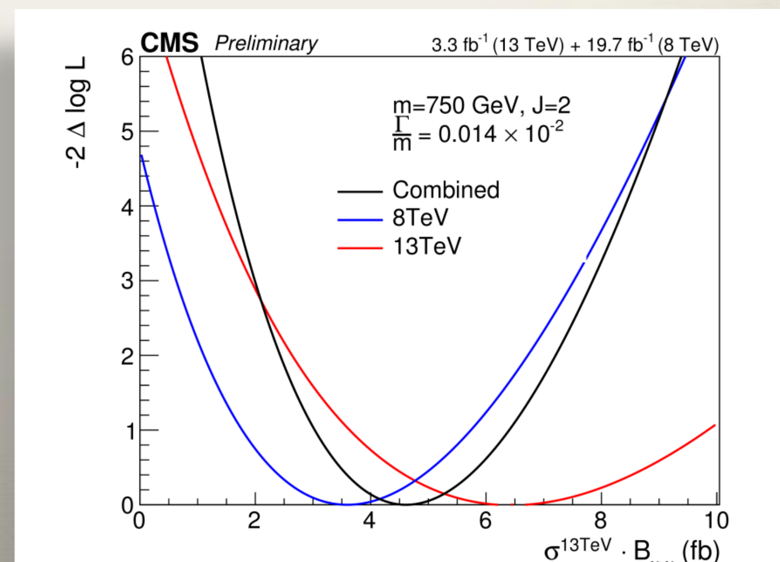
$\Gamma/m = 1.4\text{x}10^{-2}$ J=2



Combined 8+13 TeV results
X->γγ (CMS)

1) Largest excess observed at **m_X = 750GeV and for narrow width.**
2) **Local significance: 3.4σ**
3) Taking into account mass range 500-3500GeV (and all signal hypotheses), **"global" significance becomes 1.6σ**





??? X->$\gamma\gamma$ @ 750 GeV ???

1) Is the excess real? Statistics: 2016 data will confirm o disprove…
2) If true, interpretation far from straightforward and needs decisive results in other channels (ZZ, Zγ, WW, l^+l^-, etc.)
3) Some tension between 8 TeV & 13 TeV. Signal increases at most x5 if from gg or bb, $\gamma\gamma$ background x2.3. 8 TeV still in the game!
4) (J=0) Higgs-like scalar loop decays give narrow width, tree level decays to SM fermions would result in tiny BR(X->$\gamma\gamma$). Excluded by direct searches!

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{\gamma\gamma}} \approx 10^5$$

5) Sizable BR(X->$\gamma\gamma$) requires extra fermions in the loop!
6) SU(2) invariance implies existence of ZZ, Zγ, WW decay modes as well. None have been observed (yet?).
7) (J=2) RS KK Graviton has universal couplings to SM fields but no evidence in e.g. e^+e^-, $\mu^+\mu^-$, etc.

$$\Gamma(h^{(1)}_{\mu\nu} \to \gamma\gamma) = 2\Gamma(h^{(1)}_{\mu\nu} \to \ell^+\ell^-)$$

$\sigma(pp \to S \to \ell^+\ell^-) < 5$ fb [ATLAS-CONF-2015-081]

$\sigma(pp \to S \to \ell^+\ell^-) \lesssim 3$ fb [CMS-EXO-15-004]

EXECUTIVE SUMMARY

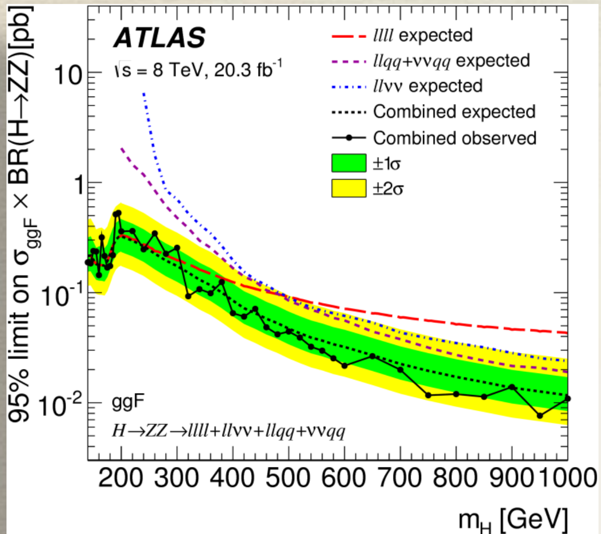
No BSM euphoria in the scalar sector
… yet

2016 hunting season on LHC is now open!
STAY TUNED!!!

BONUS MATERIAL

Direct searches @ 8 TeV

Heavy H->ZZ/WW



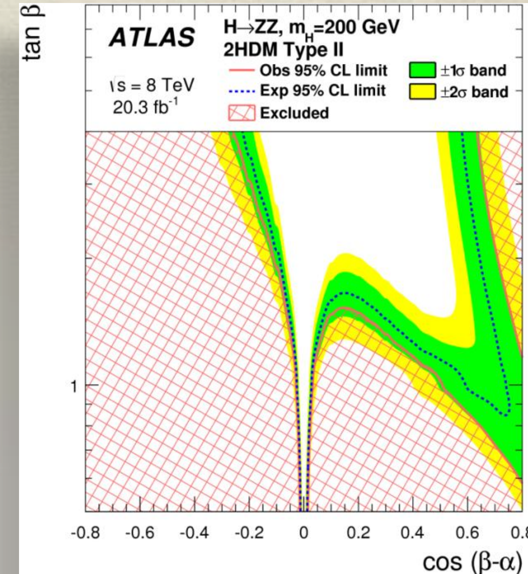
ATLAS: arXiv:1507.05930

H->ZZ

4l, 2l2ν, 2l2q final states

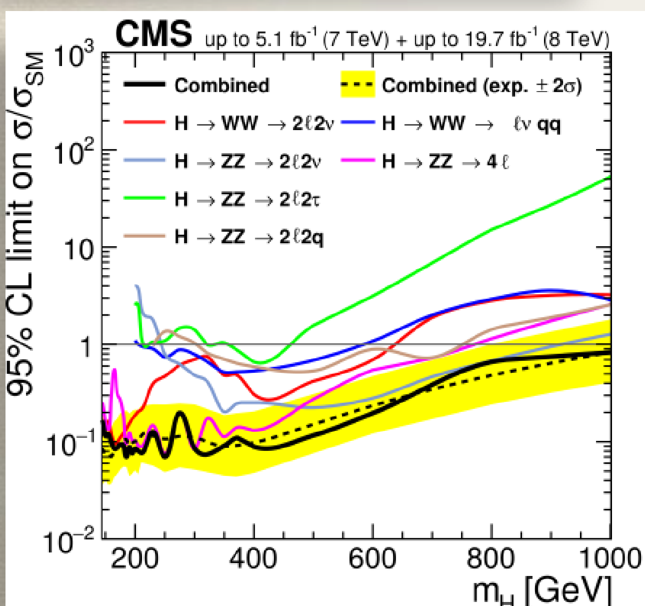
Limits on σ×BR(H->ZZ) for ggf and VBF production.

Limits in the context of 2HDM type II

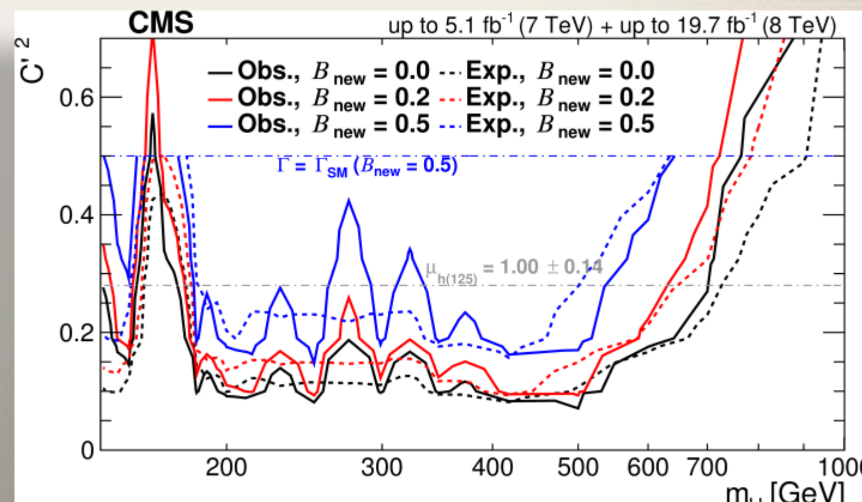


CMS: arXiv:1504.00936

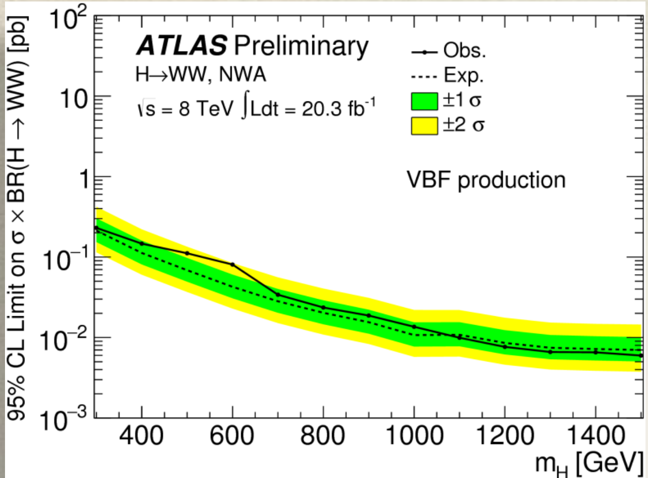
H->WW,ZZ WW->lνlν, lνqq, ZZ->2l2l, 2l2q, 2l2ν



EW singlet Higgs



Heavy H->ZZ/WW

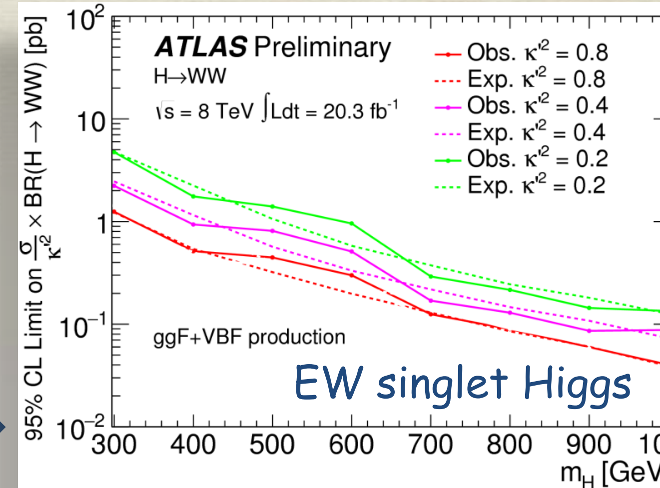


ATLAS: **arXiv:1509.00389**

H->WW, lνlν, lνqq.

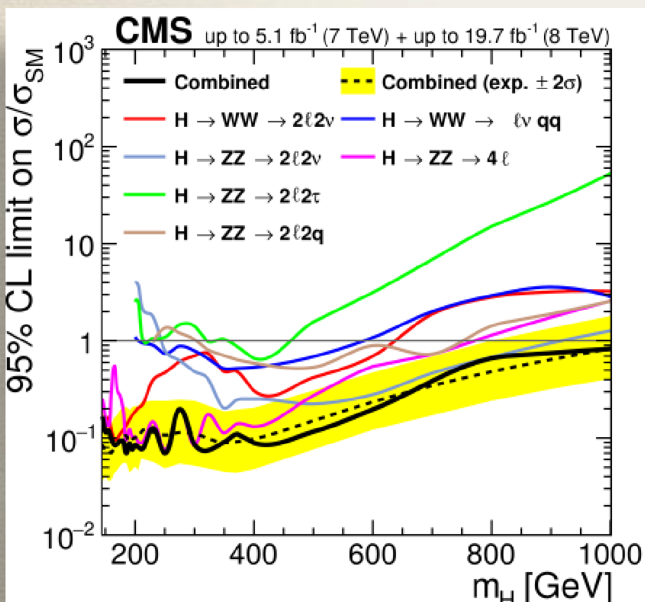
Range 200 - 1500 GeV

Limits in the context of EW singlet Higgs

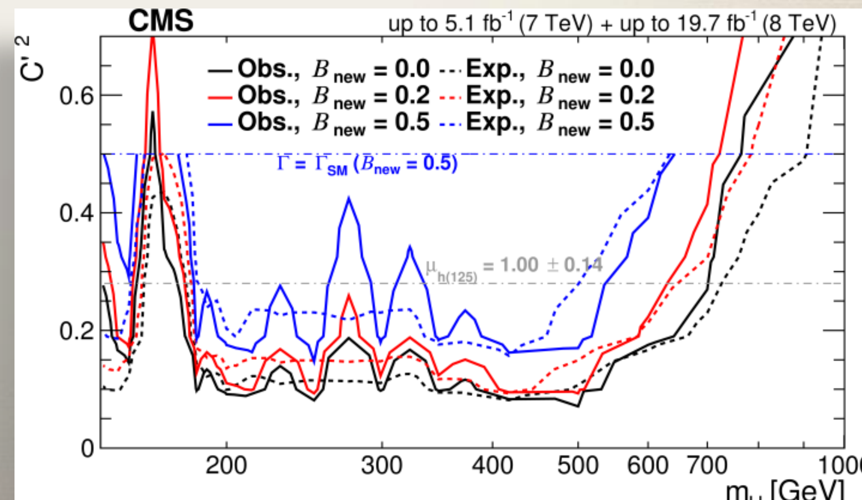


CMS: **arXiv:1504.00936**

H->WW,ZZ WW->lνlν, lνqq, ZZ->2l2l, 2l2q, 2l2ν



EW singlet Higgs



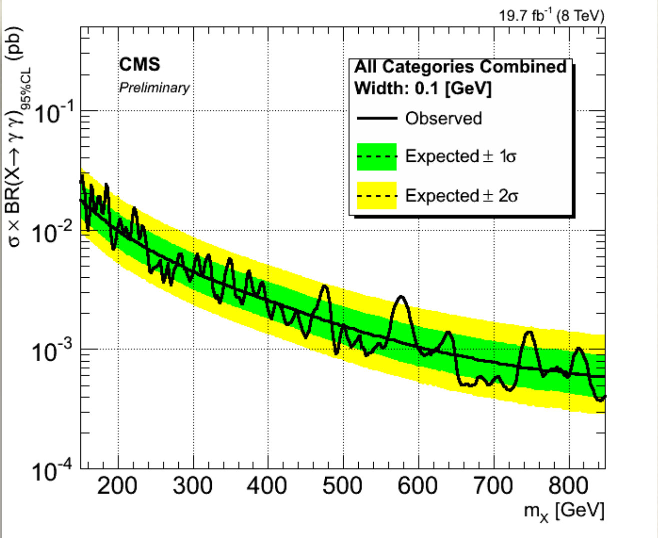
X->γγ,bb

ATLAS: PRL 113, 171801 (2014)
CMS: arXiv:1506.02301

X->γγ

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

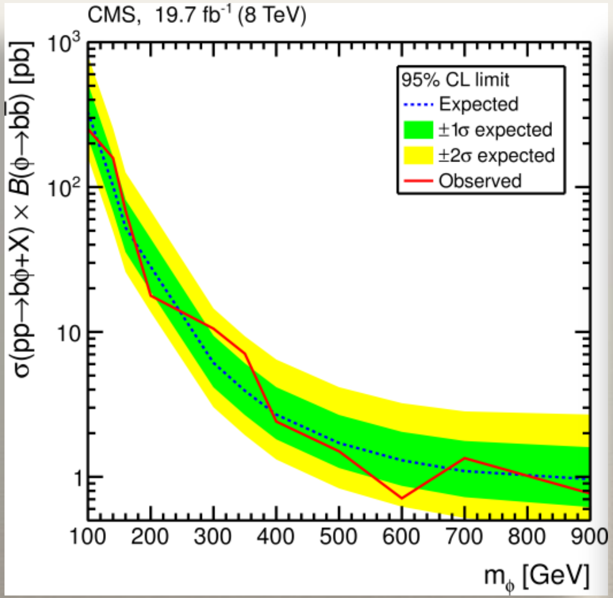
Spin 0 narrow hypothesis (spin 2 very similar)

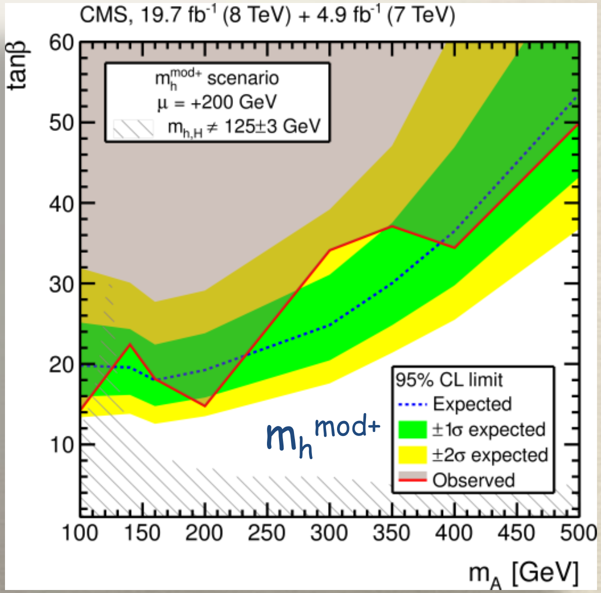


ϕ->bbar

CMS: arXiv:1506.08329

Heavy Higgs produced in association with a b quark





ATLAS combination on hh production

❖ Both resonant and non-resonant hh production

❖ Decay channels: **bbbb, bb$\tau\tau$, bb$\gamma\gamma$, WW$\gamma\gamma$**

❖ Limits set for resonant H->hh: σ(gg->H)$\times$BR(H->hh) assuming H is narrow (<1.5%).

❖ Limits on MSSM scenarios on m_A-tan(β) inferred. Here hMSSM exmpl.

❖ SM prediction @125 GeV: 9.9 ± 1.3 fb

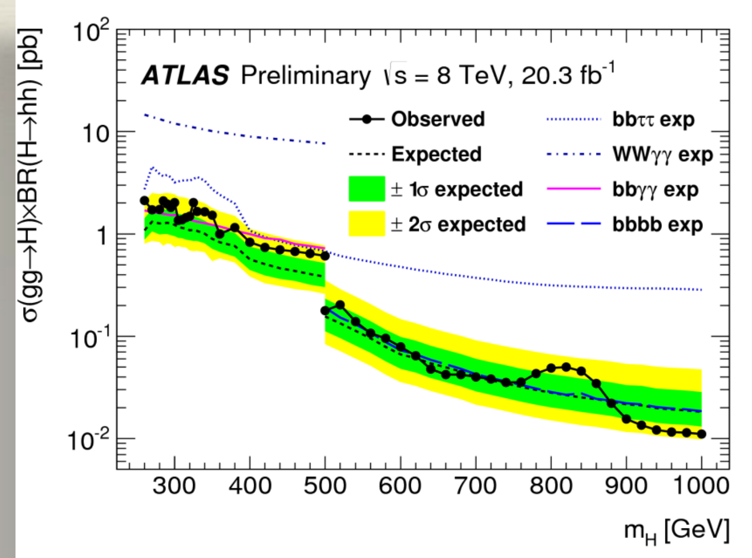
non-resonant limits on x-section [pb]:

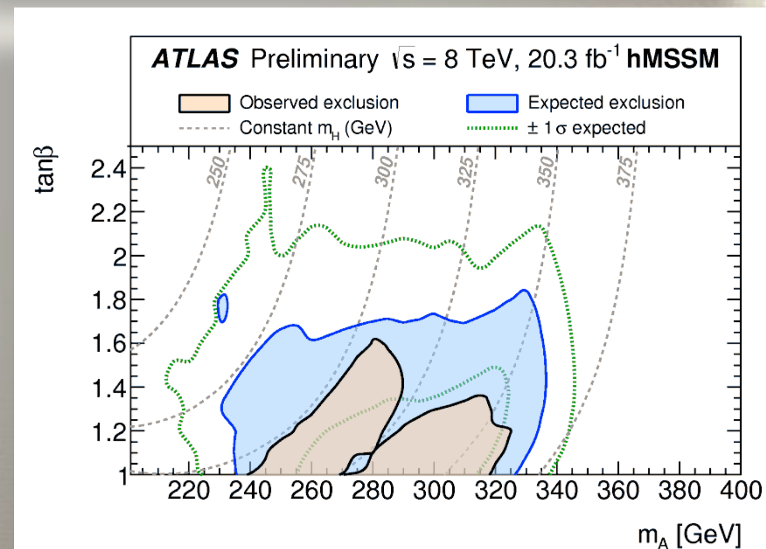
	$\gamma\gamma$bb	$\gamma\gamma$WW*	bb$\tau\tau$	bbbb	Combined
Exp.	1.0	6.7	1.3	0.62	0.47
Obs.	2.2	11	1.6	0.62	0.69

X->HH->bbbb CMS: arXiv:1503.04114

X->HH->$\gamma\gamma$bb CMS: CMS-PAS-HIG-13-032

ATLAS: HIGG-2013-33





A->Zh, H/A->A/H+Z

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

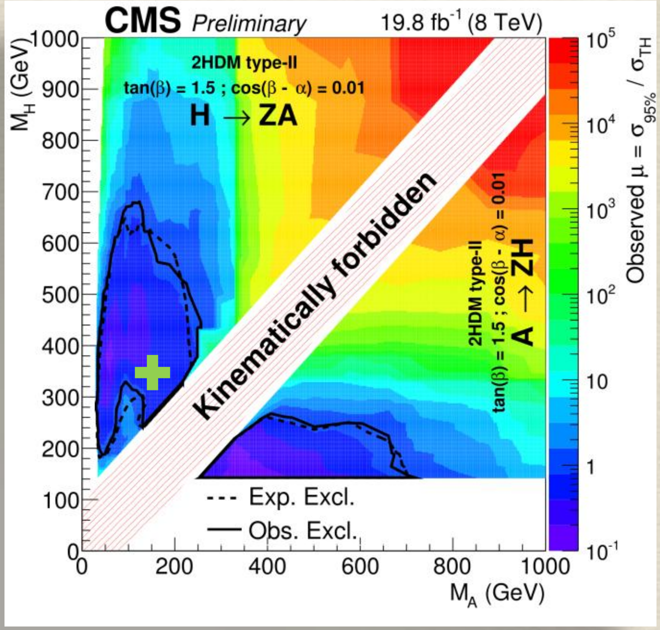
ATLAS: **Phys. Lett. B 744 (2015) 163-183**

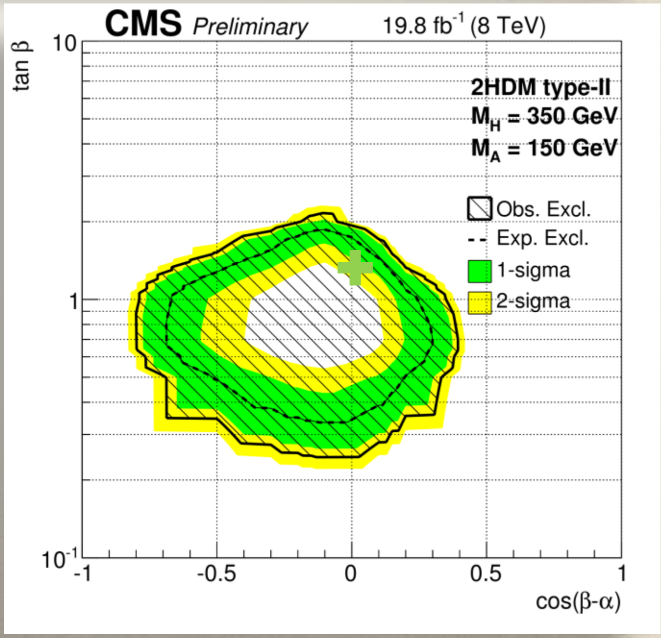
CMS: **arXiv:1504.04710**

CMS:

arXiv:1503.04114

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

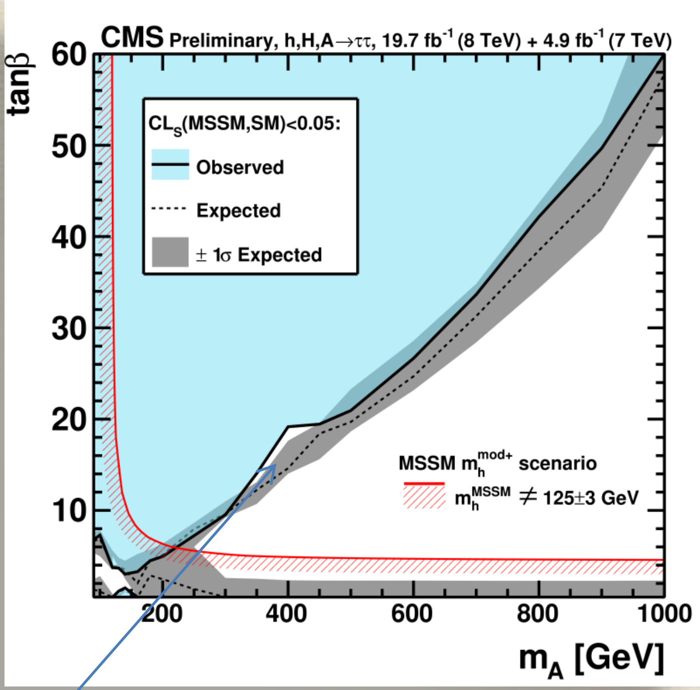


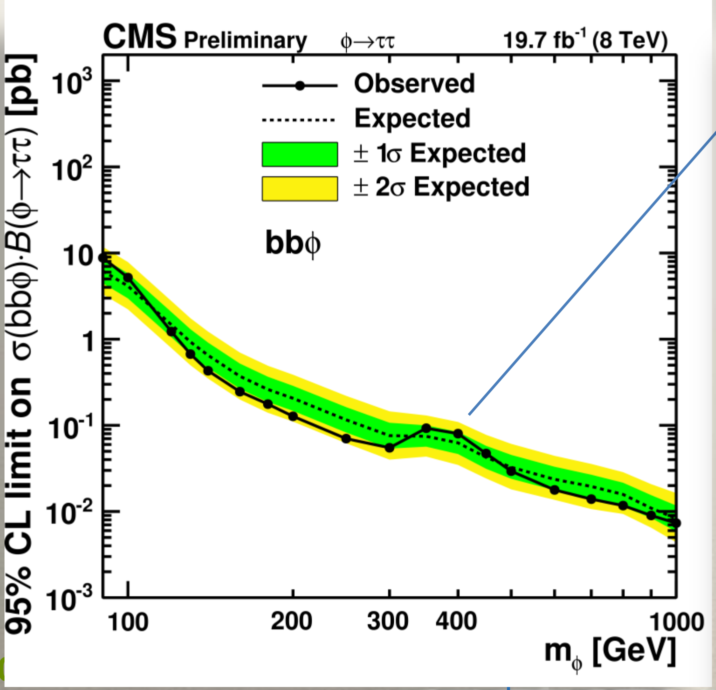


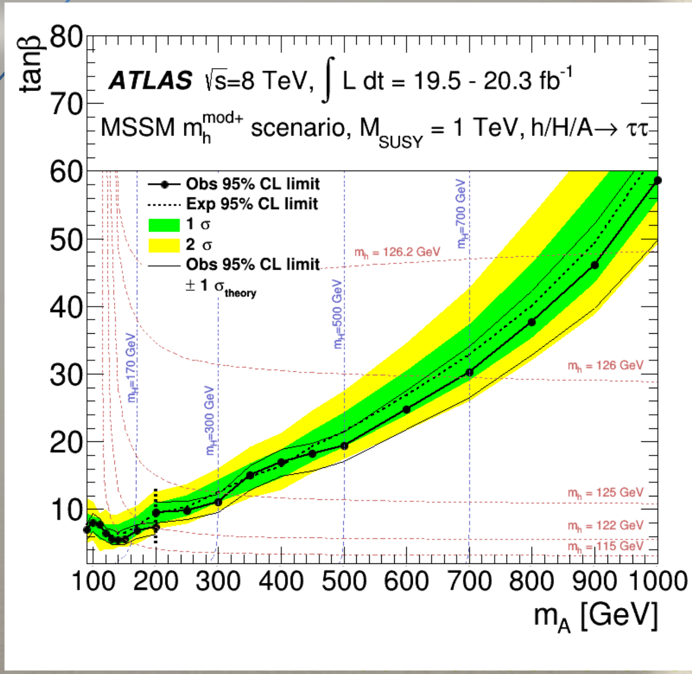
MSSM Higgs→ττ

CMS: CMS PAS HIG-14-029
ATLAS: JHEP 1411 (2014) 056

- ATLAS & CMS
- Channels searched:
  - h/H/A $\to\tau_e\tau_\mu$ (+$\tau_\mu\tau_\mu$ CMS)
  - h/H/A$\to\tau_{lep}\tau_{had}$
  - h/H/A$\to\tau_{had}\tau_{had}$
- MSSM Higgs couplings to down type quarks and leptons enhanced for large tan(β)

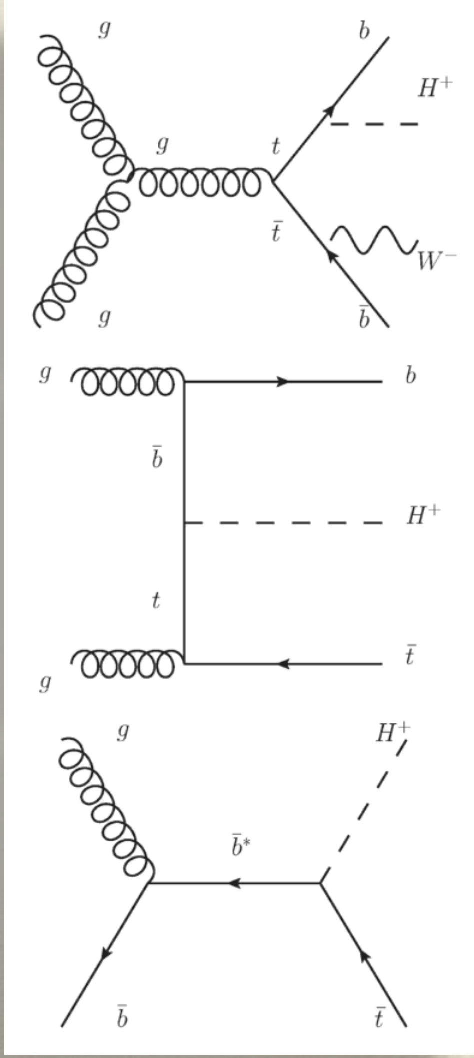






Charged Higgs

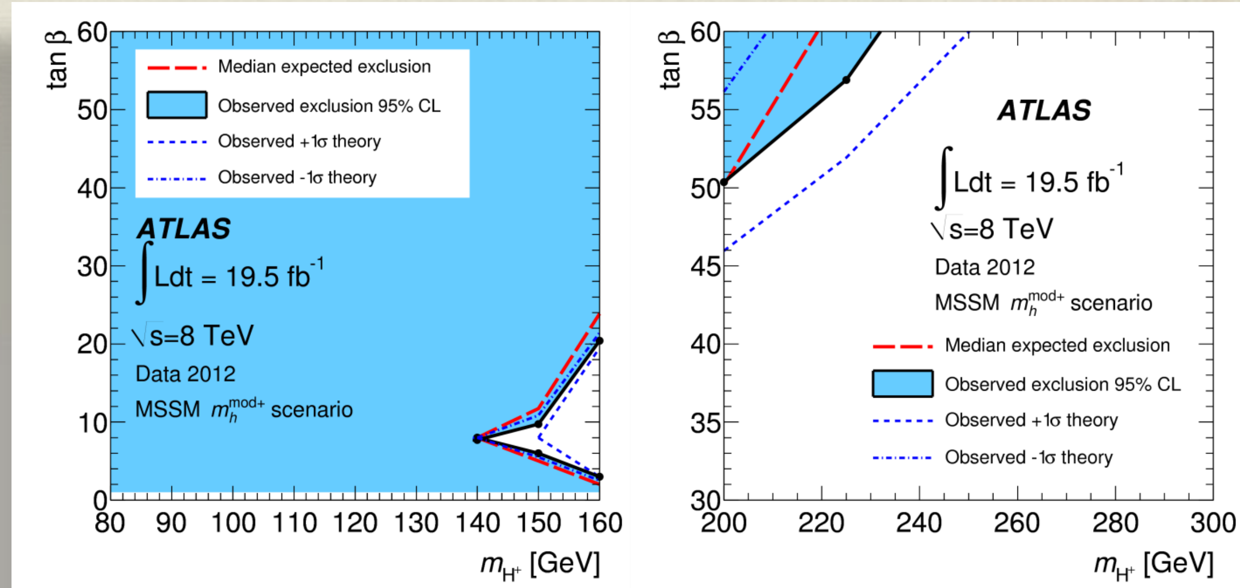
- A charged Higgs particle would spectacularly sign BSM. Needed with more than one HD (notably SUSY).
- Within MSSM BR($H^+ \to \tau\nu$) remains significant in large range of masses for high tan(β).
- For low tan(β) $H^+ \to tb$ dominates for $m_H > m_t$
- $H^+ \to \tau\nu$ saturates the decay for $m_H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

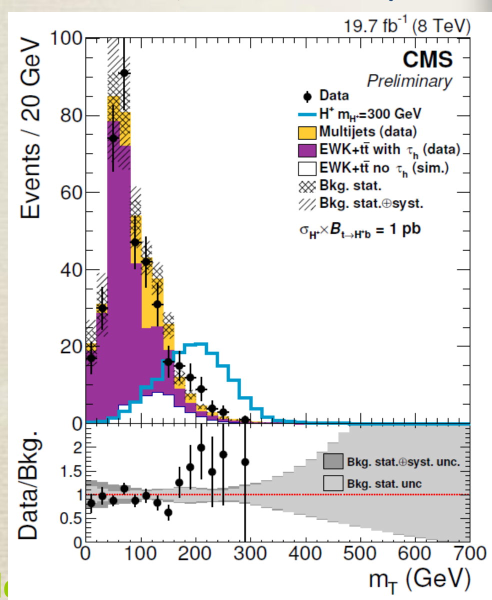


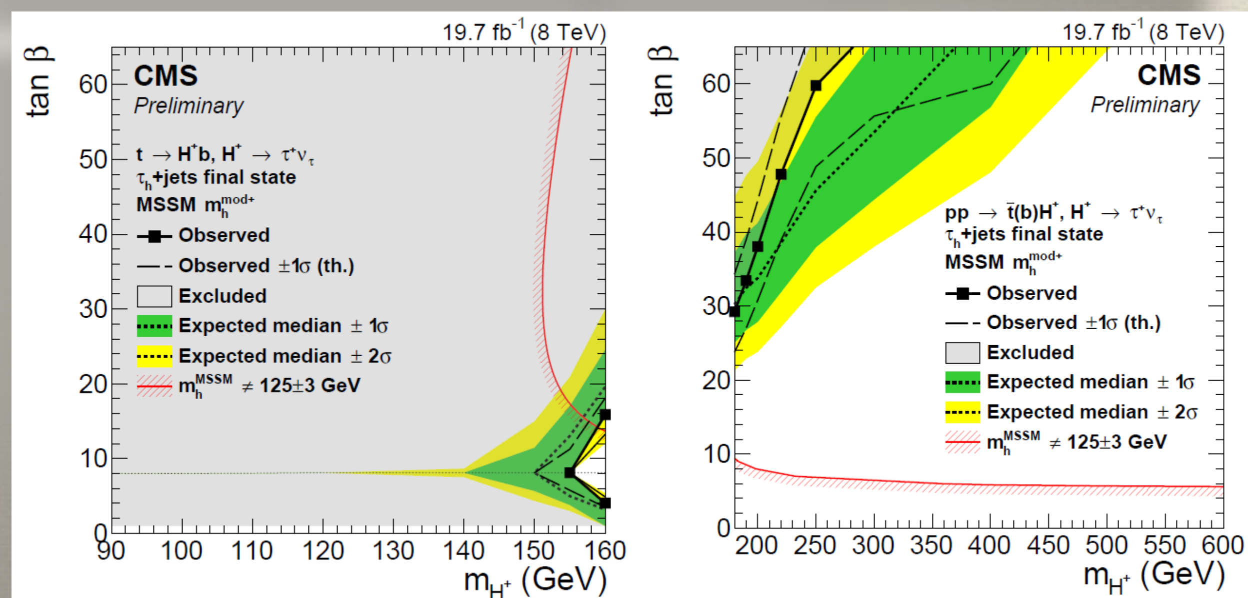
Charged $H^+ \to \tau\nu$ (had)

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+} exmp.



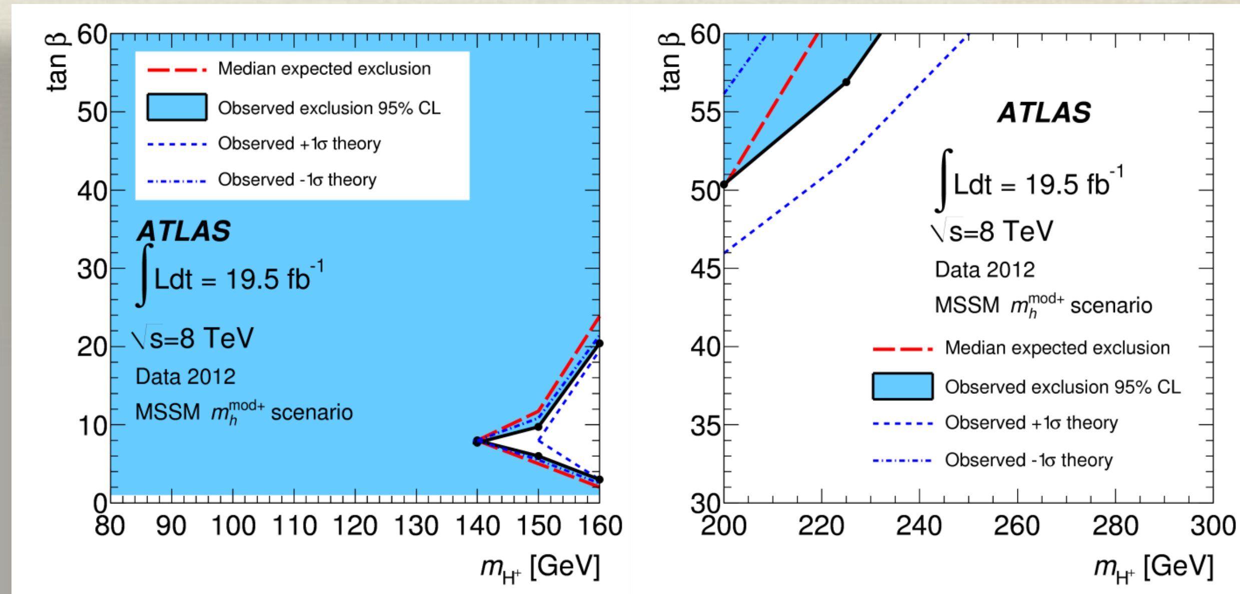


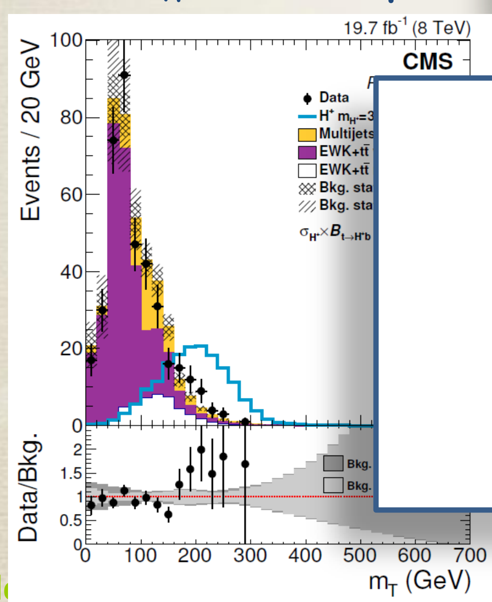


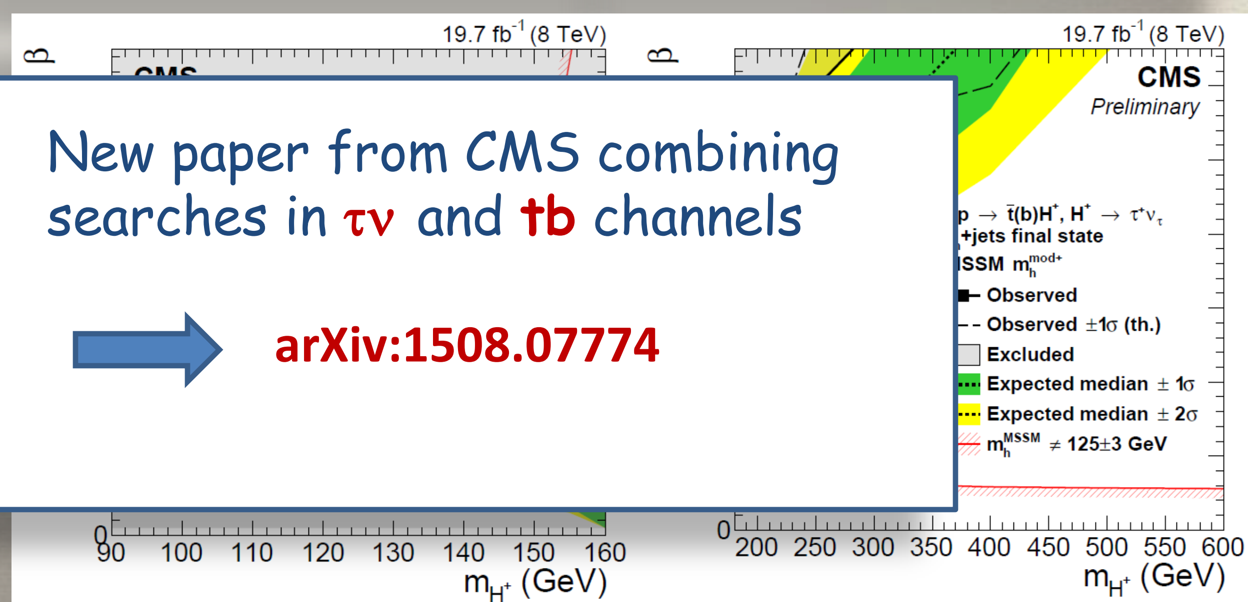
Charged $H^{+} \to \tau\nu$ (had)

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+} exmp.







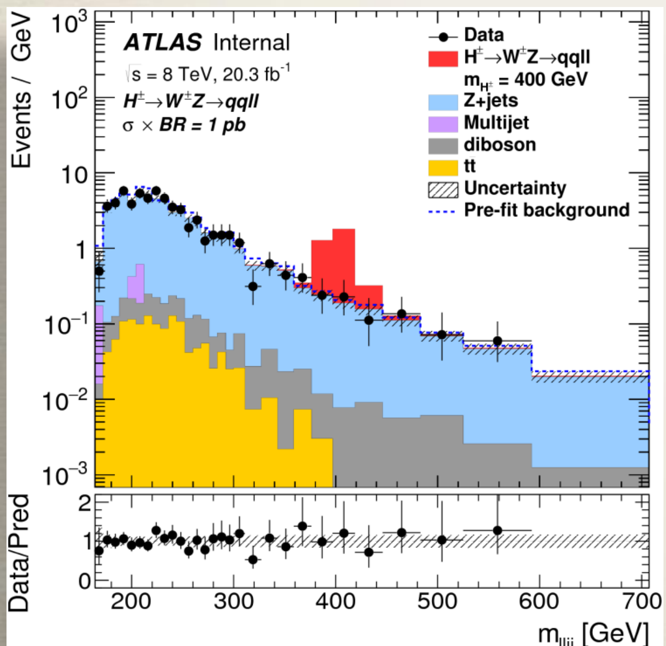
New paper from CMS combining searches in $\tau\nu$ and **tb** channels

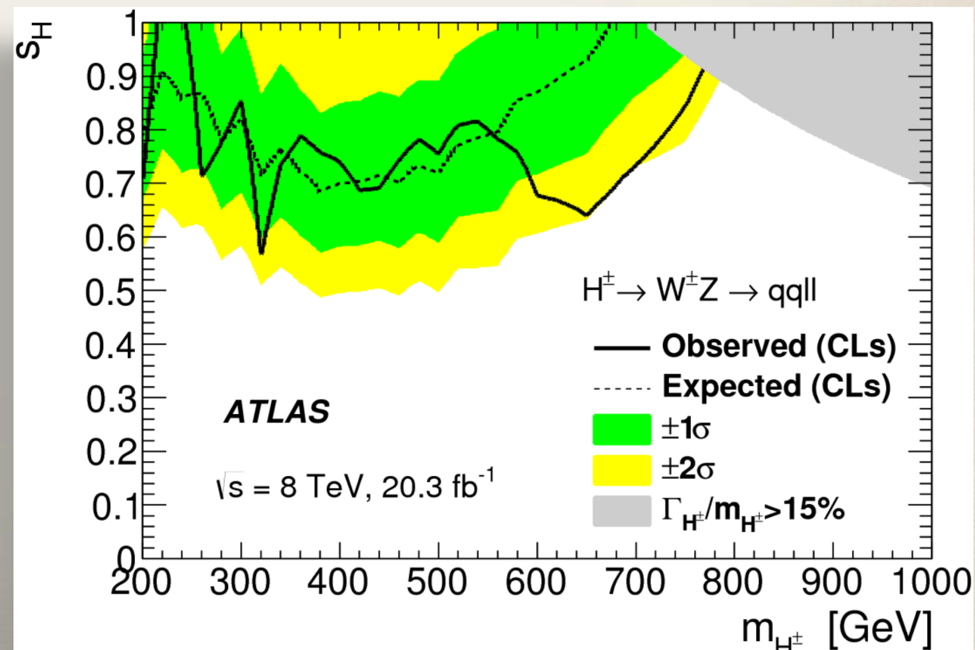
→ **arXiv:1508.07774**

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($H^\pm$->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^{mod+} scenarios)

ATLAS:

EXOT-2013-24

$H \to aa \to \gamma\gamma\gamma\gamma$

Signature: ≥ 3 isolated γ

Search for di-photon resonance (m_{23}).

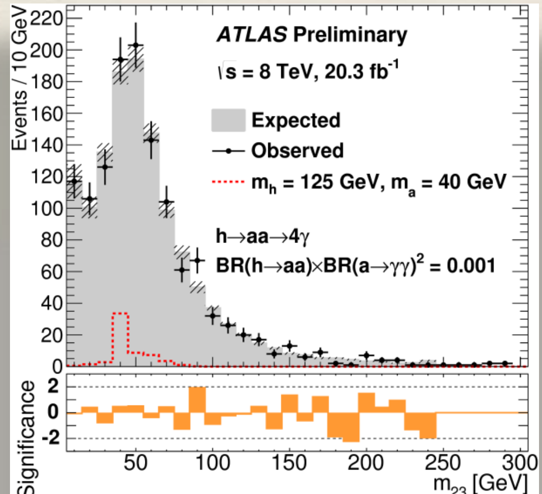
$h_{125} \to aa \to \gamma\gamma\gamma\gamma$

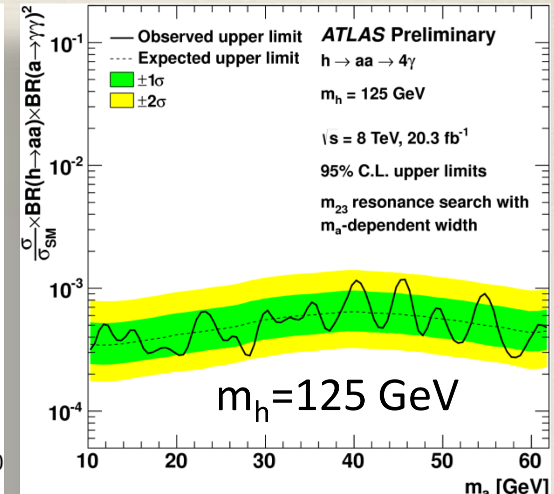
$H \to aa \to \gamma\gamma\gamma\gamma$ $300 < m_H < 600$

Search for $m_a < 250$ GeV

Limits on:

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





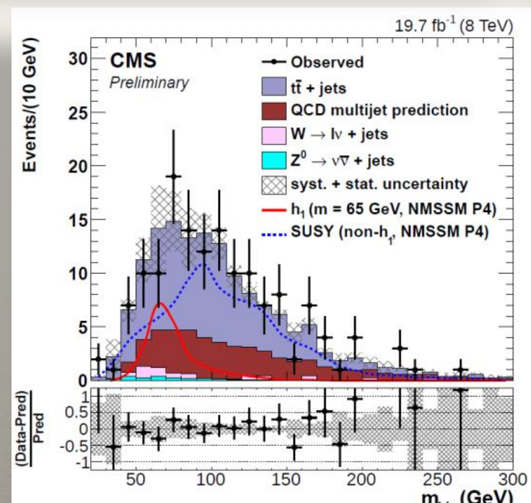
CMS:

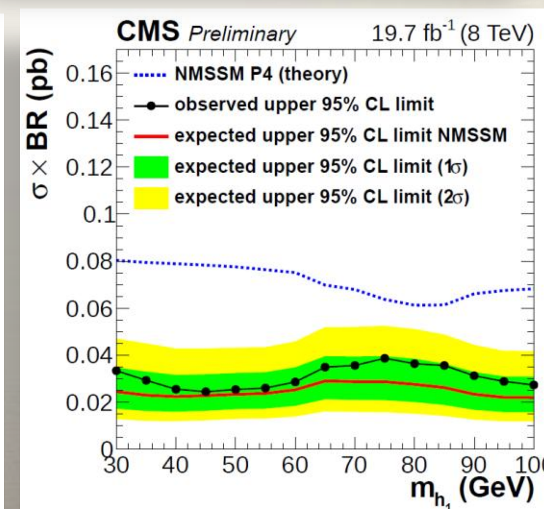
CMS PAS HIG-14-030

$a \to bb$

SUSY cascade tagged by $E_T^{miss} > 200$GeV and large H_T plus two b-tagged jets.

Limits within the coloured SUSY mass scale of 1TeV.

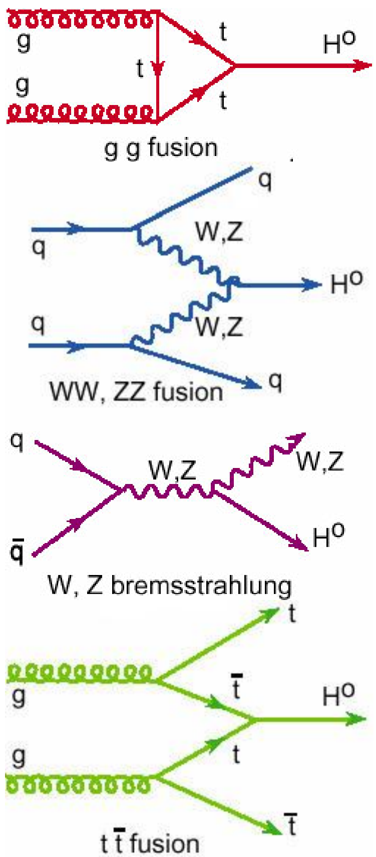




Auxiliary

SM Higgs production @ LHC

(~25 fb^{-1}/exp has been collected till LS1)



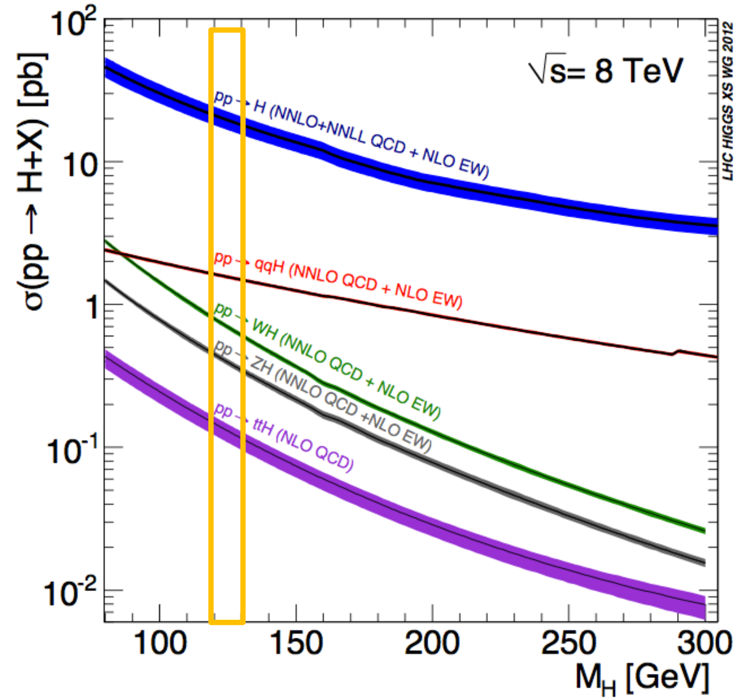
~19pb
(0.95pb)

~1.5pb
(0.07pb)

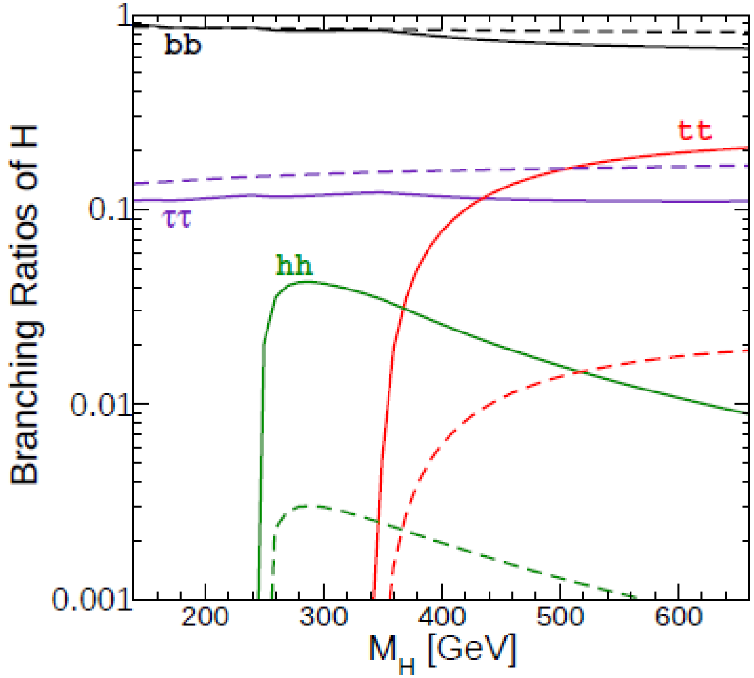
~1.0pb
(0.21pb)

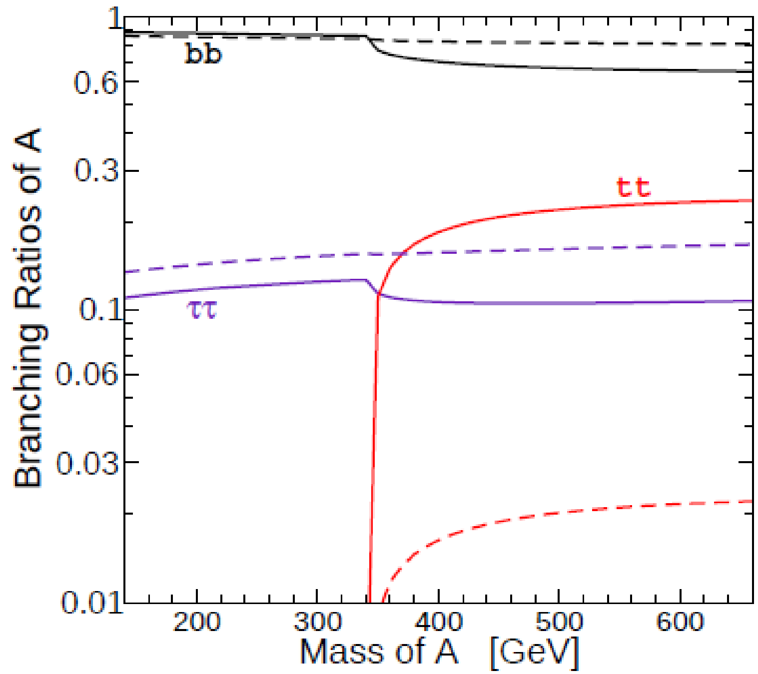
~0.1pb
(0.004pb)

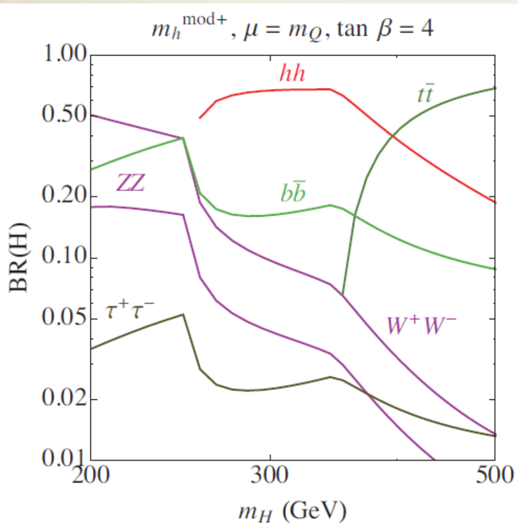
Tevatron

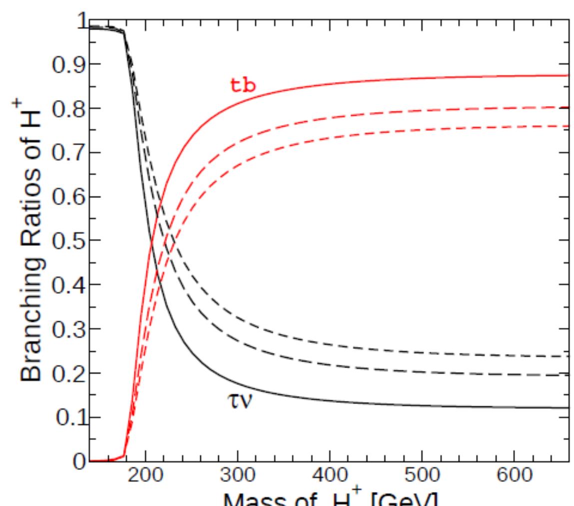


Solid: $\tan\beta = 10$, dashed: $\tan\beta = 20$.









Solid: $\tan\beta = 10$,

long dashed: $\tan\beta = 20$,

short dashed: $\tan\beta = 30$.

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

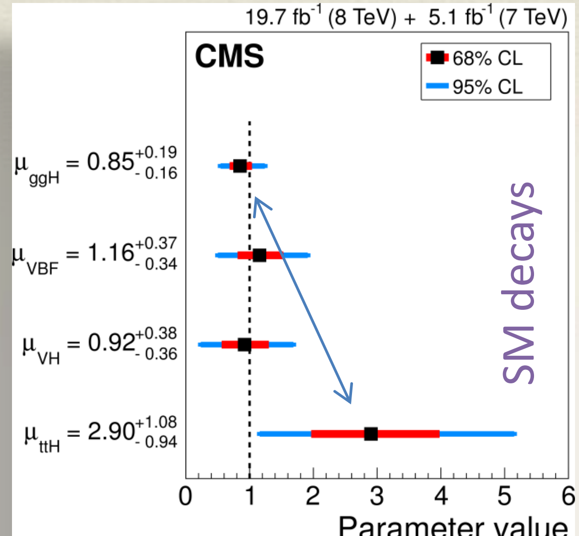
Extensive coupling studies

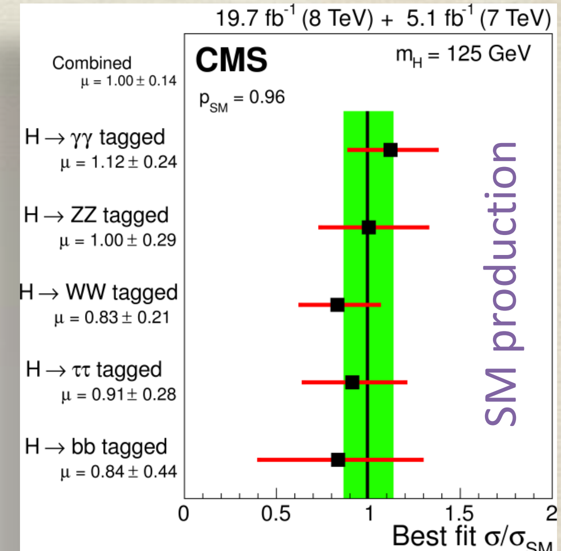
dedicated talks:
Marco Pieri, Wouter Verkerke

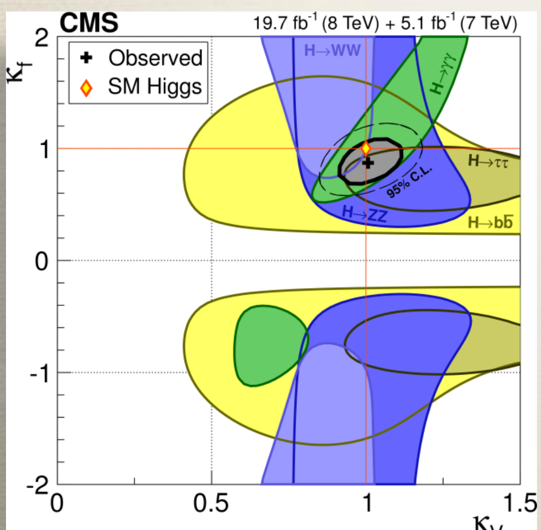
arXiv:1412.8662

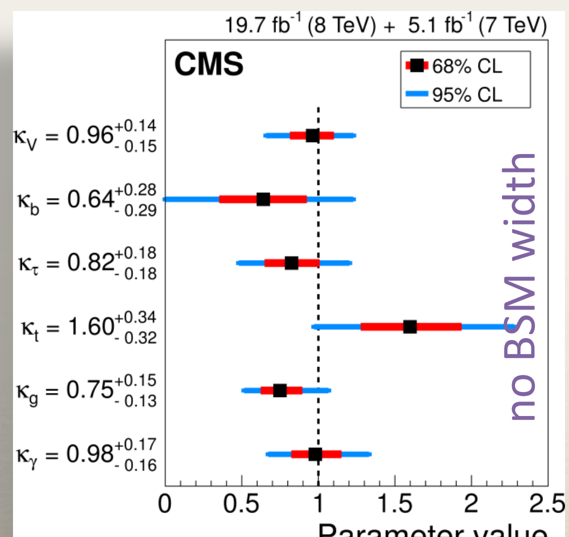
$\mu = \sigma/\sigma_{SM}$, $\kappa_H^2 = \Gamma_{tot}/\Gamma_{SM}$
$\kappa_p^2 = \sigma/\sigma_{SM}$, $\kappa_d^2 = \Gamma/\Gamma_{SM}$
$\lambda_{ab} = \kappa_a/\kappa_b$, $\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$

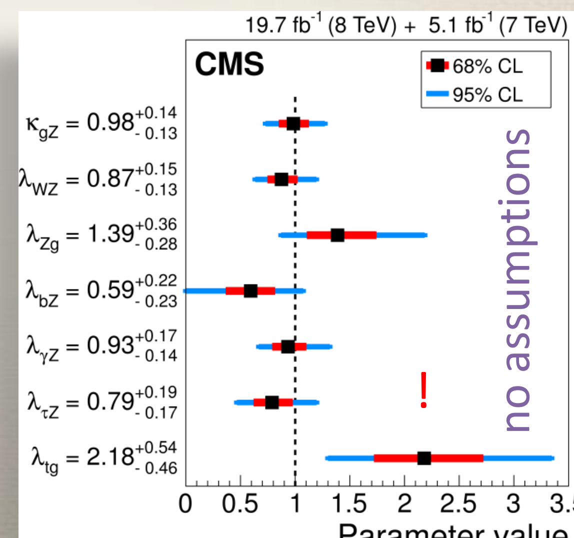
- ❖κ_V, κ_f common factors for couplings to vector bosons and fermions, respectively.
- ❖Assumption of no BSM loops/width, except for λ
- ❖Interferences alow to resolve signs!









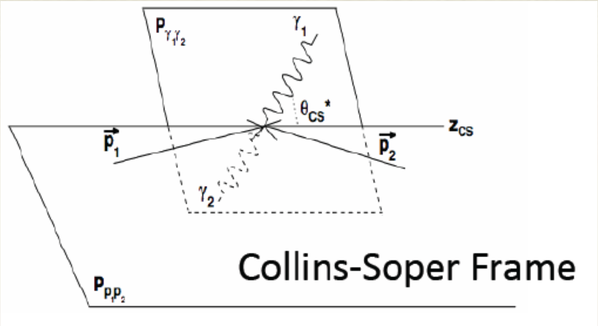


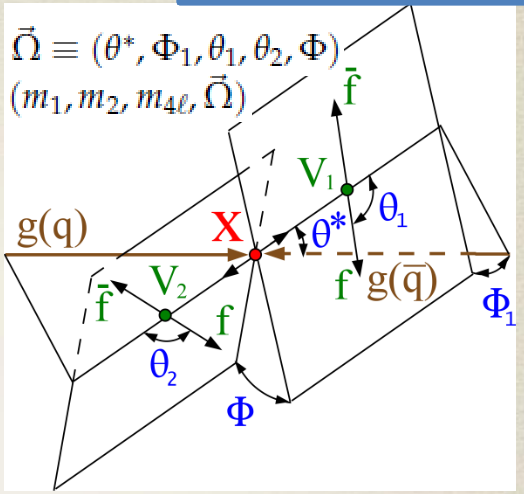
J^{CP} of the 125 GeV Higgs

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

dedicated talks:
Manuela Venturi,
Kerstin Tackmann

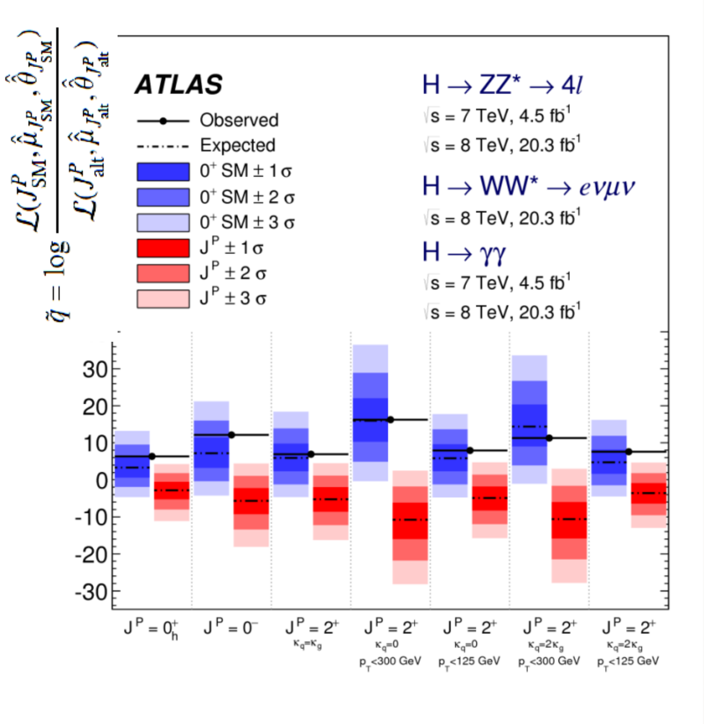
Testing for alternative J^{CP} scenarios using decay kinematics.
ZZ: full kinematics available
WW: $m^{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\varphi^{\ell\ell}$ and m_T
$\gamma\gamma$: $\cos(\Theta_{CS}^*)$, $p_T^{\gamma\gamma}$

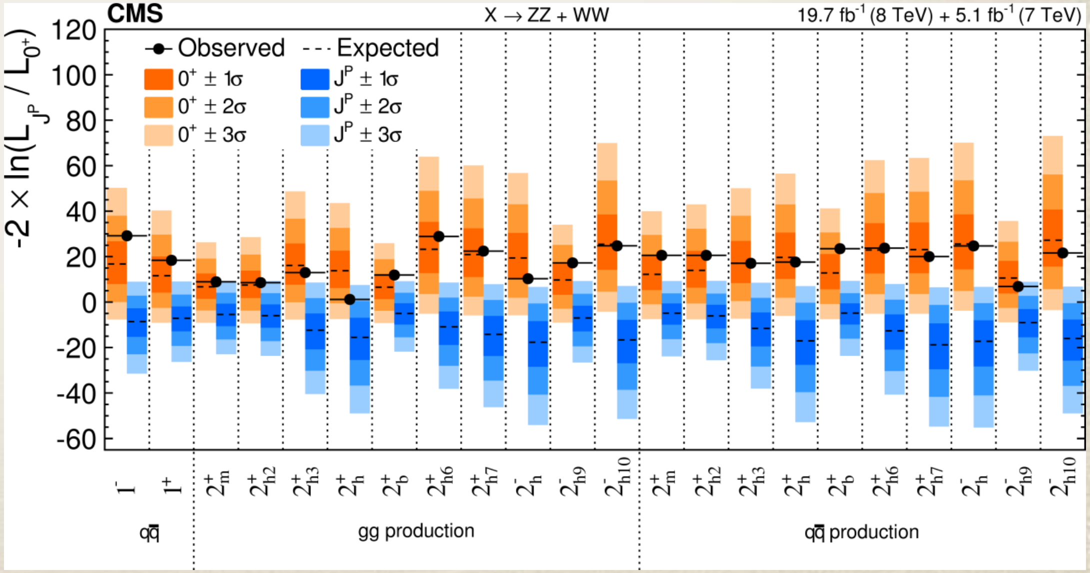




Exclusions @ 99% CL or better

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





Higgs $d\sigma_H/dx$

HOT

ATLAS:

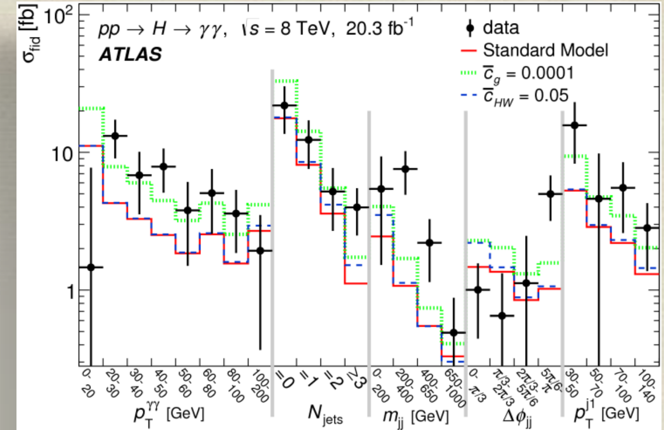
arXiv:1508.02507

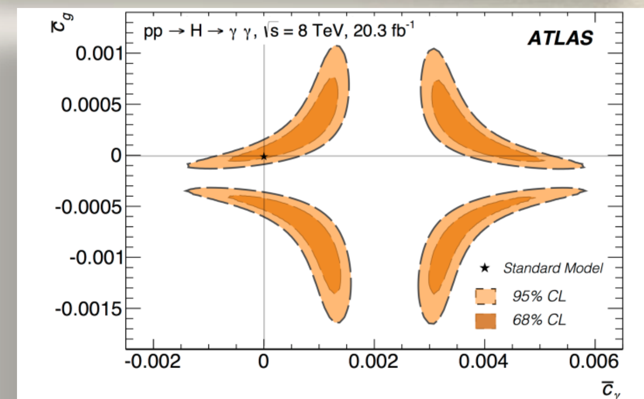
❖Constraints on Wilson coefficients for anomalous CP-even and CP-odd int. in the EFT (operators ≥dim6)

❖Use $H\to\gamma\gamma$. $d\sigma/dx$:

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

dedicated talk:
Kerstin Tackmann





CMS:

CMS-PAS-HIG-14-028

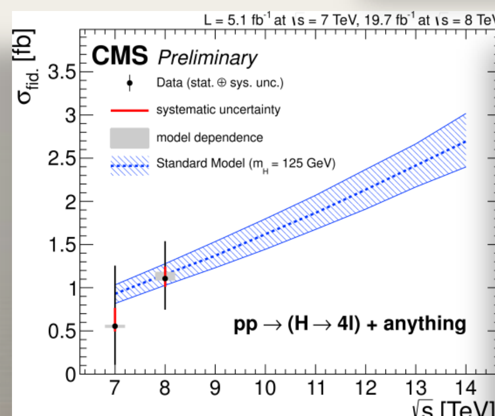
❖Study of the H->ZZ->4l channel

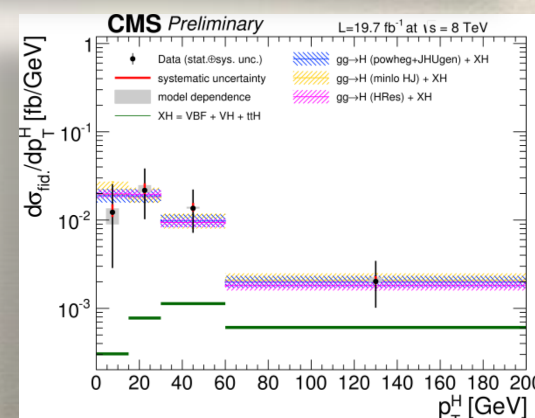
❖Extract fiducial x-sections both inclusive and differential.

❖$d\sigma/dx$:

p_T^H, y^H, N_{jets}, p_T^{j1},Δy_{Hj1}

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





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.

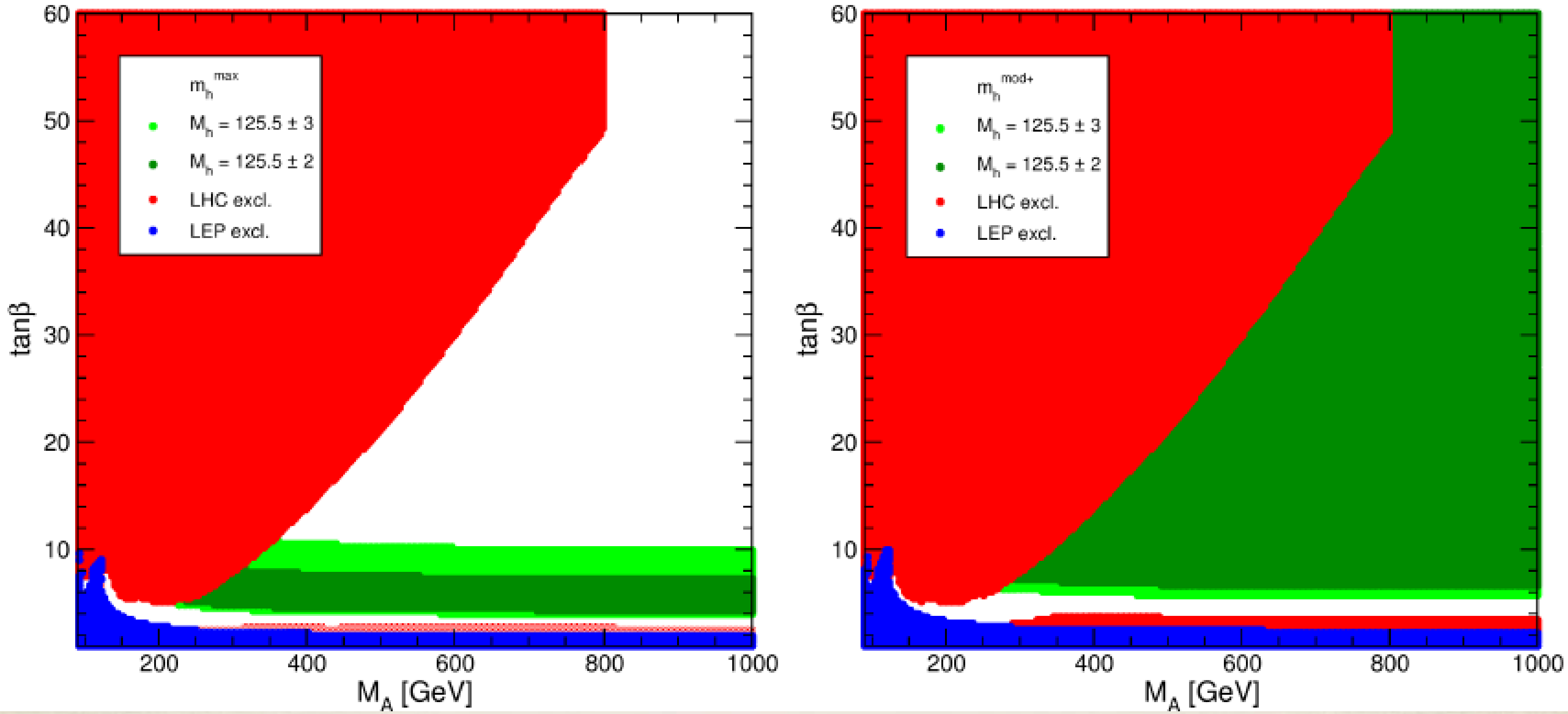
$$\tan\beta \equiv v_2/v_1 \qquad g_{hVV}^{2HDM}/g_{hVV}^{SM} = \sin(\beta-\alpha)$$

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

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.

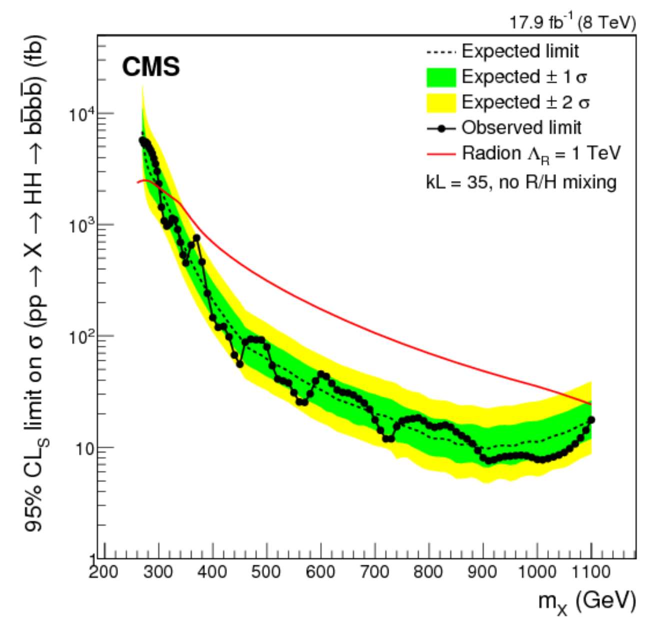


CMS: Search for X->HH

X->HH->bbbb

arXiv:1503.04114

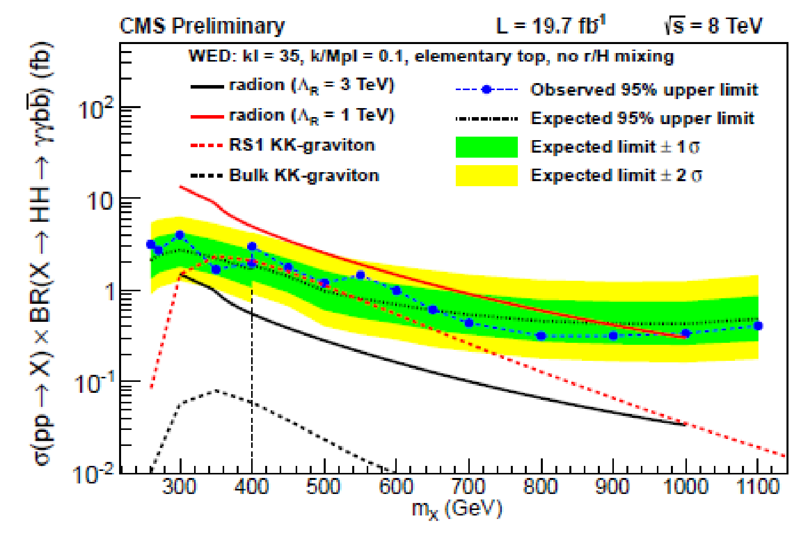
❖ Model independent search
❖ Using four b-tagged jets.
❖ QCD bkg estimated from data control regions



X->HH->γγbb

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}.



hh->bbbb

ATLAS:

arXiv:1506.00285

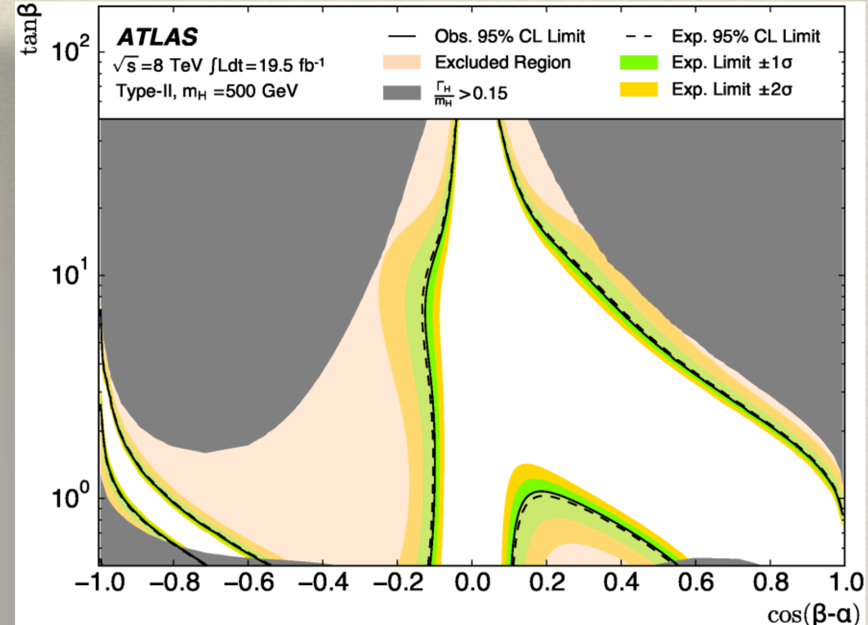
❖ Using both pairs of resolved anti-k_t b-tagged jets and trimmed fat anti-k_t jets with two other b-jets.

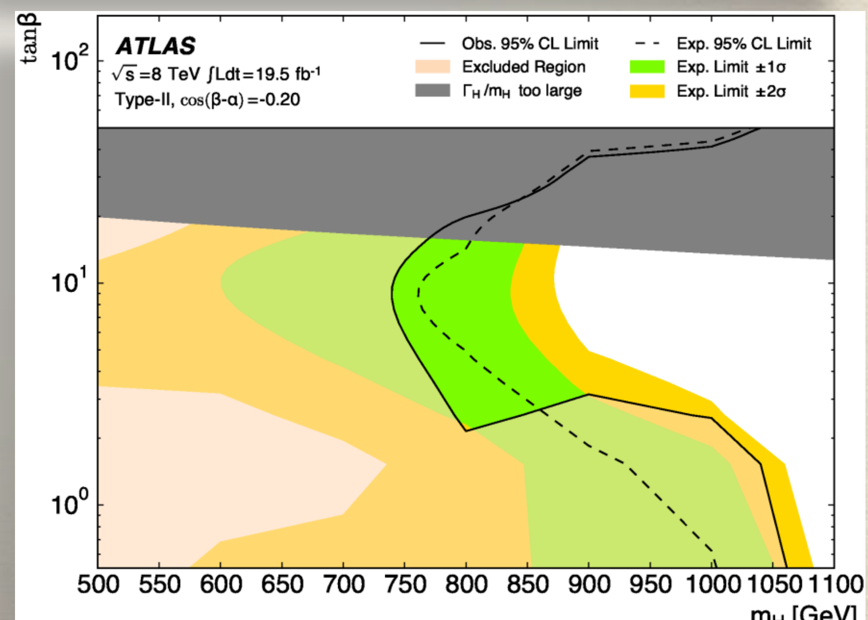
❖ Sensitivity in the range of 500-2000 GeV

❖ Limits derived for both RS G^*_{KK} as well as H→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->hZ, Z->ll,$\nu\nu$, h->bb,$\tau\tau$

❖ h denotes here the observed Higgs with mass of 125 GeV

❖ $m_A \in (220; 1000)$ GeV

❖ 2HDM (type I & II) limits are given for specific choice of m_A or $\cos(\beta-\alpha)$.

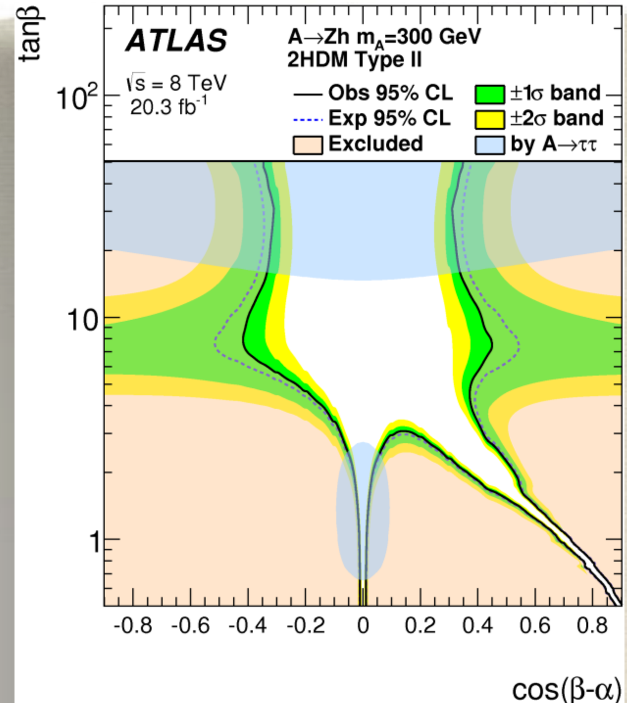
❖ Here example of 2HDM type II with m_A=300 GeV or $\cos(\beta-\alpha)$=0.10

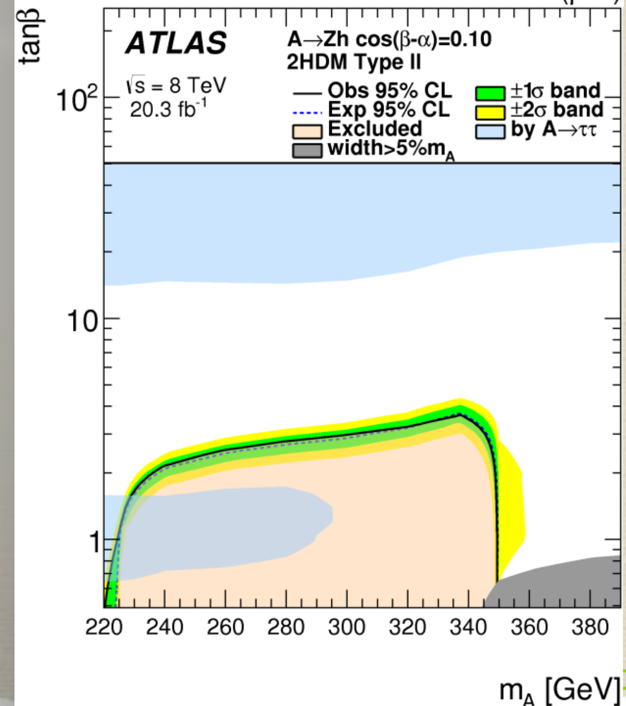
❖ Assumptions for calculating the limits:

$m_A = m_H = m_{H\pm}$, m_h = 125 GeV

and $m^2_{12} = m^2_A \tan\beta / (1 + \tan^2\beta)$

❖ Blue shaded areas are excluded by A-> $\tau\tau$ analysis [JHEP 1411 (2014) 056]

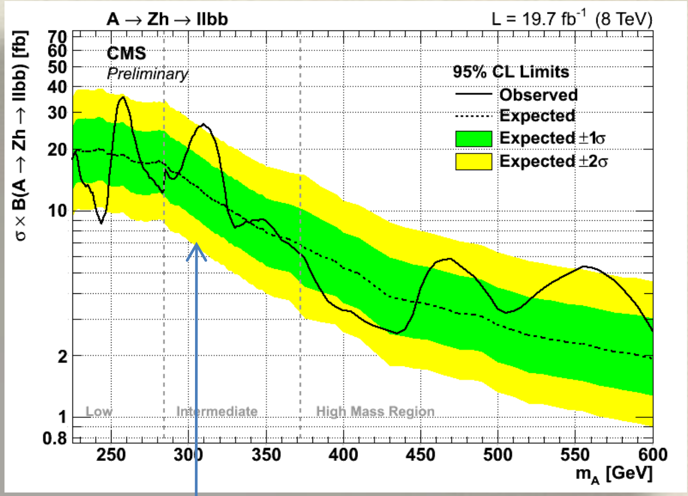


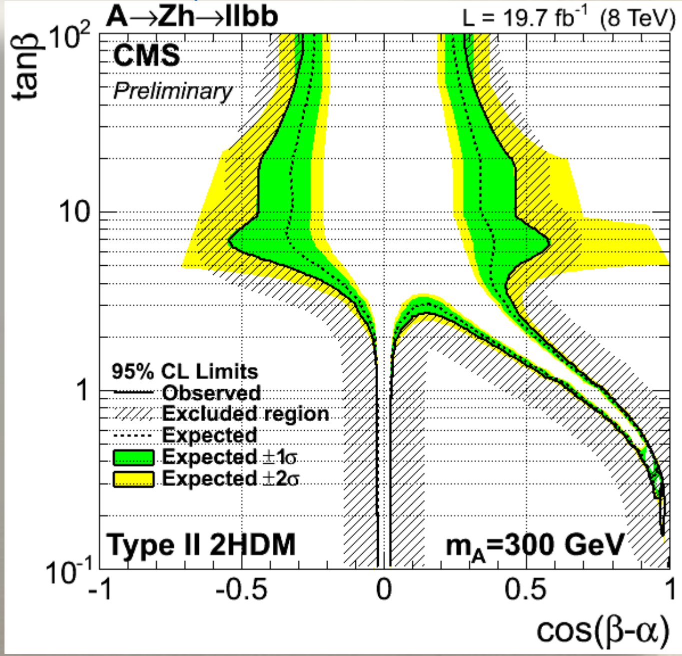


HZ production

CMS: **arXiv:1504.04710**

- A->hZ, Z->ll, h->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





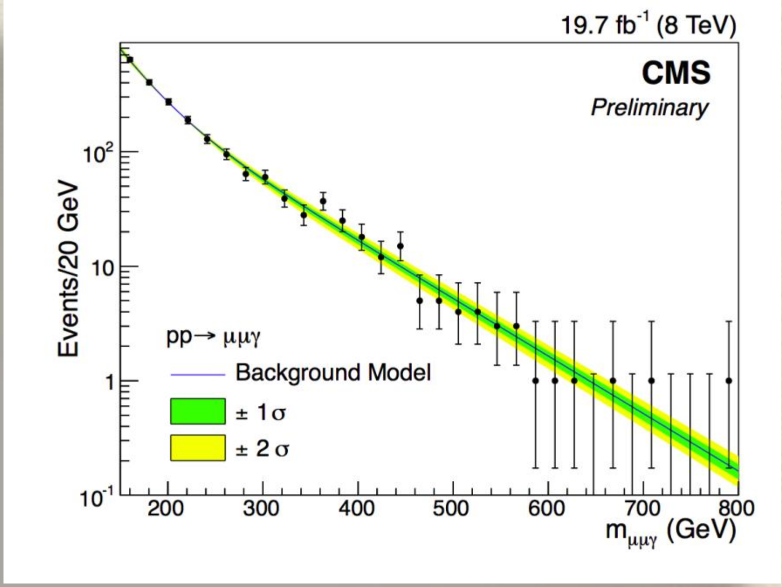
CMS-PAS-HIG-13-025

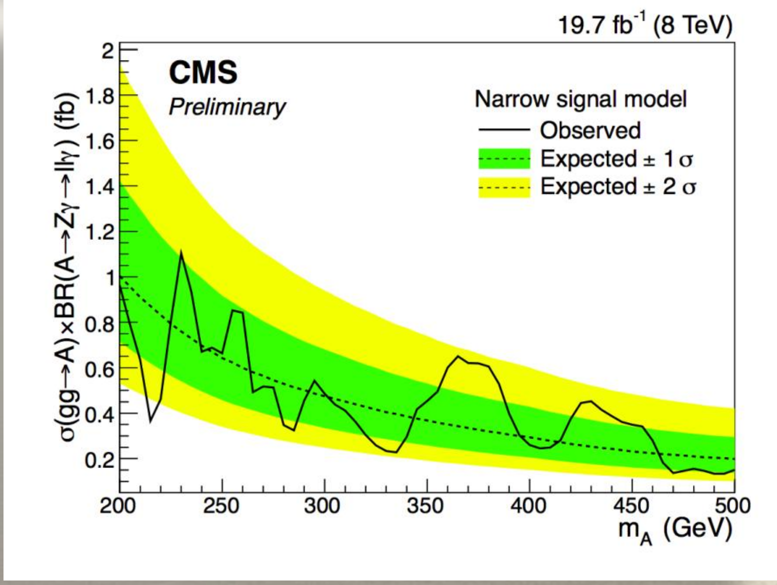
- H->hh & A->Zh
- Sensitivity up to 360 GeV
- Limits derived for 2HDM type I & II.

Search for A->Zγ

CMS PAS HIG-14-031

- A->Zγ, Z->ll (e or μ)
- Model independent
- In particular, probes for composite Higgs models with SU(4) chiral symmetry breaking.
- Sensitivity up to the ttbar threshold.





NMSSM

ATLAS:

arXiv:1505.01609

H->aa->$\mu\mu\tau\tau$

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->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.

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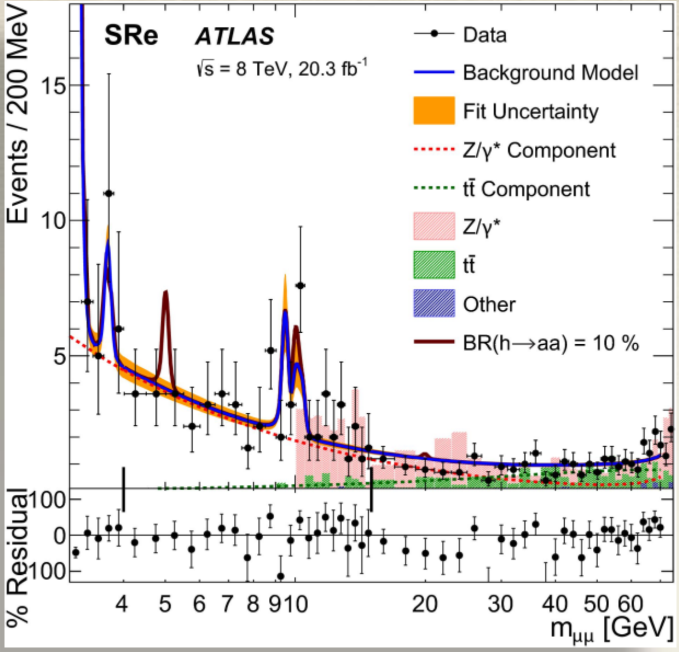
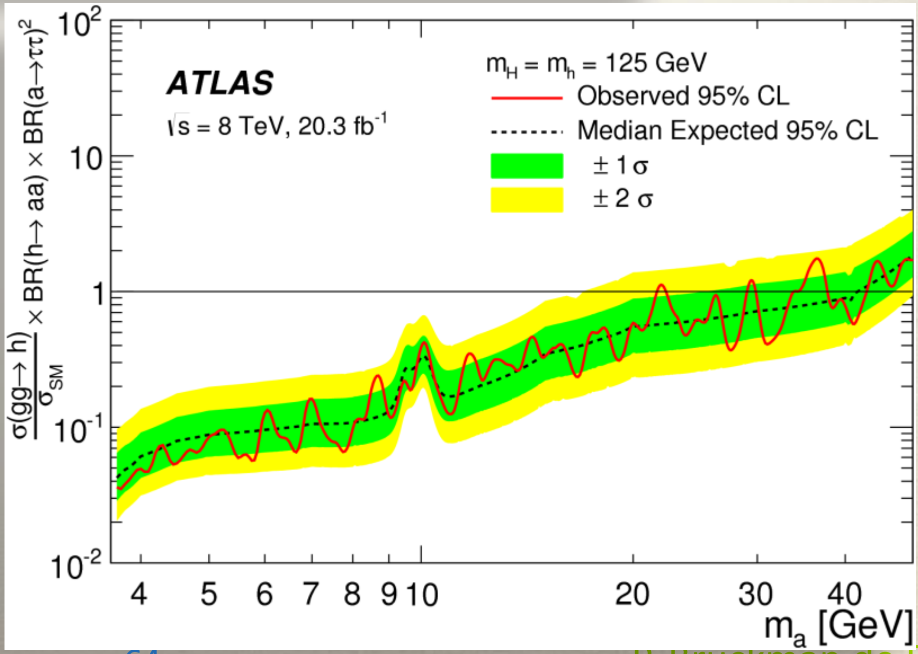
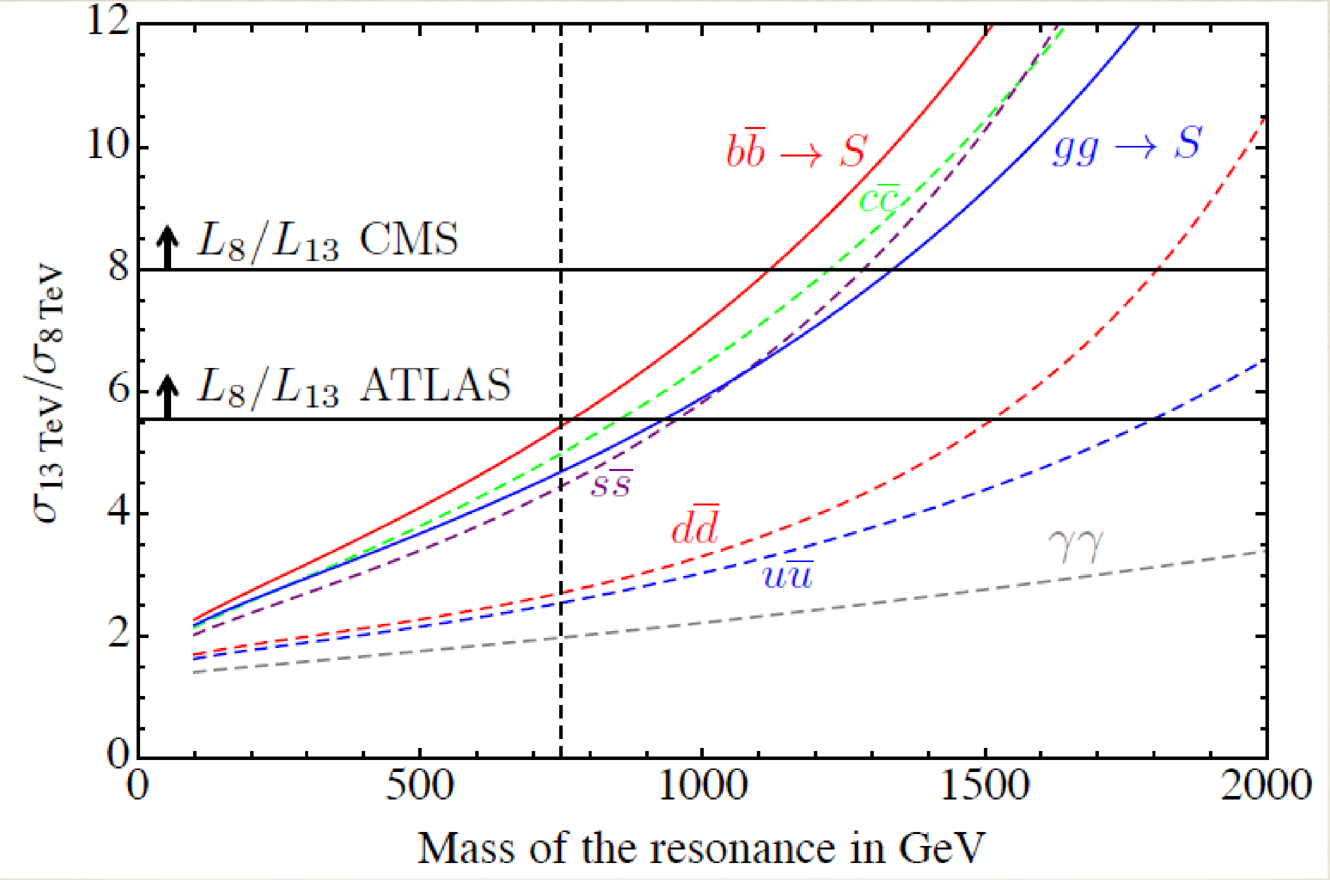




R. FRANCESCHINI et al.

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[8, 9]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[11]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[12]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[13]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[14]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[15]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[16, 17]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[18]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[19]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[20]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[7]	$< 1300\ (r/5)$

operator	$\dfrac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)}$	$\dfrac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)}$	$\dfrac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)}$
WW only	$2/\tan^2\theta_W \approx 7$	$1/\tan^4\theta_W \approx 12$	$2/\sin^4\theta_W \approx 40$
BB only	$2\tan^2\theta_W \approx 0.6$	$\tan^4\theta_W \approx 0.08$	0



$\sigma(pp \to \gamma\gamma)$	CMS	ATLAS
8 TeV	(0.5 ± 0.6) fb	(0.4 ± 0.8) fb
13 TeV	(6 ± 3) fb	(10 ± 3) fb

ATLAS: **ATLAS-CONF-2015-059**