Searches for BSM Higgs bosons, Higgs rare and BSM decays, and di-Higgs production

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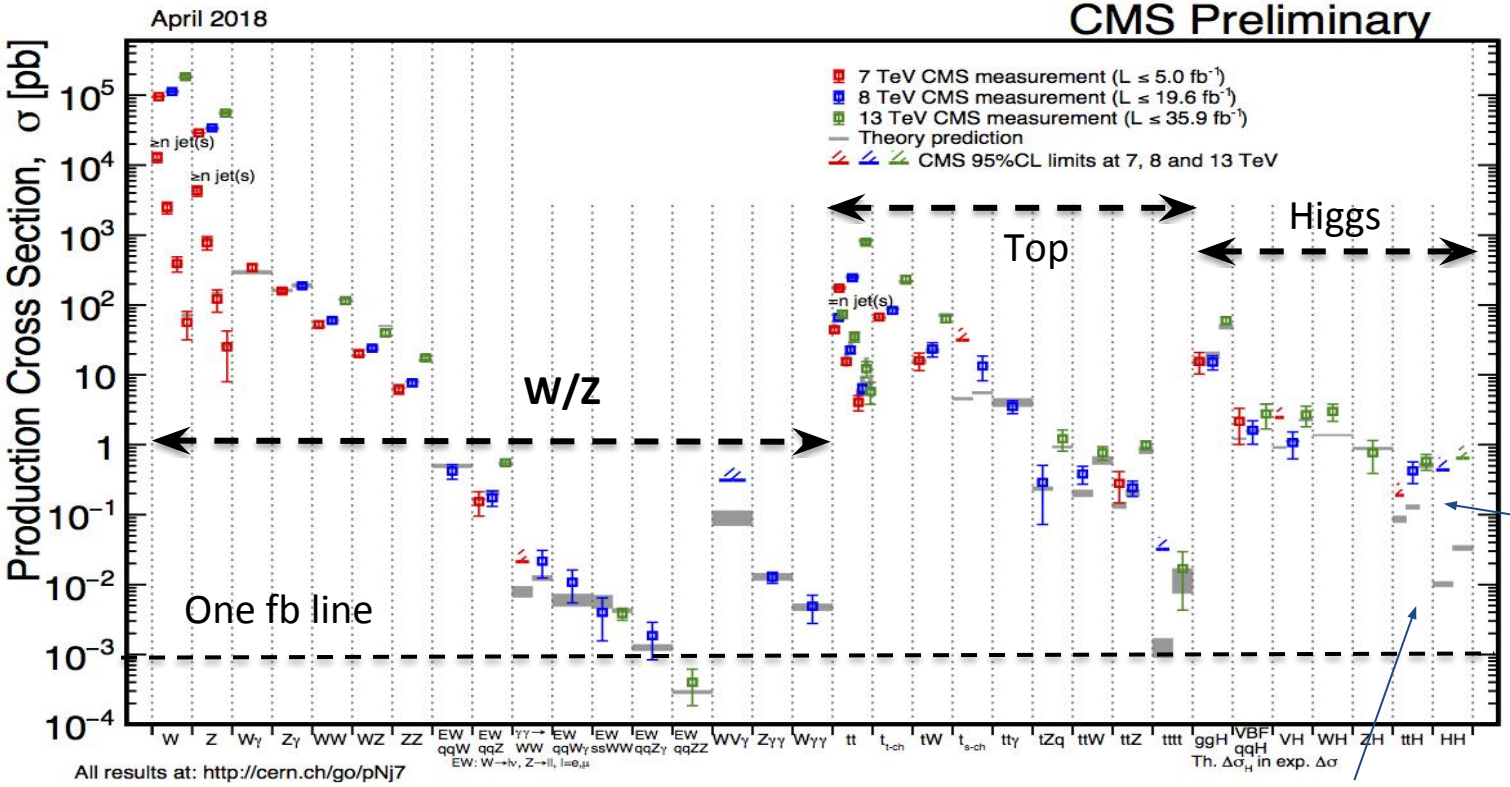
on behalf of the ATLAS & CMS collaborations

LHCP 2018 - Bologna June 4-9

Challenging the SM

searching for another Higgs boson



Observation of HH would indicate BSM effect

Observed ttH
7,8,13 TeV : 5.2σ (4.3σ exp) (arXiv:1804.02610)

Theory motivations

Extended phenomenology from theoretical models (Higgs SM sector + *scalar, doublet, triplet …*)

→ Direct searches @ collider complementary to indirect constraints (b->s γ , g-2) and connected to BSM (i.e. dark matter)

Scalar singlet

They are not charged under the SM symmetries

Direct production of light scalar or from the h_{125} decay

- ➢ 2HDM + scalar
- ➢ theories for light Dark Matter with scalar mediator

doublet

Two-Higgs Doublet Models (2HDM) extend the SM by adding one Higgs doublets, lead to 5 Higgs bosons H^+, H^-, A (CP-odd), H and h (CP-even)

4 types according to couplings of two Higgs doublets with fermion sector:

Type-I: only one doublet couples to fermions

Type-II: up vs. down

Lepton Specific: quark vs lepton

Flipped Coupling: b enhanced τ suppresed

triplet

Fermiophobic $H^{\pm}$,$H^{\pm\pm}$ bosons appear in Higgs sectors extended by a scalar triplet Φ

- ➢ couplings to W and Z bosons at tree level
- ➢ e.g. Georgi-Machacek (GM) model

Introduction into Exotic Higgs Sector

Full coverage of a broad mX range is crucial to maximize the sensitivity to different models

→ Extended phenomenology from theoretical models (higgs SM sector + *scalar, doublet, triplet* …)

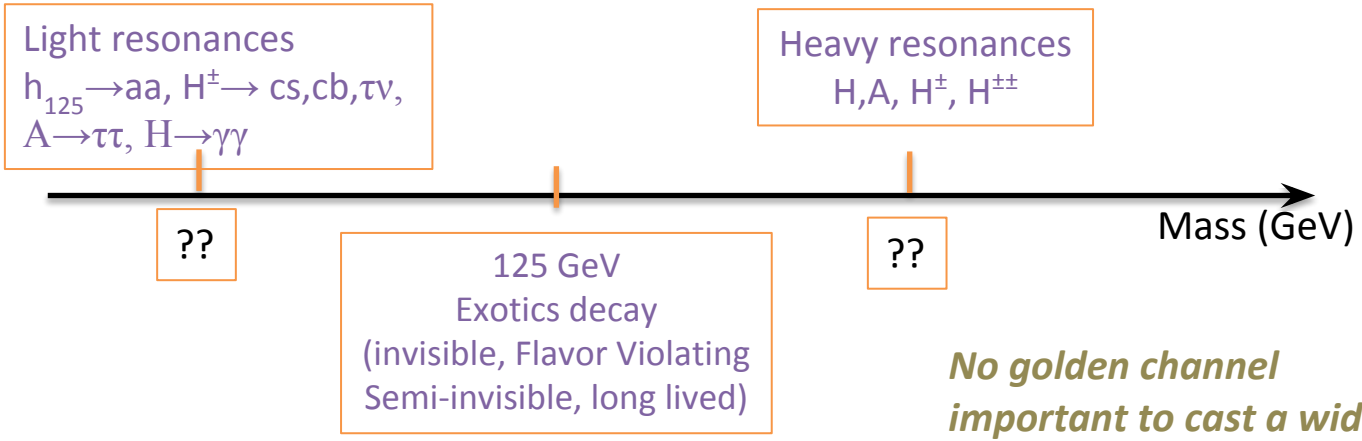
→ Direct searches @ collider complementary to indirect constraints (b->s γ , g-2) and connected to BSM (i.e. dark matter)

→ Multiple analysis techniques

i.e. boosted objects, soft triggers, high p_T btagging, mva …

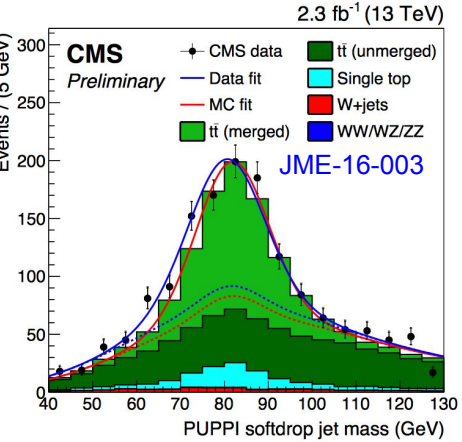
→ General enhancement of production xsection from PDF at 13TeV

i.e. exploit different production modes: gluon fusion, VBF, bb/tt radiation, W/Z associated



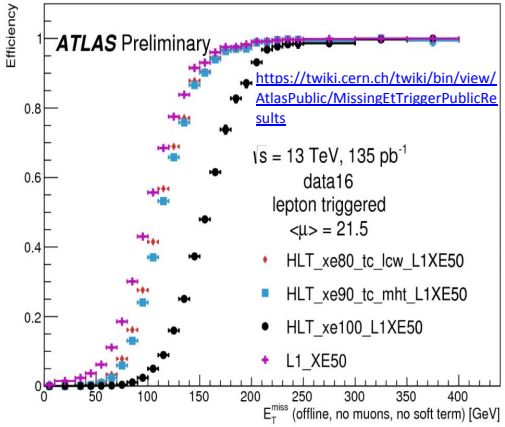
No golden channel
important to cast a wide net

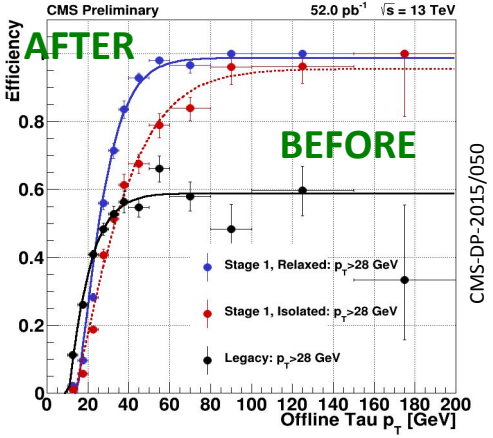
Experimental handles



MET triggers suffers threshold dictated by the rate

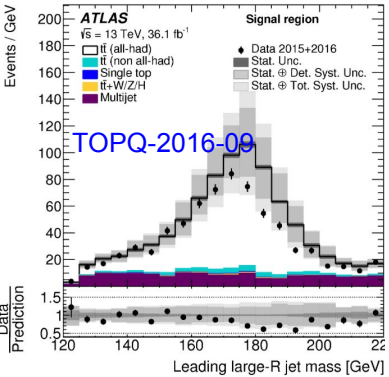
Multivariate techniques are exploited to find rare signals on top of bkg

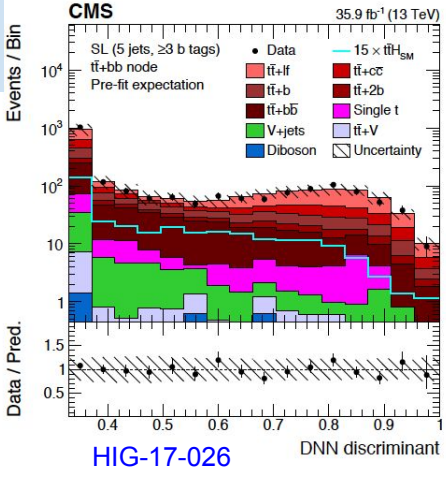


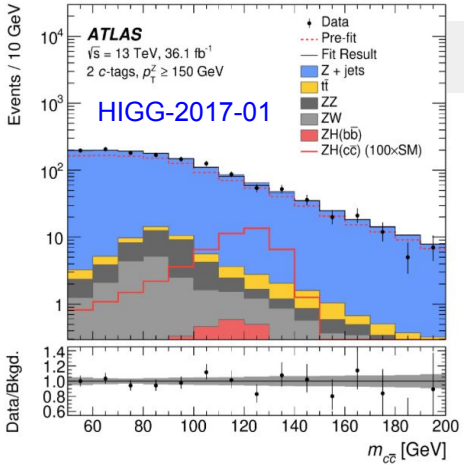


Run 2 major upgrade of the L1 trigger system increases the τ_h collection efficiency.

Boosted W/Z and Top became standard candles

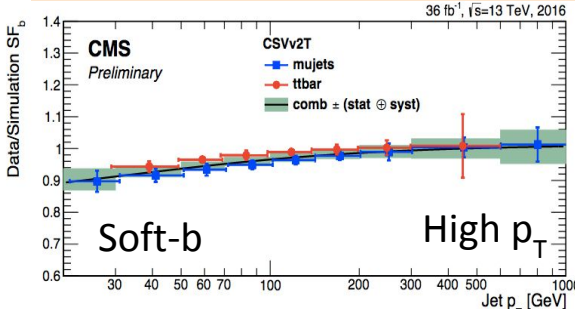




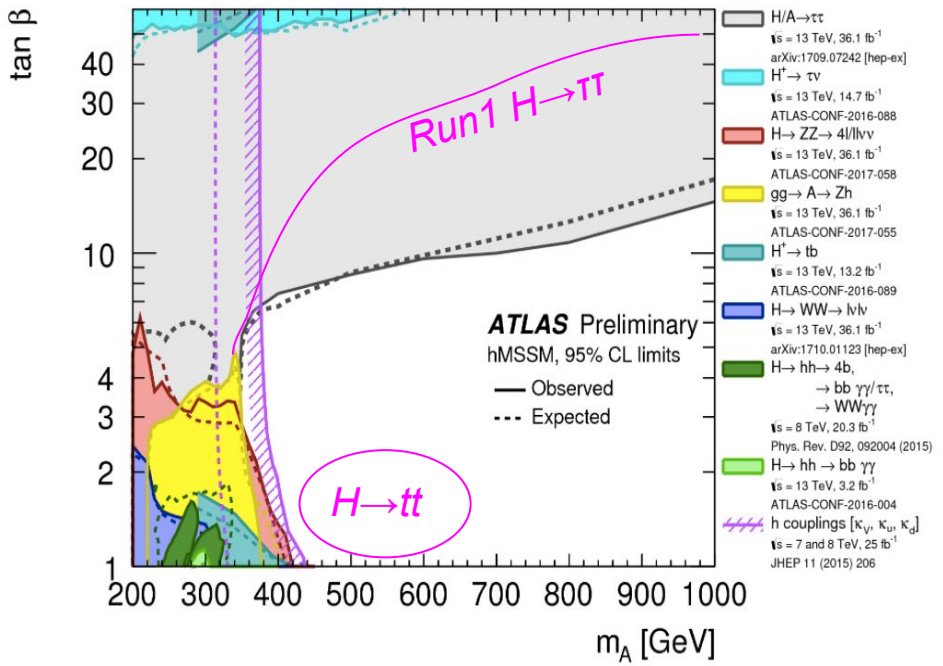


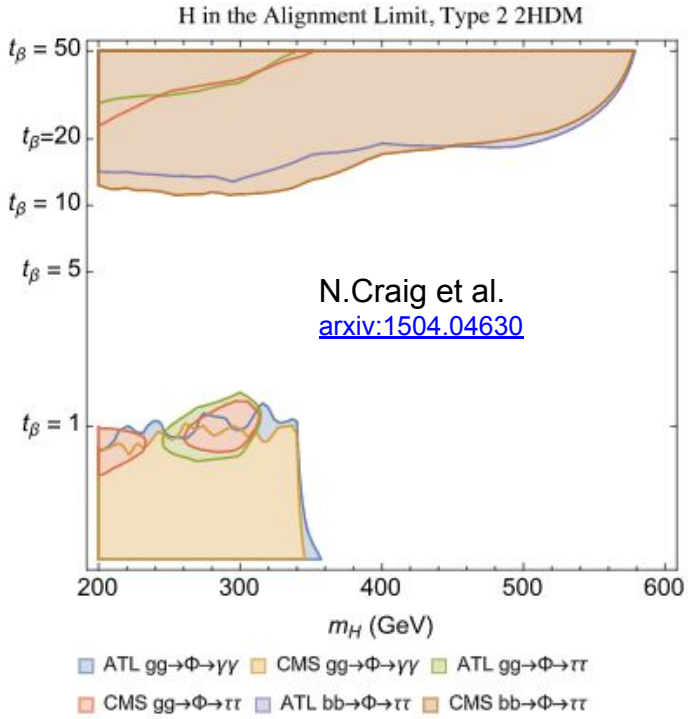
Charm tagging giving results.

Low and high pT bTagging play a key role to suppress the ttbar background.



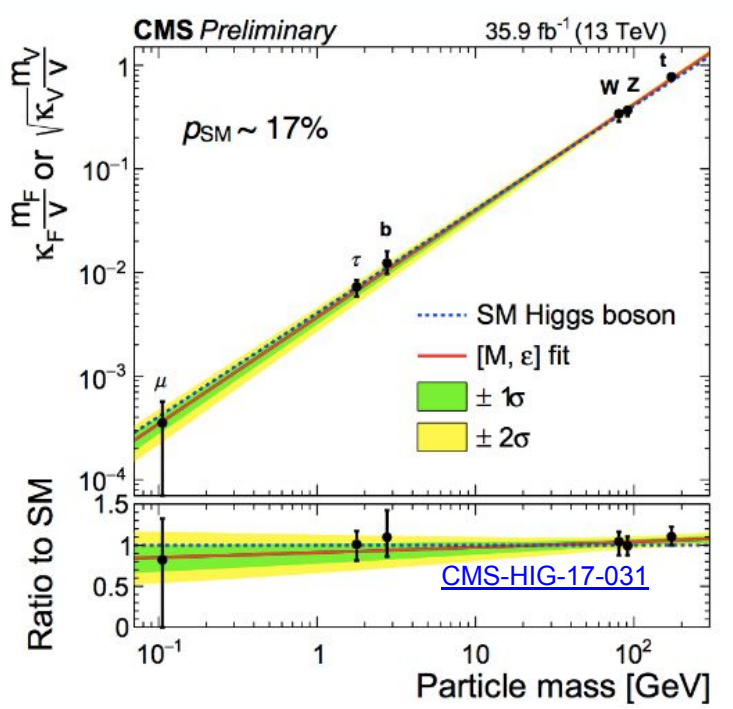
Unknown dynamics
Additional Higgs like scalars





Indirect constraints in BSM model imposed by h_{125}
Low tanβ, high mass generally unexplored
One analysis dominates in one case but not a general statement

Higgs → 3rd generation fermion



BSM scenarios leading search channels:

A/H→tt : CMS Eur. Phys. J. C 77 (2017) 578 ATLAS: Phys. Rev. Lett. 119, 191803 (2017)

A/H→bb : *CMS arxiv:1805.12191*

$H^{\pm}$→tb : CMS JHEP 11 (2015) 018 , ATLAS-CONF-2016-089

A/H→ττ CMS *arxiv:1803.06553* ATLAS: JHEP 01 (2018) 055

$H^{\pm}\to\tau_h\nu$ *CMS-PAS-HIG-16-031*, *ATLAS-CONF-2016-088*

More in talk by Andrey Popov

Not imposed by a fundamental symmetry
→ searches exist in other decay modes

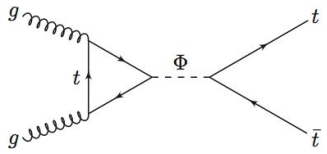
h_{125} : established *ad-hoc* hierarchical Yukawa couplings ∝mf

A/H→μμ, $H^{\pm}$→ cs,cb

Phys. Rev. Lett. 119, 191803 (2017)

H→tt

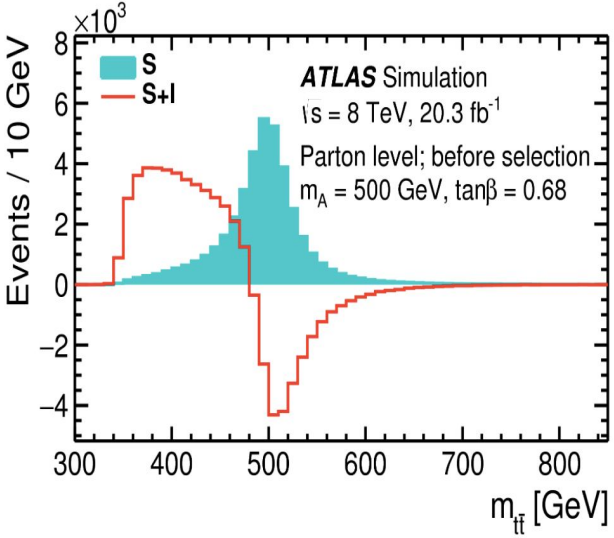
MSSM: Higgs + doublet

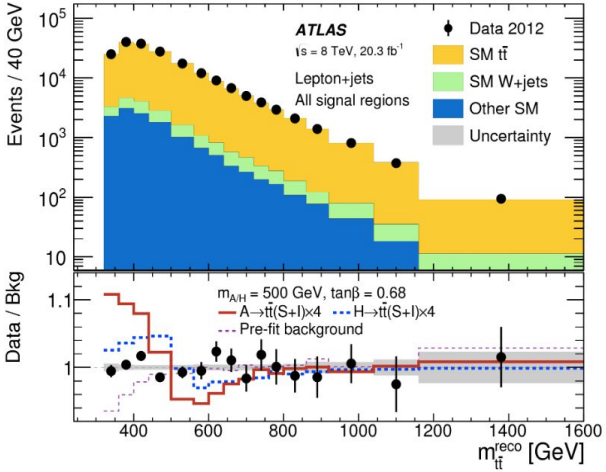


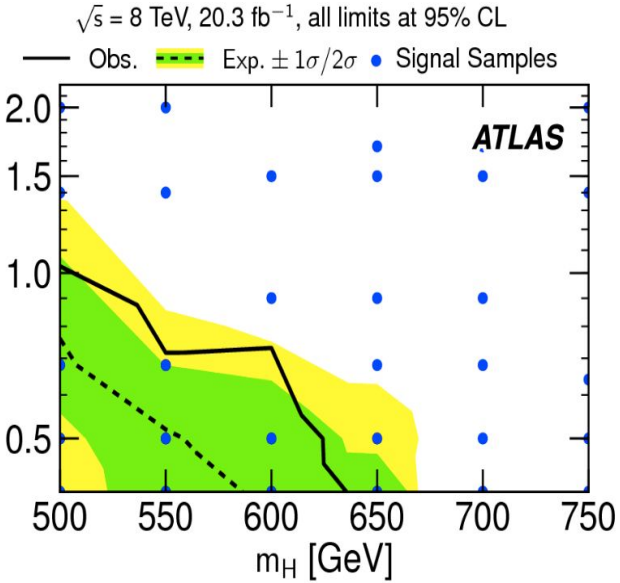
Significant interference between the gg→ttbar production and A/H→ tt.

- 1 e/μ + >=4jets + MET
- Discriminating variable: invariant mass of the top pair

Upper Limits on Scalar H, pseudo-scalar (A) for Type-II 2HDM





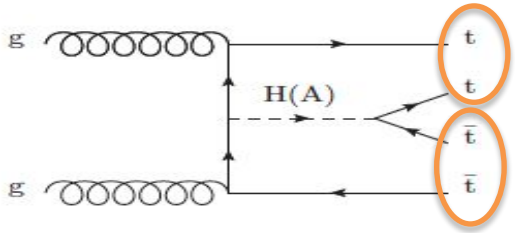


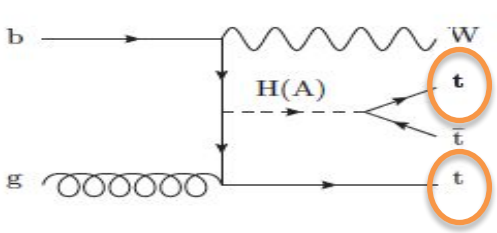
Eur. Phys. J. C 77 (2017) 578

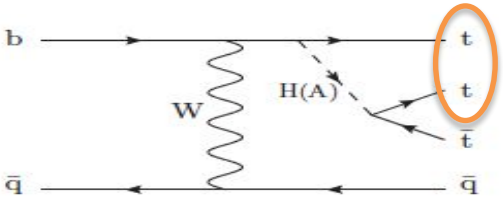
tt A/H→tt tt

MSSM: Higgs + doublet
N.Craig et al arxiv:1605.08744

Free from interference

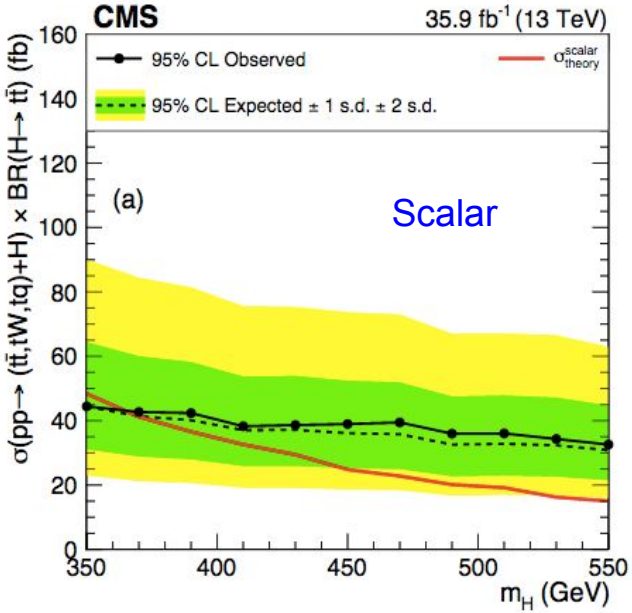


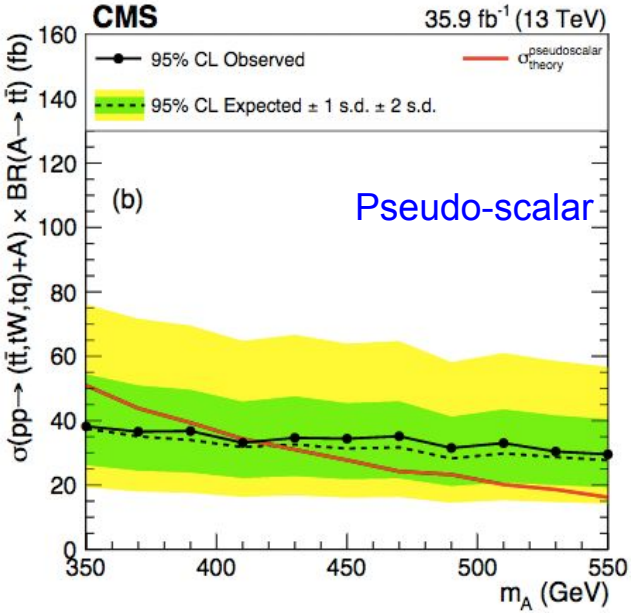




Same Sign leptons signature helps to kill the overhelming background. O(100) search regions binned in N_j, N_b, H_T, MET, m_T, and lepton p_T.

Statistics limited, expect continued progress in future.



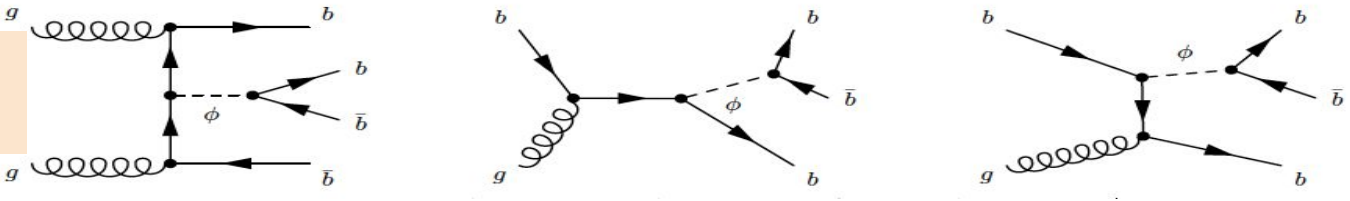


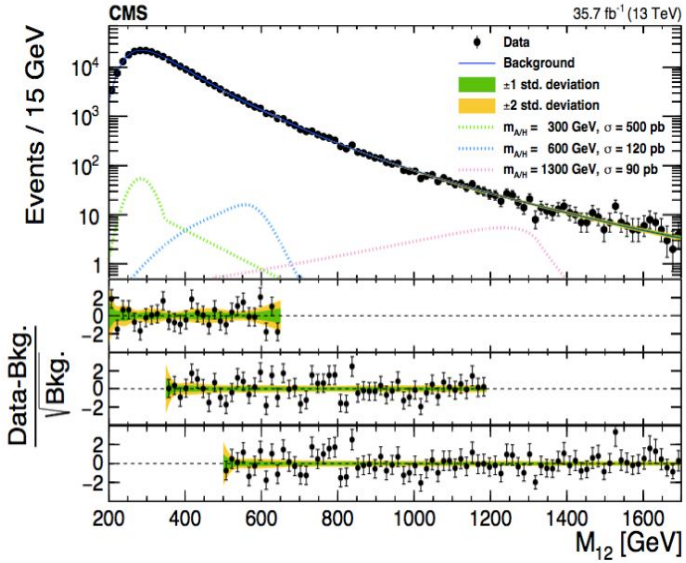
A/H→bb

arxiv:1805.12191

Flipped model

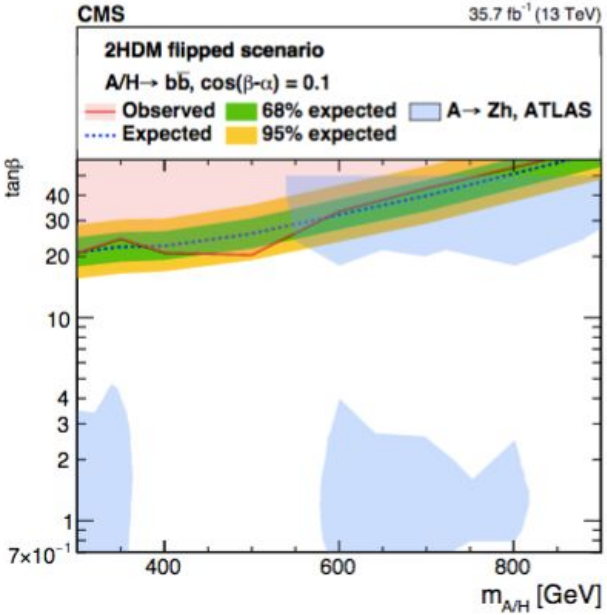
Unique *Coupling to down-type fermion*





QCD multijet is the main background

- Three subranges to reduce bias from the choice of the background model
- Signal shape for different signal hypothesis

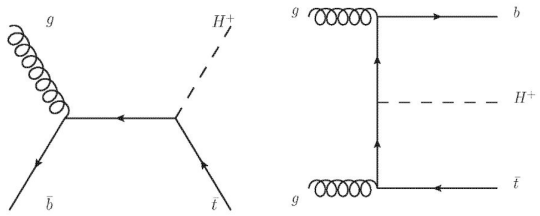


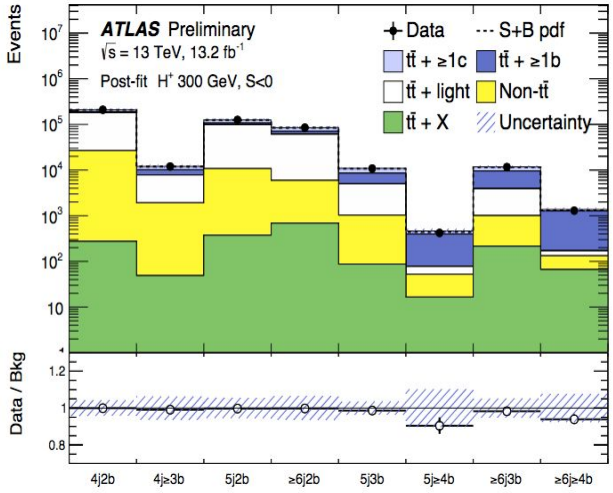
$(b)tH^{\pm} \rightarrow (b)ttb$

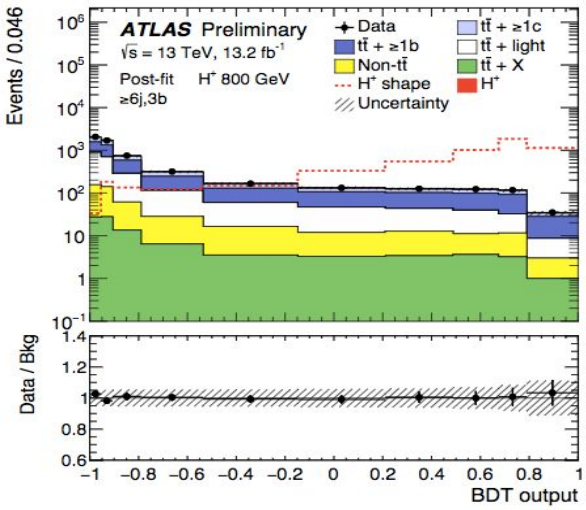
ATLAS-CONF-2016-089

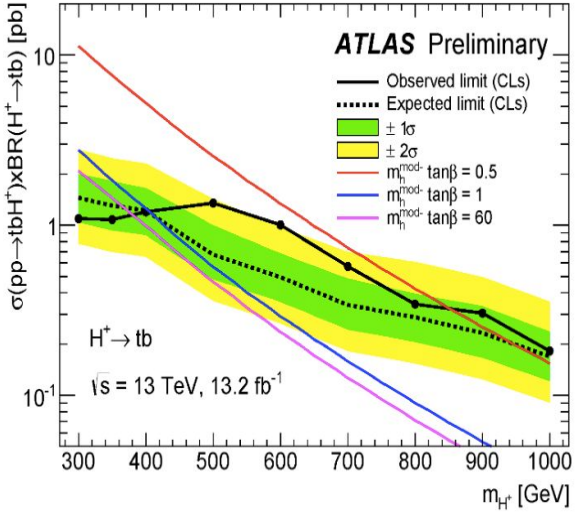
MSSM: Higgs + doublet

TTbar + HF production the major background.
Analysis categorized in jet and bjet multiplicity.
MVA discriminant used to separate the small signal respect to the background.









$H^{\pm} \rightarrow \tau_h \nu$

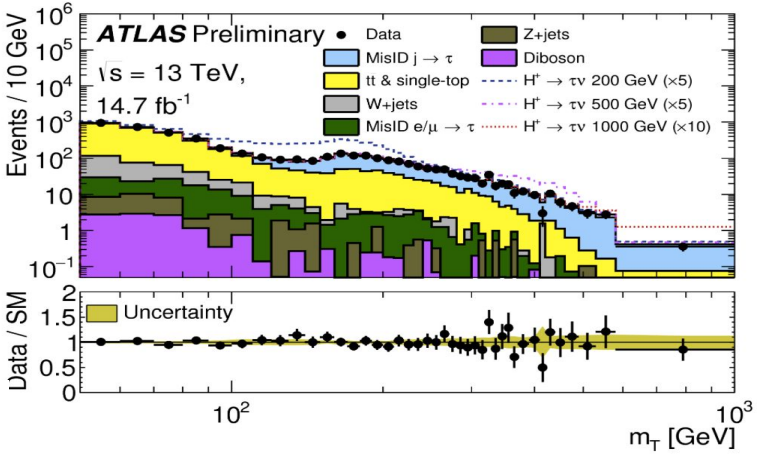
CMS-PAS-HIG-16-031
ATLAS-CONF-16-088

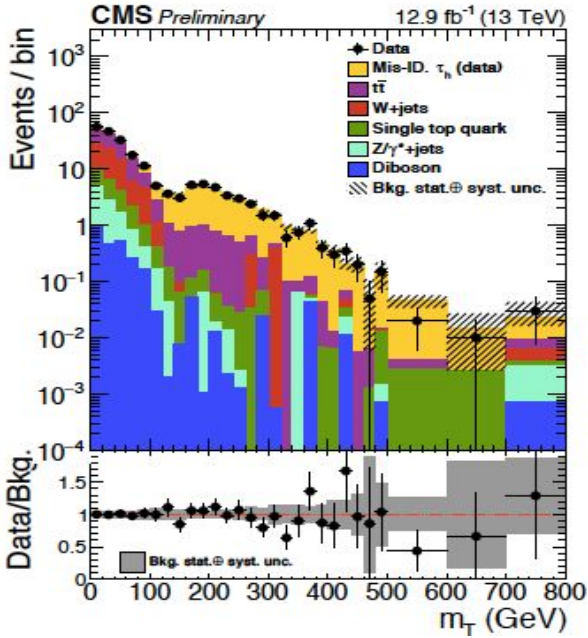
MSSM: Higgs + doublet

Hadronic tau final state

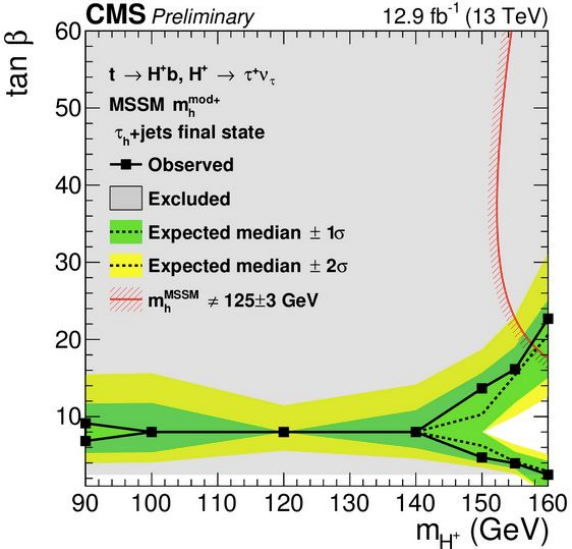
Signal extraction w/

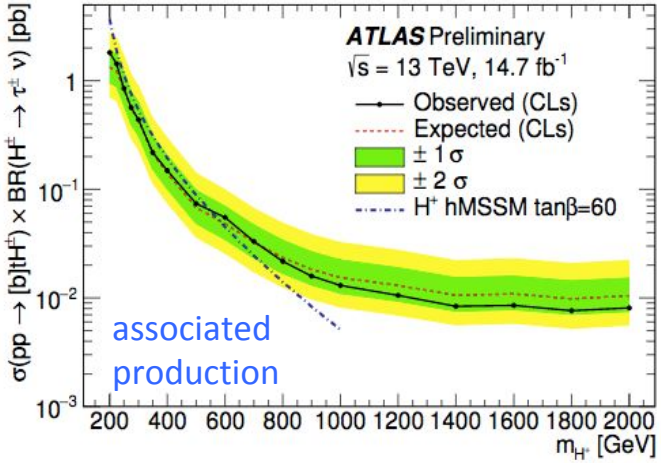
$$m_T^2 = 2 \cdot p_T^{\tau^h} |\vec{E}_T| \left(1 - \cos\Delta\phi(\vec{E}_T, \tau^h)\right)$$





ttbar decay





associated production

Heavy Higgs → dibosons

In this talk

Bump hunting on dibosons mass spectrum

	$W^\pm$	Z	γ	$H/A/h_{125}$
$W^\pm$	**$WW \to 2l2\nu$** CMS-HIG-16-023,2015 ATLAS-HIGG-2016-31 **$WW \to l\nu qq$** ATLAS EXOT-2016-28 **$H^{\pm\pm} \to W^\pm W^\pm$** CMS-PAS-SMP-17-004			
Z	**$H^\pm \to W^\pm Z \to 3l\nu$** CMS-HIG-16-027,2016 **$H^\pm \to W^\pm Z \to l\nu qq$** ATLAS EXOT-2016-28	**$ZZ \to 2l2q$, $2l2\nu$, $4l$** CMS-HIG-17-012,2016 36fb **$ZZ \to 2l2\nu$, $4l$** ATLAS-HIGG-2016-19 **$Z\ W/Z \to 2q2\nu$** B2G-17-004		
γ	**$W/Z/h_{125}(\to qq) + \gamma$** ATLAS-HIGG-2016-19	**$Z\gamma \to (2l,2q) + \gamma$** CMS-EXO-17-005, 2016 36fb	**$\gamma\gamma$** CMS-EXO-16-027,2016 36fb (*) ATLAS PLB 775 (2017) 105	
$H/A/h_{125}$	**$W/Z(\to l\nu, 2l, 2\nu) + h_{125} \to bb$** B2G-17-004 **$W/Z + h_{125}$** CMS-HIG-16-010 ,2015 EXOT-2016-10, EXOT-2016-34	**$Z(\to 2l) + H/A(\to bb)$** CMS-HIG-16-010 ,2015 (**) **$Z + H$**		**$h_{125} h_{125}$**

(*) also mass $X \to \gamma\gamma$ 80-125 8TeV HIG-14-037
(**) also $Z(\to 2l) + AH/A(\to \tau\tau)$ 8TeV HIG-14-034

H→ZZ→2l2q, 2l2ν, 4l

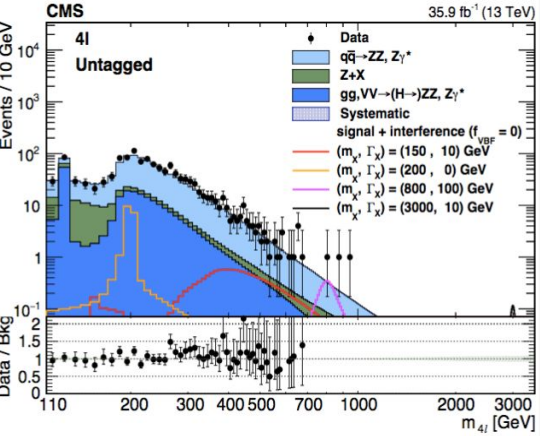
arxiv:1804.01939

MSSM: Higgs + doublet

4l

ggH, VBF

Lowest BR
Low reducible background
Clear Bump Hunt

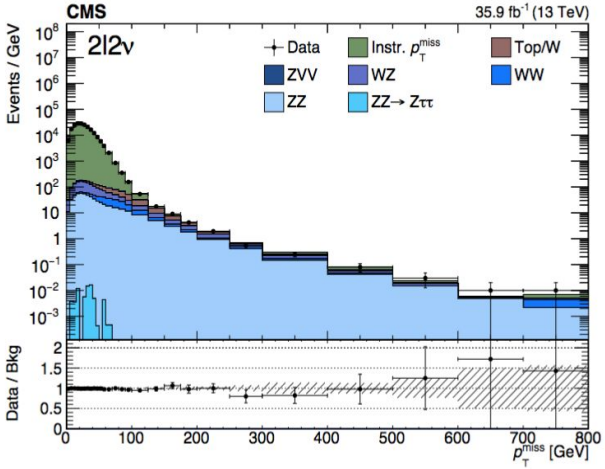


2l2ν

ggH, VBF
Signal extraction w/

$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M_Z^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$

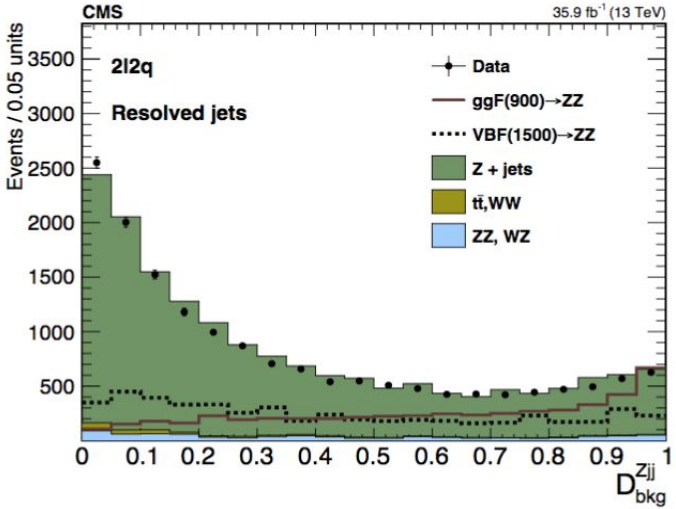
Limits as function of MH and Γ



2l2q *Largest BR*

explored both the boosted and resolved Z⟶qq
ggH, VBF

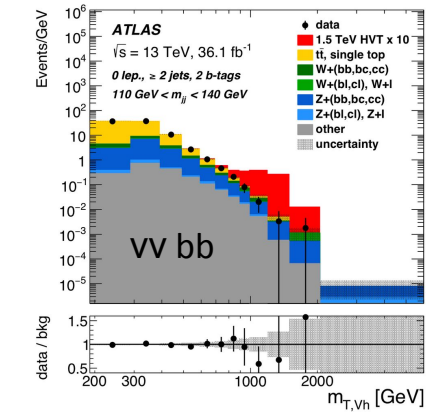
Search over Mzz and $\mathcal{D}_{Zjj} = \left[1 + \frac{\mathcal{P}_{Zjj}(\vec{\Omega}^{X\to 2\ell 2q}|M_{ZZ})}{\mathcal{P}_{X\to 2\ell 2q}(\vec{\Omega}^{X\to 2\ell 2q}|M_{ZZ})}\right]^{-1}$

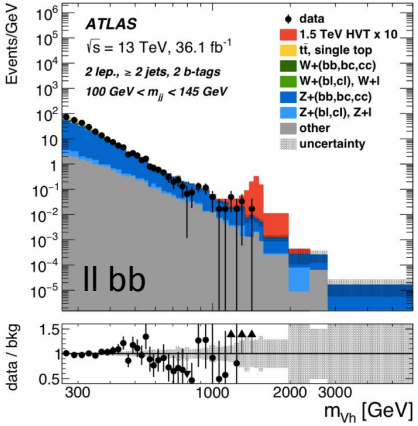


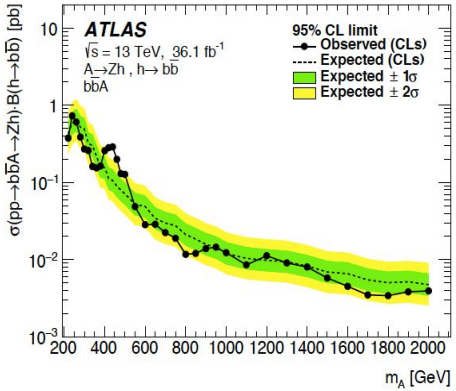
H→Vh→llbb

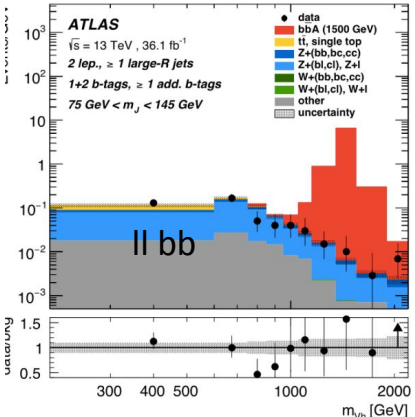
JHEP 03 (2018) 174 :
Resonant A-> W/Z h_{125}→
ll bb, lv bb, vv bb

Result on the gluon fusion and associated production

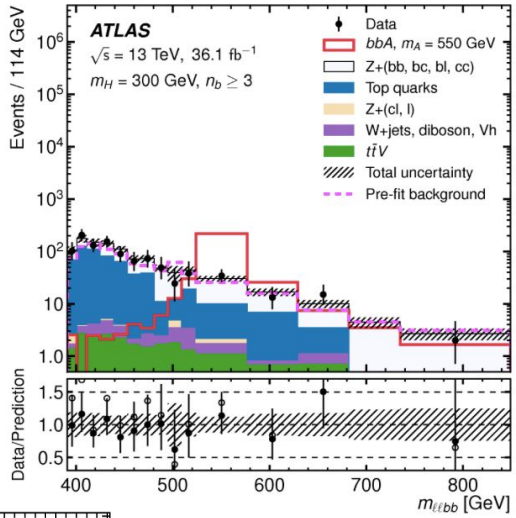


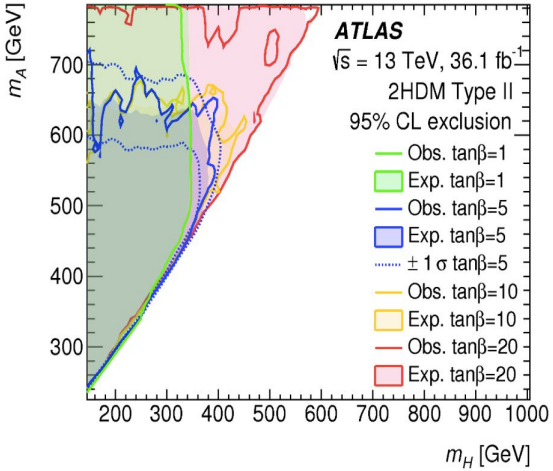






arxiv:1804.01126
Resonant
A →Z H → ll bb

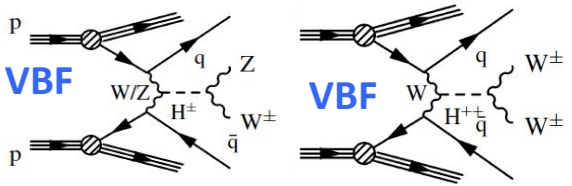




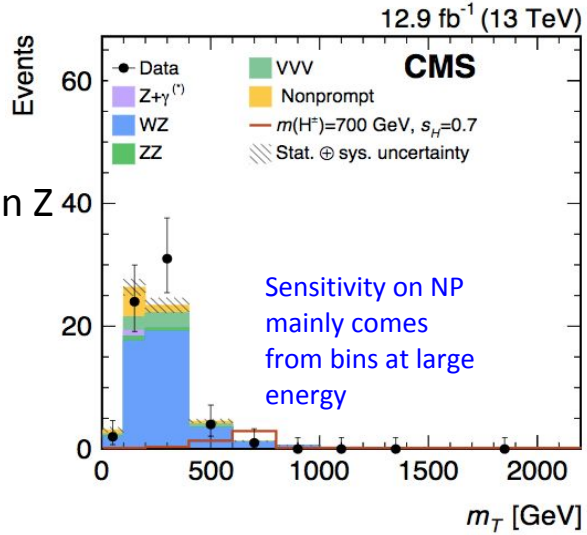
$H^{\pm} \rightarrow W^{\pm}Z$

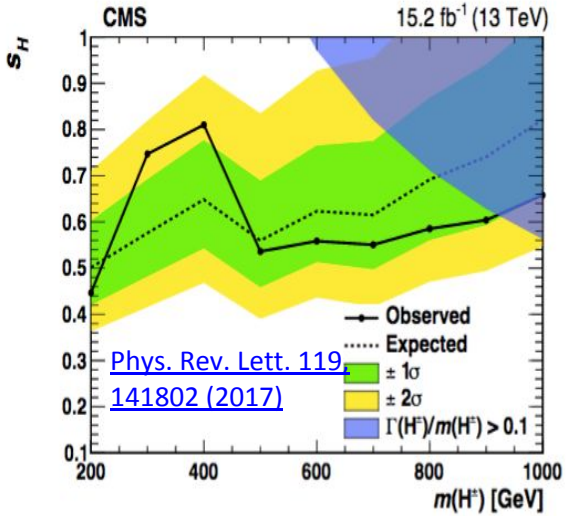
Three leptons search, with two OS on Z

$$M_T(WZ) = \sqrt{(E_T^Z + E_T^W)^2 - (\bar{p}_T^Z + \bar{p}_T^W)^2}$$



H. Georgi and M. Machacek
Higgs + SU(2) triplet

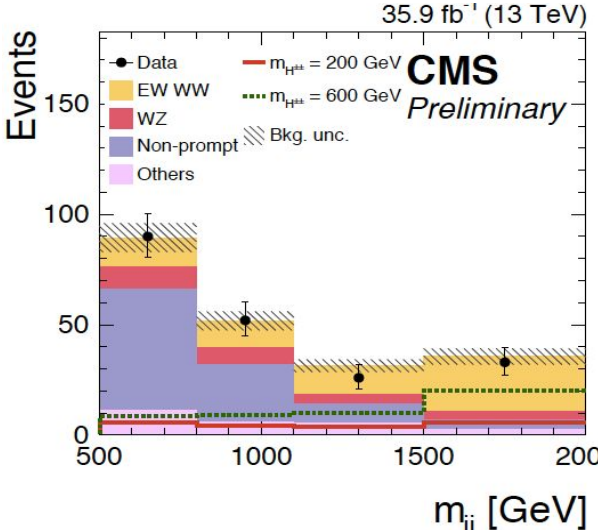


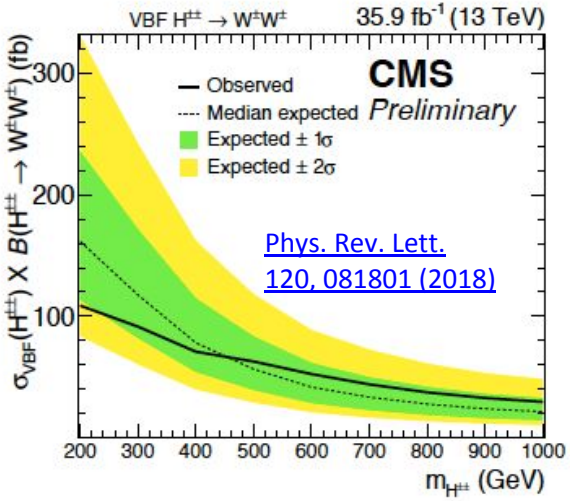


Phys. Rev. Lett. 119, 141802 (2017)

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

Same sign leptons





Phys. Rev. Lett. 120, 081801 (2018)

$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$

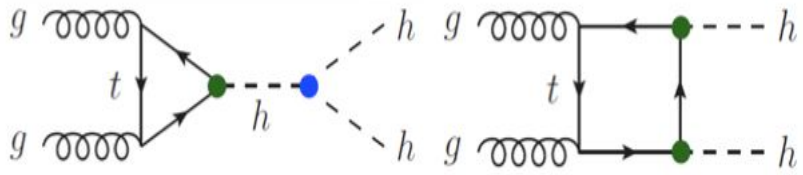
ATLAS: Eur. Phys. J. C 78 (2018) 199

CMS-PAS-HIG-16-036

Both statistics limited, expect continued progress in future.

Di Higgs production

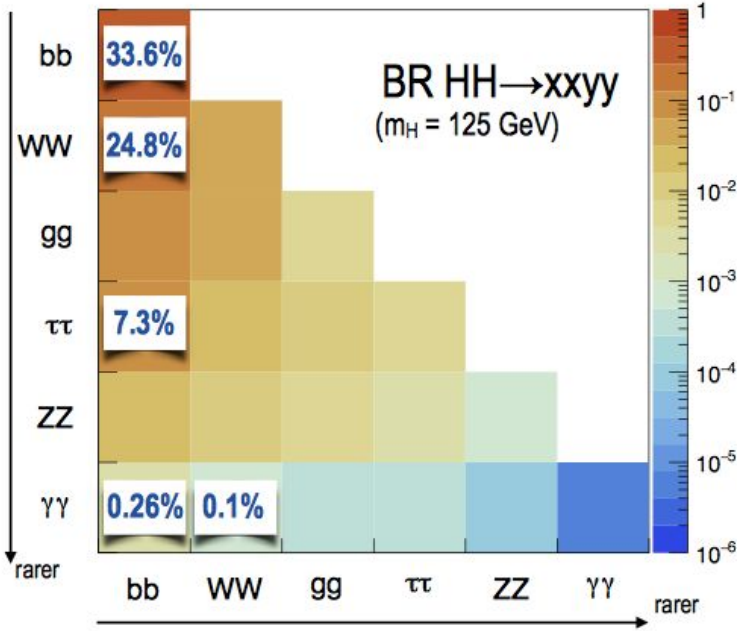
Dedicated talk by Nan Lu



SM cross section @ 13 TeV $33.53^{+4.3\%}_{-6.0\%}(\text{scale}) \pm 2.3\%(\alpha_s) \pm 2.1\%(\text{PDF})$ fb
not accessible with the Run2 data

BSM effects lead to:

- the presence of resonant hh process.
- the enhancement of the non-resonant hh production cross section and the modification of the kinematics of the decays.

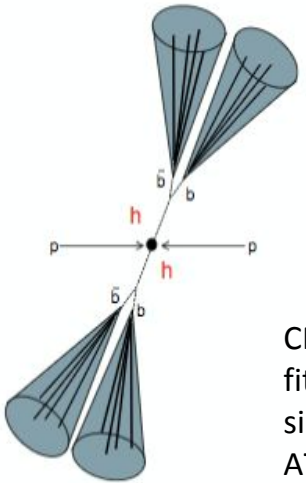


Very different theoretical motivation, but similar experimental signature.

One H→bb or H→WW decay required to keep BR high enough

Highlights on HH→bbbb

Resolved



4 AK4jets:

B-jet triggers

4 btag jets:

ATLAS: ε 70% WP

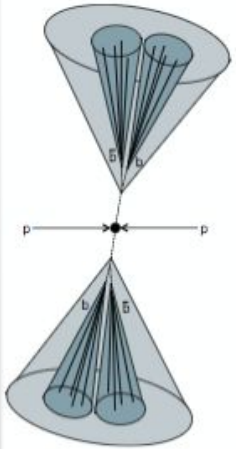
CMS: new DeepCSV

CMS:
fit function form taken from mbb-X sidebands

ATLAS:

- 2b2j sample to model the 4b,
- normalisation factor and kinematic corrections in control regions in m2jlead–m2jsubl plane

Boosted



Two large cone jets:

ATLAS R=1.0

CMS R=0.8

High pT FatJet trigger

ATLAS:

btag R=0.2 track jets

1or2 btag jets per large-R jet

CMS:

double btagged

SDmass and n-subjettiness

Probe mass > 1TeV

Probe mass up to ~ 1TeV

Di Higgs

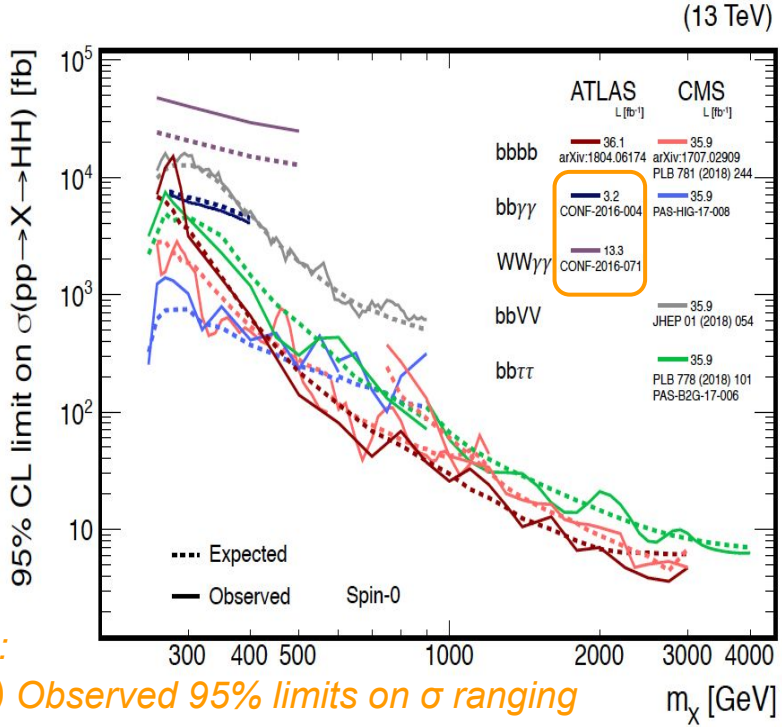
bbbb : high BR but large contamination from multijet background (dominant at high mass)

bb VV: high BR, large irreducible tt

bbγγ and bbττ with similar sensitivity at low mass

WWγγ-> studied by ATLAS

σ/σ_{SM}	CMS	ATLAS
bbVV	<79 JHEP 01 (2018) 054	
bb bb	<342 HIG-PAS-16-026	<13 arxiv:1804.06174
bb ττ	<31.4 Phys. Lett. B 778 (2018) 101	
bb γγ	<23.6 arxiv:1806.00408	<22 NEW paper in preparation
WW γγ		<230 NEW paper in preparation



ATLAS new (36 /fb):

bb γγ (WW γγ) Observed 95% limits on σ ranging from 1.14 to 0.12 pb (40 to 6.1 pb)

Complementarity of the channels in different mass ranges → much gain from a combination

Tested anomalous trilinear and BSM Higgs couplings as well.

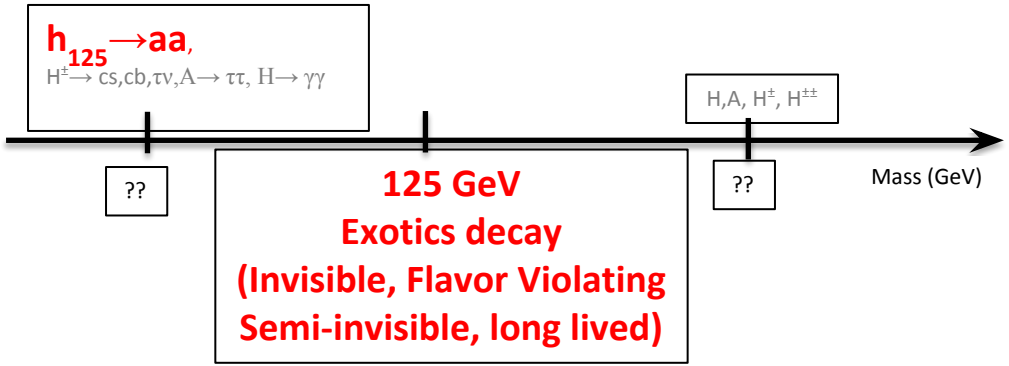
Rare h_{125} boson decay

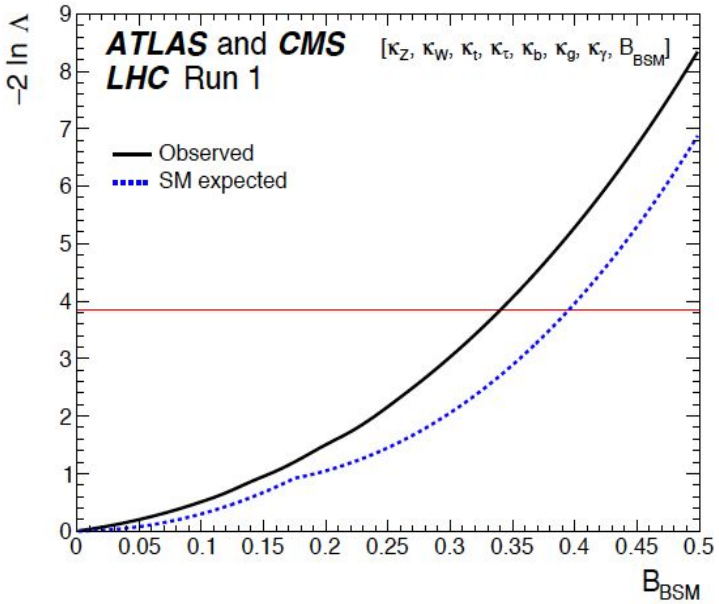
JHEP08 (2016) 045

SM-like Higgs @ 125 is narrow

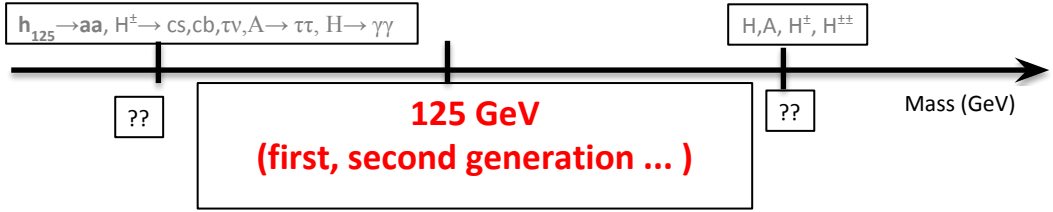
But room for BSM

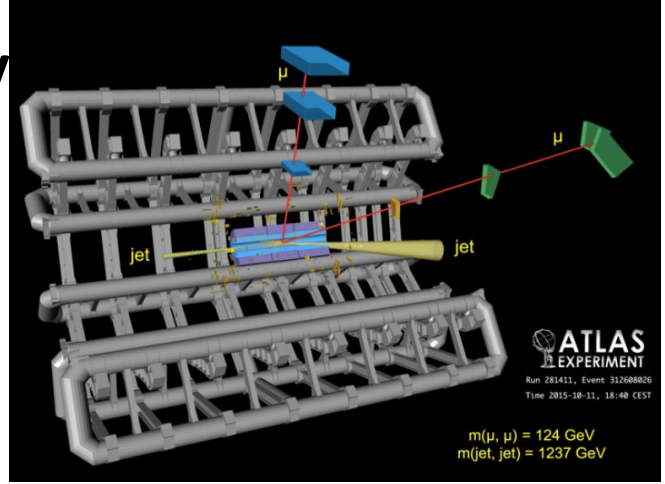
B_{BSM} < 0.34 (0.39) obs (exp) ATLAS + CMS combined





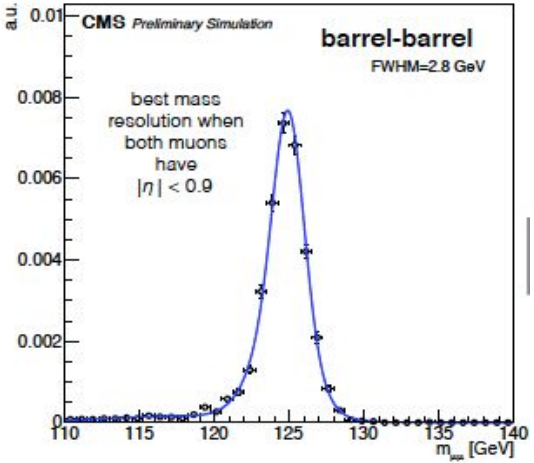
Rare $h_{125} \rightarrow \mu\mu$ decay

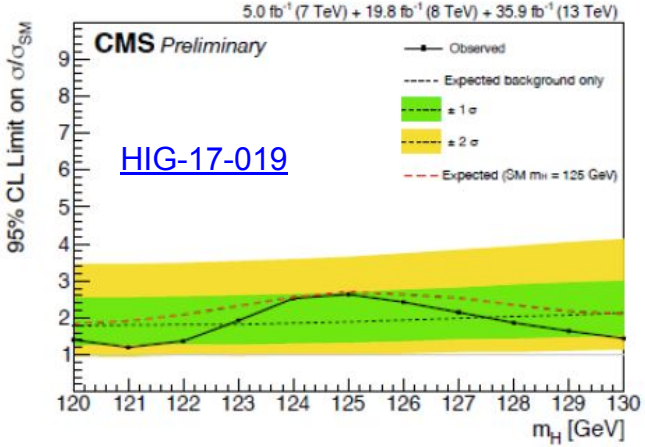




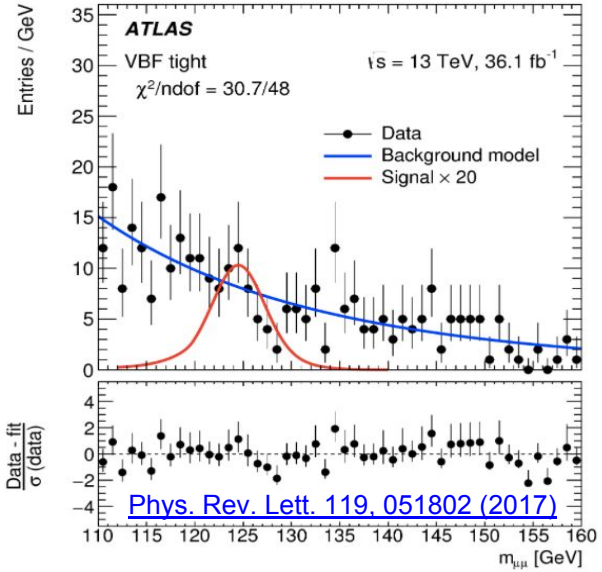
Most sensitive category is in the VBF channel

Less than 3 sigma away from SM





HIG-17-019



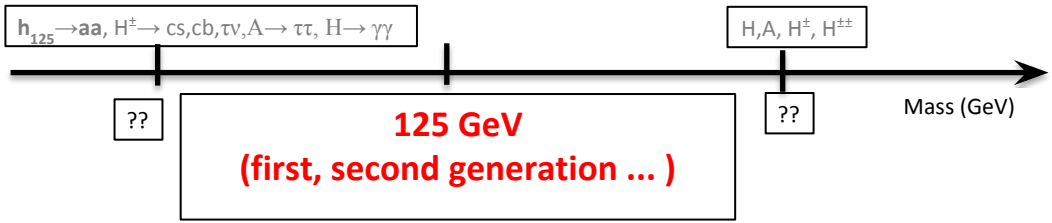
Phys. Rev. Lett. 119, 051802 (2017)

Dedicated talk by Andrew Haas

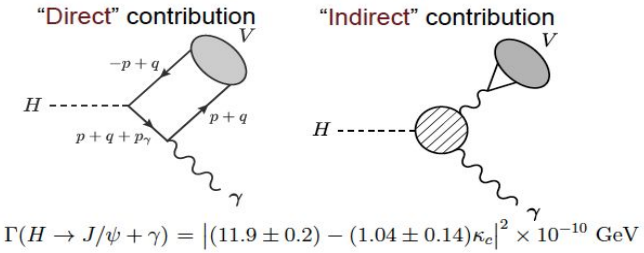
M.D'Alfonso (MIT)

Statistics limited, expect continued progress in future.

Rare h_{125} boson decay



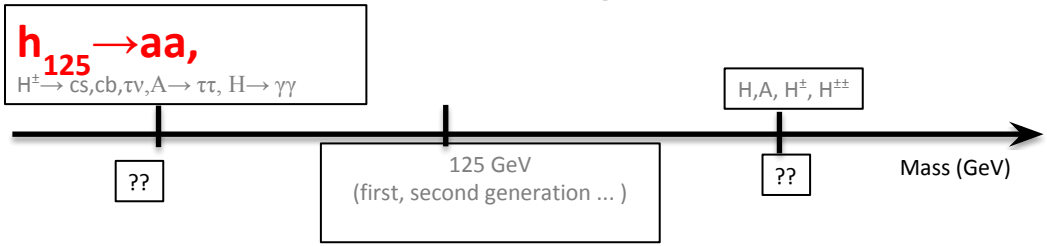
$h_{125}\to Q\gamma$ clean probe for higgs quark coupling of 1st/2nd generation



Dedicated talk by Andrew Haas

13TeV(36 /fb) , 8TeV	σ/σ_{SM}
$H_{125}\to Z\gamma$ (ATLAS) JHEP 10 (2017) 112	< 6.6
$H_{125}\to Z\gamma$ (CMS) PAS-HIG-17-007	< 8
$H_{125}\to\gamma^*\gamma$ (CMS) PAS-HIG-17-007	< 4
$H_{125}\to\rho\,\gamma$ (ATLAS) arxiv:1712.02758	< 52
$H_{125}\to\varphi\,\gamma$ (ATLAS) arxiv:1712.02758	< 208
$H_{125}\to j/\psi\,\gamma$ (CMS) Phys. Lett. B 753 (2016) 341	<540
$H_{125}\to j/\psi\,\gamma$ (ATLAS) Phys. Rev. Lett. 114, 121801 (2015)	<540
$H_{125}\to\Upsilon\gamma$ (ATLAS) Phys. Rev. Lett. 114, 121801 (2015)	$< 10^5$

$h_{125} \rightarrow aa$ decay



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

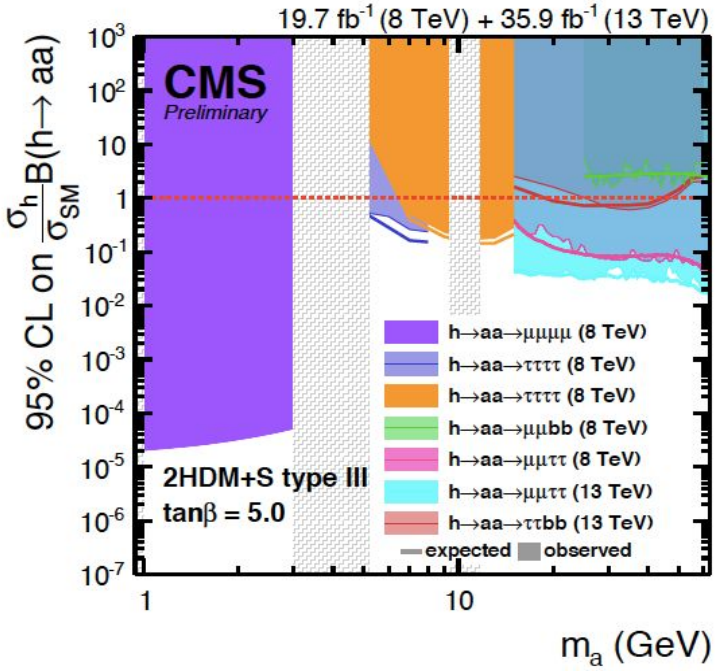
- $h_{125} \rightarrow aa \rightarrow 4\mu$:
  - CMS *13TeV,2.3 /fb* HIG-16-035
  - *ATLAS* arxiv:1802.03388
- $h_{125} \rightarrow aa \rightarrow 2\mu 2\tau$
  - CMS *arxiv:*1805.04865
  - ATLAS arxiv:1505.01609

CMS

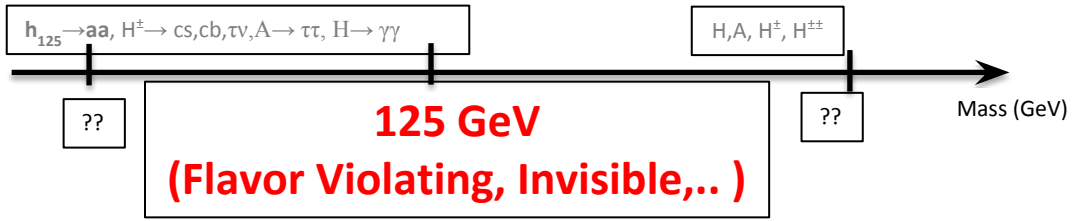
- $h_{125} \rightarrow aa \rightarrow 2b2\tau$ *arxiv:1805.10191*
- $h_{125} \rightarrow aa \rightarrow 2\mu 2b$ JHEP 10 (2017) 076
- $h_{125} \rightarrow aa \rightarrow 4\tau$ JHEP 10 (2017) 076

ATLAS

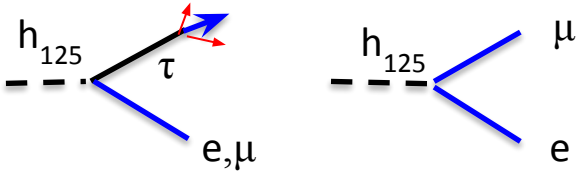
- $h_{125} \rightarrow aa \rightarrow 4b$ (*13TeV,2.3 /fb* arxiv:1606.08391 *w/ W tag)*
- $h_{125} \rightarrow aa \rightarrow 4\gamma$ (Eur. Phys. J. C 76(4) , 1-26 (2016))
- $h_{125} \rightarrow aa \rightarrow 2\gamma 2g$ (arxiv:1803.11145) *(w/ VBF tag)*

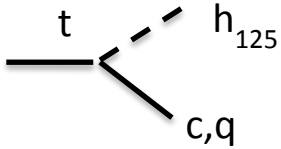


Rare h_{125} boson decay



Lepton/quark flavor violating

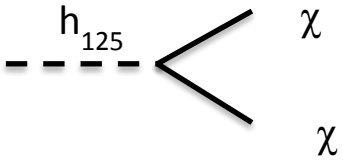




	With 8 TeV data	With 13 TeV data
BR(H→τμ)	< 1.43%	< 0.25%
BR(H→τe)	< 1.04%	< 0.61%
BR(H→eμ)	< 0.036%	

Dedicated talk by G.Zevi

Invisible Higgs



χ gives MET signature

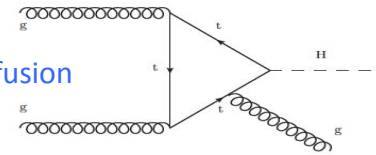
SM invisible width = 0.1% $\Gamma(h_{125})$ from h_{125}->ZZ->νννν

Invisible Higgs

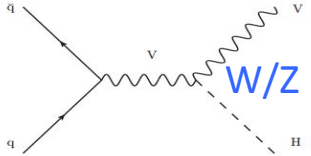
CMS-PAS-HIG-17-023
ATLAS arxiv:1708.09624

Dedicated talk by Andrew Haas

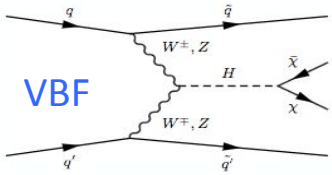
Gluon fusion



W/Z + H



VBF



High pT recoiling jet

Largest σ

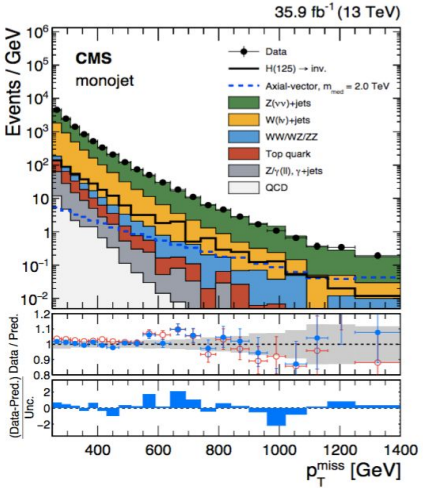
Lowest S/B

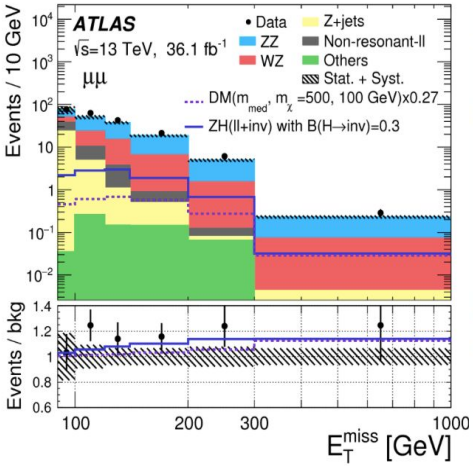
Z-> OS/SF leptons close to Mz

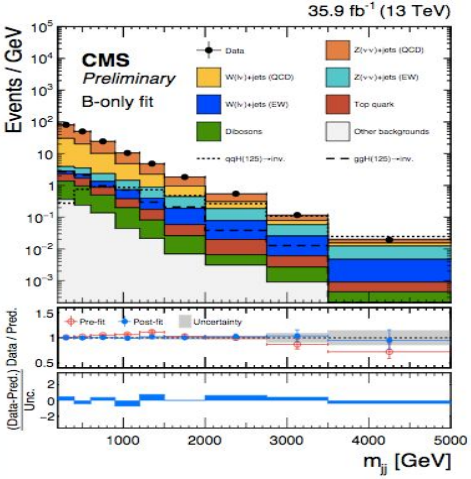
Smallest BR , Higher S/B

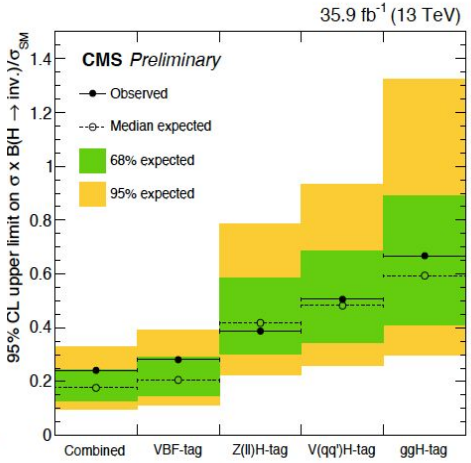
V-> qq resolved or boosted

Dijet system with
Large rapidity gap Δη(j1,j2)
Large dijet mass M(j1,j2)









Summary

A rich program of searches for Higgs bosons in the context of models beyond the SM being pursued since Run-1

Direct search of new physics exploits:

→ Production of extra higgs decaying in Standard Model particles

→ Exotic decays of the h_{125}

BSM Higgs bosons are still hiding

More decay channels being explored, more statistics to come

→ So far analyzed mainly (36 fb-1) , expected new results with 5 times large Run2 dataset !