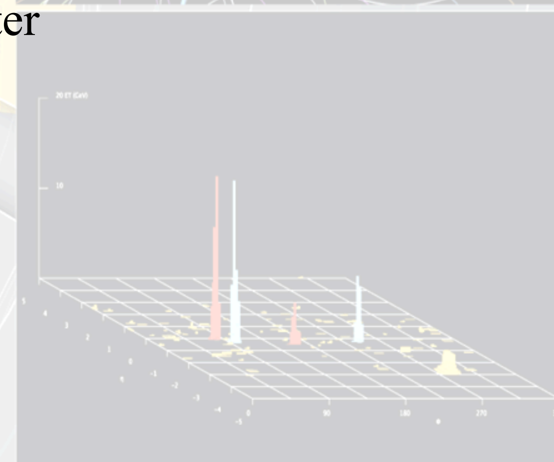
Experimental Review of Searches for Additional Higgs Bosons
Selected topics

J.-B. de Vivie (LAL)
on behalf of the ATLAS and CMS collaborations

Outline

- Introduction : known facts about the scalar sector
- Searches for additional Higgs bosons
- The light Higgs as a portal to Dark Matter



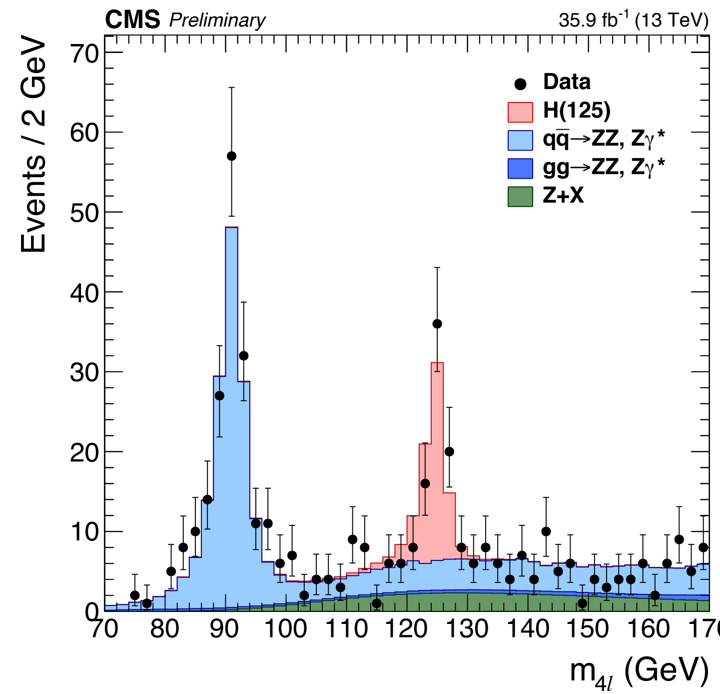
Known facts about the scalar sector

There exists a rather light scalar (w.r.t. naturalness ;-))

$$m_H^{RunI} = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}\ GeV/c^2$$

Precision already better in Run II : CMS, 4ℓ, 35.9 fb^{-1}

$$m_H = 125.26 \pm 0.20_{stat} \pm 0.08_{syst}\ GeV/c^2$$



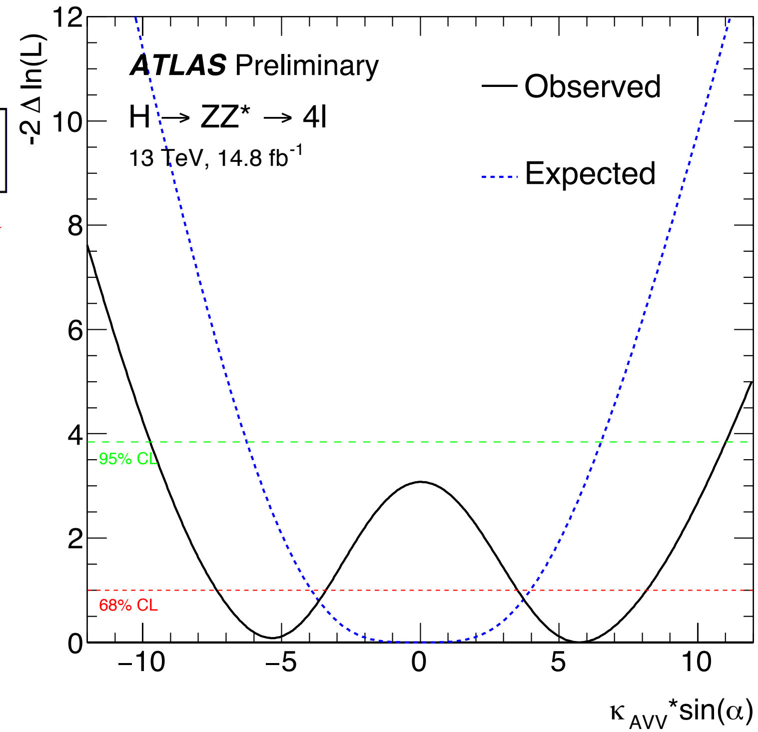
Narrow width : e.g. from direct measurement, CMS, 4ℓ, same data : $\Gamma < 1.10$ GeV @ 95% CL

And very compatible with $J^{CP} = 0^{++}$: e.g.

$$\mathcal{L} = \cos\alpha\kappa_{SM}\left[g_{HVV}V_\mu V^\mu - \frac{1}{4\Lambda\kappa_{SM}}(\kappa_{HVV}V^{\mu\nu}V_{\mu\nu} + \kappa_{AVV}\tan\alpha V^{\mu\nu}\tilde{V}_{\mu\nu})\right]$$

SM (CP-even) — CP-even, higher dimensional — CP-odd

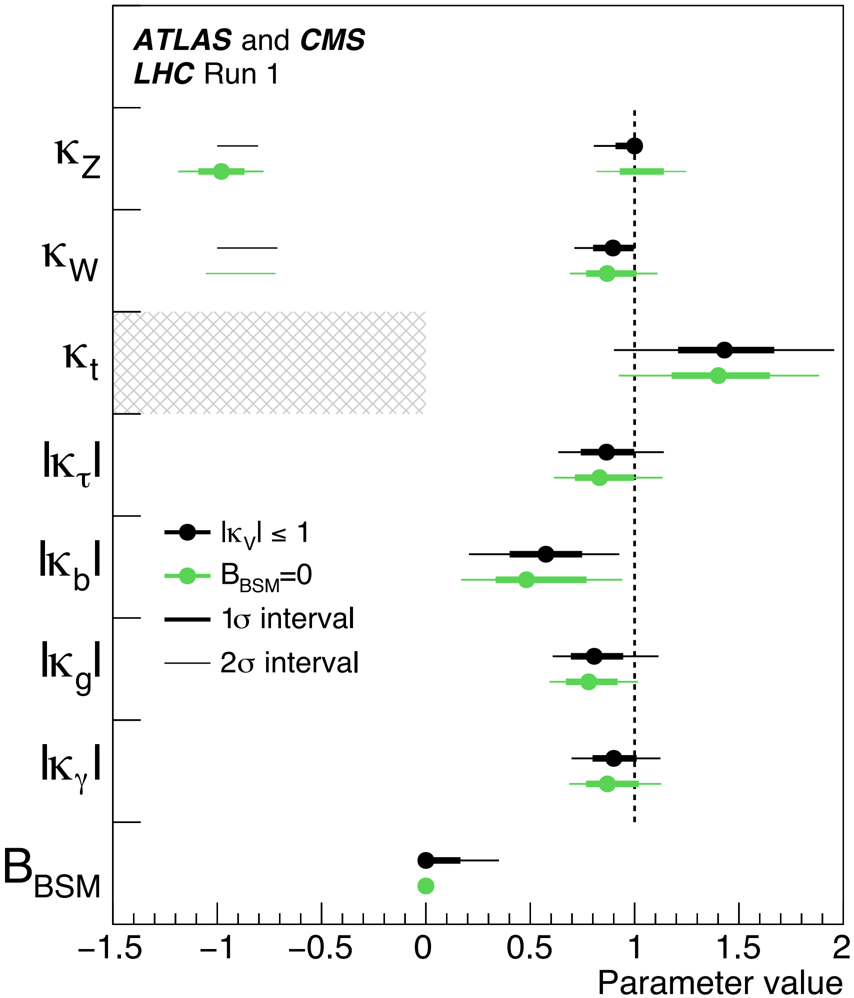
Constraint on CP-odd component (ATLAS, 13 TeV, 14.8 fb^{-1})



Coupling measurements, e.g. with potential BSM in loop : κ_γ, κ_g are coupling modifiers

$\rightarrow B_{BSM} = 0$, no assumption on κ_V, or

$\rightarrow B_{BSM} \geq 0$, $|\kappa_V| \leq 1$



Assuming $|\kappa_V| \leq 1$ $^{(*)}$:

$B_{BSM} < 0.34$ @ 95% CL

$\Rightarrow$ still plenty of room for New Physics
e.g. invisible decays, decays to
light scalar pairs, light dark vector bosons, etc…

($^{(*)}$ another possible assumption :
equality of on-shell and off-shell couplings
leads to slightly less stringent limit in ATLAS)

(ATLAS Run I, combining with direct
$H \rightarrow$ invisible searches, can remove
assumption on κ_V and get $B_{inv} < 0.23$)

⇒ Most of the measurements aiming at characterizing the new boson discovered by ATLAS and CMS point to a particle ***very compatible with the SM Higgs boson***

a light, narrow width, elementary at the TeV scale, CP-even scalar particle coupling to massive particles

In the most simple test (a single modifier) a precision of order O(10%) as been reached with similar contributions from stat. and theory systematic uncertainties

Precisions on constraints obtained on ratios of cross-sections or branching ratios are at the O(30%) level

Both experiments are actively working on going beyond the κ framework

→ simplified / differential cross-sections

→ Higgs-Effective-Field theory

A huge success and yet a small disappointment :

no sign of new physics in the characterization yet !

⇒ decoupling ? alignment ? nothing ? ☹

Searching for hints of beyond the standard model physics in the scalar sector

A huge number of possible analyses to corner the BSM Higgs sector

- Rare decays barely accessible at HL-LHC (Quarkonium+γ, $VP^{(*)}$ e.g. $W^{\pm}\rho^{\mp}$)

- 125 GeV Higgs as a portal to new physics : BSM production and decays

  (e.g. FCNC production $t \to qH$, LFV decay $H \to \mu\tau$,
  decays into light (pseudo)scalars $H \to aa$…)

- Additional Higgs bosons : singlets, nHDM, triplets

Not covered in this talk : the exotic width, e.g.

$h_{125} \to aa$ (light (pseudo)-scalar pairs, nMSSM, …)

$\to Z_{(D)}Z_D$ (dark photon)

$\to$ LFV (see A. David)

The panorama : a (not exhaustive) list

Charged Higgs bosons	H+ ➛ $\tau\nu$
	H++ ➛ W+W+
	VBF H+ ➛ WZ
	H++ ➛ l+l+
	VBF H++ ➛ W+W+
	H+ ➛ tb
	H+ ➛ cs/cb (low mass)
	H+ ➛ 3l (SUSY decays)
	H+ ➛ Wh
	H+ ➛ Wy
	H+ ➛ $\mu\nu$
	H+ ➛ tb (s-channel)

Di-Higgs production	(H➛) hh ➛ bb$\tau\tau$
	(H➛) hh ➛ bbWW
	(H➛) hh ➛ WWWW
	(H➛) hh ➛ yyWW
	(H➛) hh ➛ yybb
	(H➛) hh ➛ 4b
	(H➛) Sh,SS ➛ 4l+MET
	(H➛) hh ➛ yyττ

Heavy neutral Higgs boson decays into fermions	H/A➛(b)$\tau\tau$ (LH,HH)
	ggF H/A➛tt
	4top, SS dilepton
	(tt/bb)H, H➛tt
	(b)H/A➛(b)bb
	H/A➛(b)μμ

Higgs boson decays into low-mass resonances	h ➛ 2a ➛ bbμμ
	h ➛ ZdarkZ(dark) ➛ 4l
	h ➛ 2a ➛ 4μ
	h ➛ 2a ➛ jjyy
	h ➛ x1x2 ➛ bb+MET
	h ➛ 2a ➛ 4y (multiphoton)
	h ➛ 2a ➛ 4b
	h ➛ 2a ➛ μμττ
	h ➛ 2a ➛ bbττ
	h ➛ 2a ➛ 4τ
	h ➛ yy+MET
	h ➛ Za ➛ llμμ
	(bb)a
	H+ ➛ a1W

Heavy neutral Higgs boson decays into VV/VH (DBL)	*VV ➛ llqq/$\nu\nu$qq*
	VV ➛ lνqq
	H ➛ ZZ ➛ 4l, ll$\nu\nu$
	Vh semi-leptonic
	Vh fully hadronic
	High-mass H ➛ Zy
	High-mass H ➛ yy
	A ➛ ZH ➛ llbb (mass split)
	H ➛ WW ➛ lνlν
	A ➛ Zh ➛ (ll/bb)$\tau\tau$

Higgs boson decays with MET	*mono-H (yy+MET)*
	mono-H (bb+MET)
	V(jj) + H➛inv
	Z(ll) + H➛inv
	VBF H➛inv
	mono-H (4l+MET)
	ggF H➛inv (monojet)
	ttH➛inv
	H➛yydark

LFV, FCNC, rare decays	h ➛ Qy (various channels)
	FCNC t ➛ qh (various channels)
	H ➛ $\tau\mu$, τe, eμ (LFV)
	* h ➛ZJ/ψ, ZY

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	VBF H+ → WZ
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	H+ → tb
	H+ → cs/cb (low mass)
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	H+ → Wh
	H+ → Wγ
	H+ → $\mu\nu$
	H+ → tb (s-channel)
Di-Higgs production	(H→) hh → bb$\tau\tau$
	(H→) hh → bbWW
	(H→) hh → WWWW
	(H→) hh → γγWW
	(H→) hh → γγbb
	(H→) hh → 4b
	(H→) Sh,SS → 4l+MET
	(H→) hh → γγ$\tau\tau$

νν
c
c
Zγ
γγ
(mass split)
)ττ
ET)
ET)
T)
nojet)
s channels)
various channels)
(LFV)

Only a few selected topics are presented here

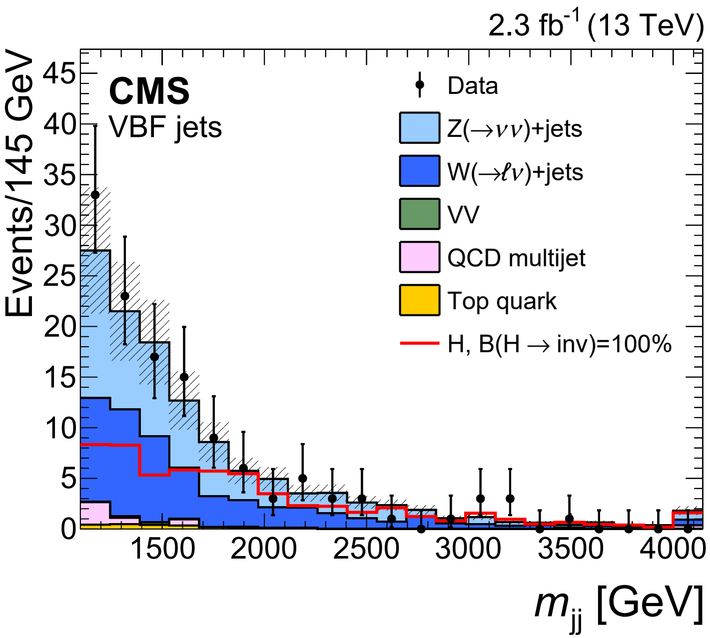
- Invisible h_{125} decays : example of the VBF analysis
- Singlet and $H \rightarrow VV$
  (of course relevant beyond singlet)
- Two Higgs Doublet Models
  - $A \rightarrow \tau\tau$
  - $H^+ \rightarrow \tau\upsilon$
  - $H \rightarrow hh$ ($bb\tau\tau$)
    (relevant in many models, e.g. singlet)
  - Cornering the wedge and low $\tan\beta$
    $A/H \rightarrow tt$
- Attacking triplet models
  - $H^+ \rightarrow WZ$
  - $H^{++} \rightarrow \ell^+\ell^+$
- Portal to dark matter
  - mono h_{125}, $h \rightarrow \gamma\gamma$, bb

The invisible width of h_{125}

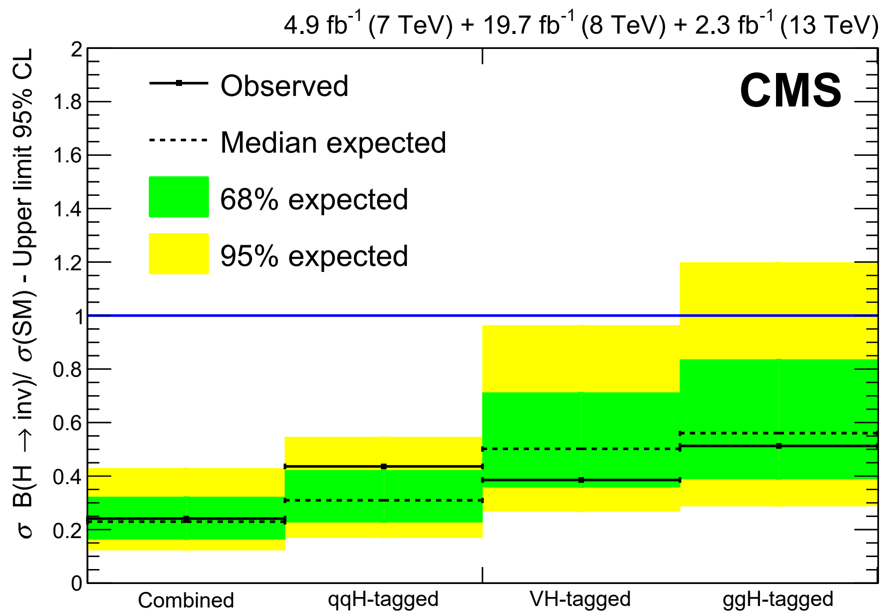
$h_{125} \to$ invisible tiny in the SM : ~ 0.1% from $h_{125} \to ZZ \to 4\upsilon$
Small SM total width ⇒ could be greatly enhanced by coupling, e.g. to dark matter (neutralinos …)

Require associated production to tag it :
⇒ ggH + high p_T jet from ISR, VH with $V \to qq$ / $\ell\ell$, or VBF topology

Example : CMS VBF, 13 TeV, 2.3 fb^{-1} : large E_T^{miss} (h125 candidate),
two jets with high rapidity separation and invariant mass



Combining 7+8 TeV (25 fb^{-1}) and 13 TeV (2.3 fb^{-1})
$B_{inv} < 0.24$



Additional Heavy Singlet

Simplest extension of the SM : add a scalar SM singlet

⇒ two scalars : h_{125} (assumed to be the lightest) and H

- h_{125} has reduced couplings ($\kappa = \cos\alpha$) to SM wrt H_{SM}

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

- H couples to SM particles via mixing ($\kappa' = \sin\alpha$) and for $m_H > 250$ GeV/c^2, $H \to h_{125}h_{125}$ opens up

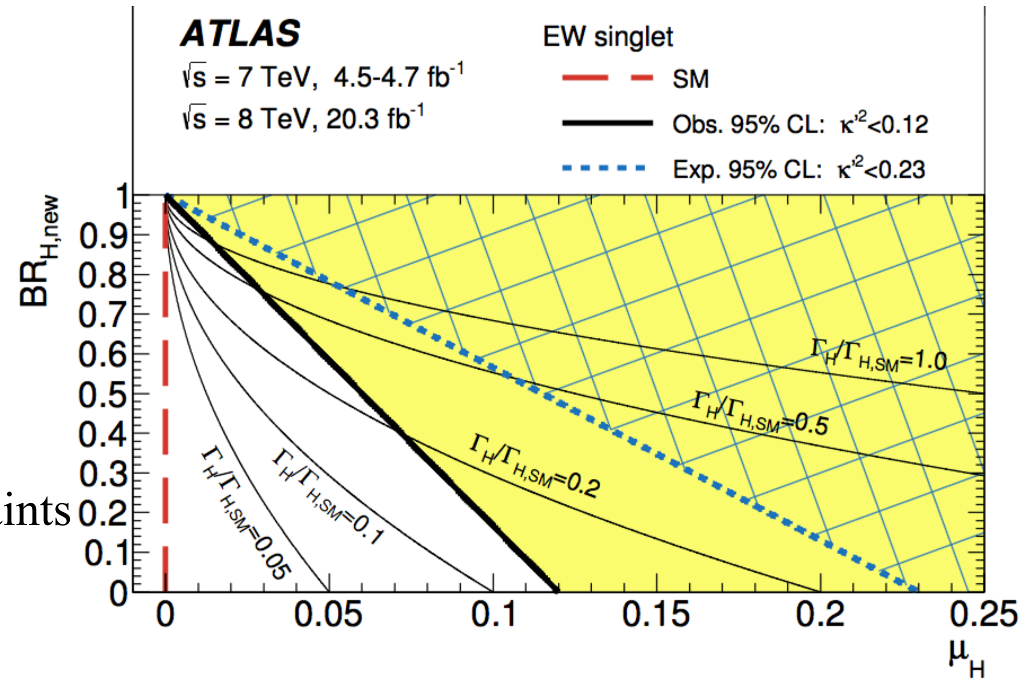
$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

Strongly constrained from h_{125} coupling measurements :

e.g. in ATLAS (Run I) :

$$\mu_h = 1.18^{+0.15}_{-0.14}$$

$$\Rightarrow \quad |\sin\alpha| < 0.35$$



⇒ Very important to consider indirect constraints from "precision" Higgs measurements (also from e.g. m_W)

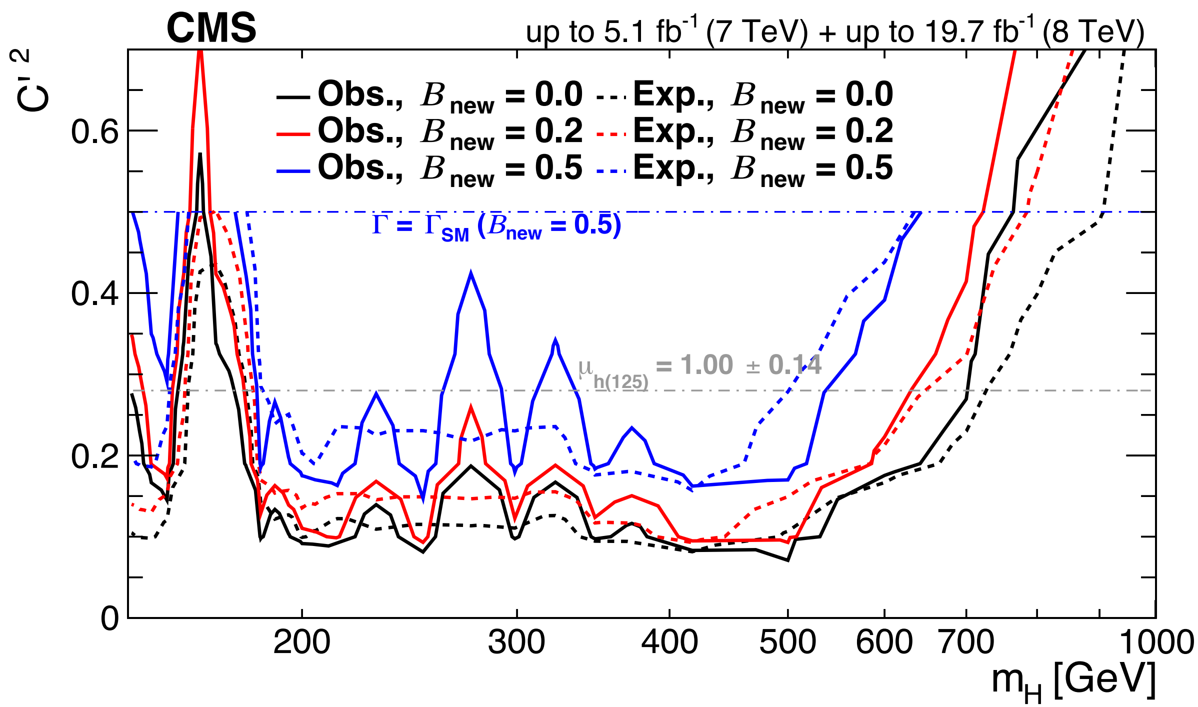
Direct searches :

Most relevant : H → WW / ZZ and H → hh

CMS Run I legacy, combining H → WW (ℓνℓν, ℓνqq) / ZZ (4ℓ, ℓℓνν, ℓℓqq)

Including VBF dedicated categories and interference effects

For $m_H > 200$ GeV/c^2
Most powerful channels
H → 4ℓ for $m_H \lesssim 500$ GeV/c^2
H → ZZ → ℓℓνν, ℓℓqq above



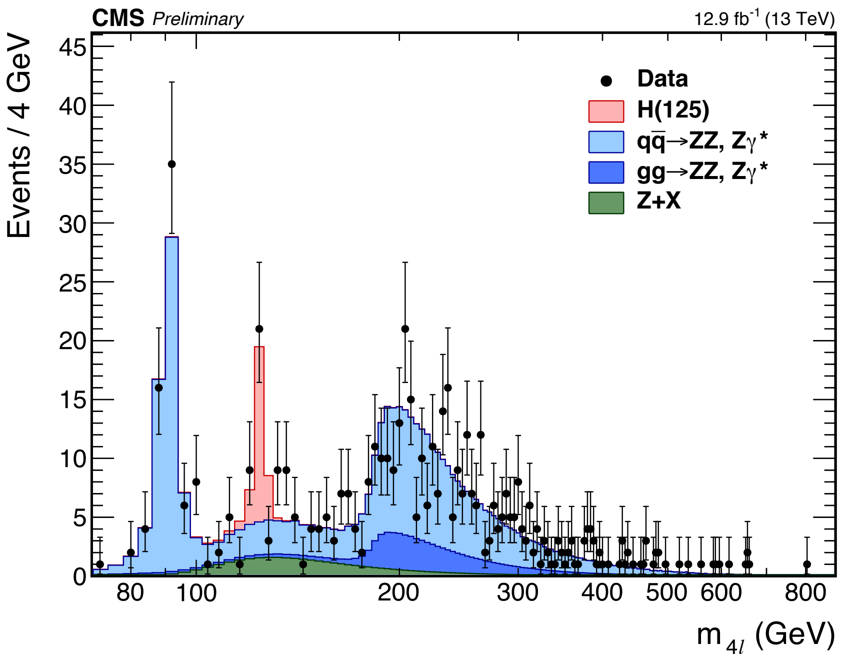
Run II searches

$H \to ZZ \to 4\ell$: Golden channel, very clean signature

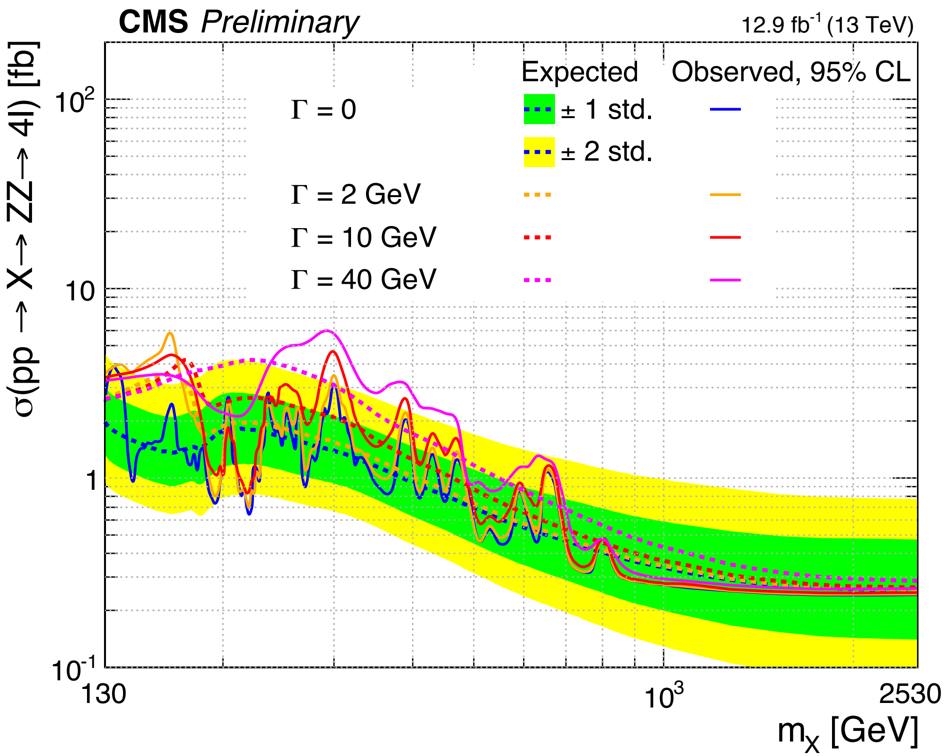
→ Improve sensitivity to VBF production with dedicated category

→ Fit of the $m(4\ell)$ distribution to extract the signal

→ Consider both narrow and large width scenarios; in the CMS analysis, refined treatment : parameterization of the full line shape for any (m_X, Γ_X) hypothesis and from ggH/VBF with X, h(125) and background interference included



Example : letting the fit decide the VBF fraction



$H \to ZZ \to \ell\ell\nu\nu$: important at high mass (also with $\ell\ell qq$, $qq\nu\nu$) where 4ℓ lack statistics

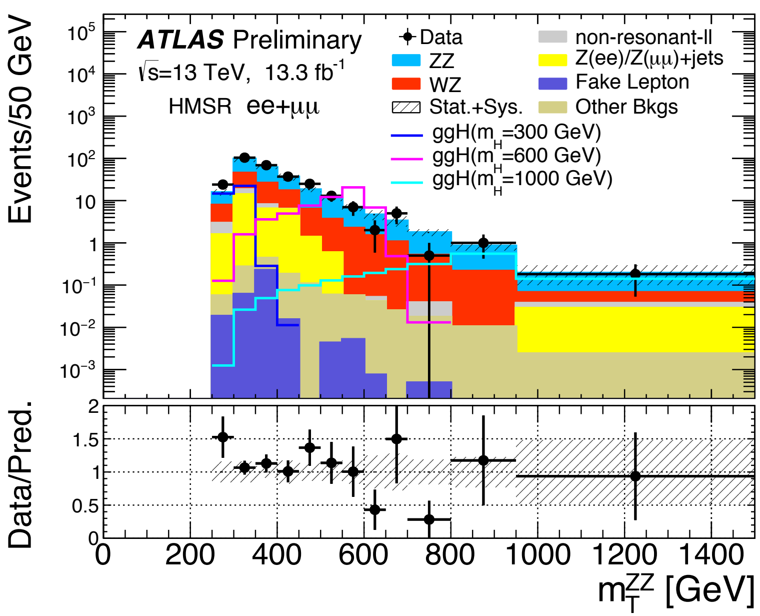
ATLAS example

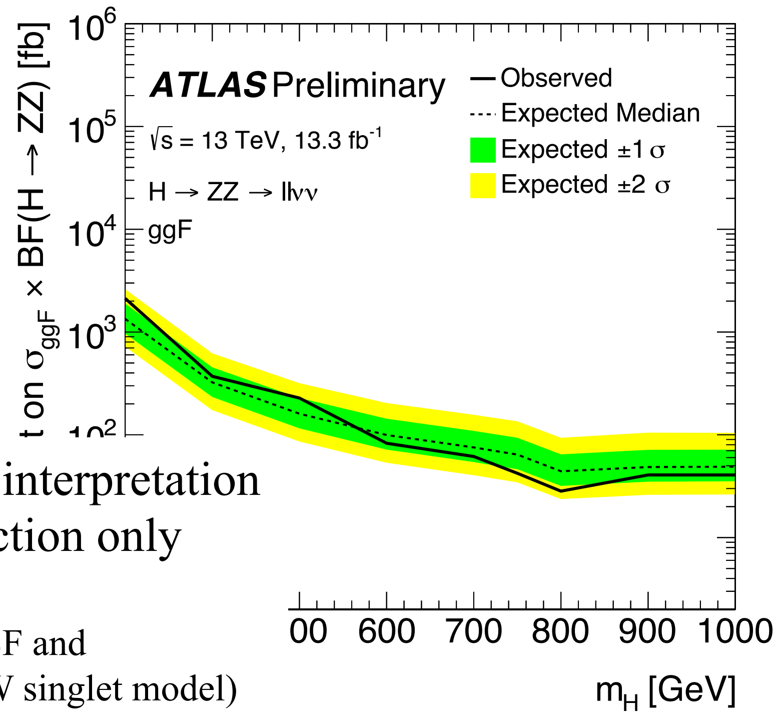
→ One lepton pair compatible with a Z, recoiling against large E_T^{miss}

→ Main backgrounds

- ~ 55% ZZ : from MC with NNLO QCD+NLO EW normalisation for qq; gg included with NLO k-factor with large uncertainty
- ~ 25% WZ : data-driven normalisation (from 3ℓ control region)
- ~ 10% Z+jets from data (ABCD method)
- ~ 10% non-resonant $\ell\ell$ (WW, …) from data (flavour symmetry $\mu\mu \sim ee \sim e\mu / 2$)

→ Fit to transverse mass distribution $(m_T^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{miss}|^2}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2$





Narrow width interpretation for ggF production only

(CMS also has VBF and combination in EW singlet model)

(One) Additional Doublet

Main effort : Two Higgs Doublet Models (2HDM) with CP :
2 CP-even (h/H), 1 CP-odd (A) and a pair of charged ($H^{\pm}$) Higgs bosons,
most important parameters : $\tan\beta = v_2/v_1$ (vev ratio), α : mixing in the CP-even, m_A, m_H, $m_{H\pm}$

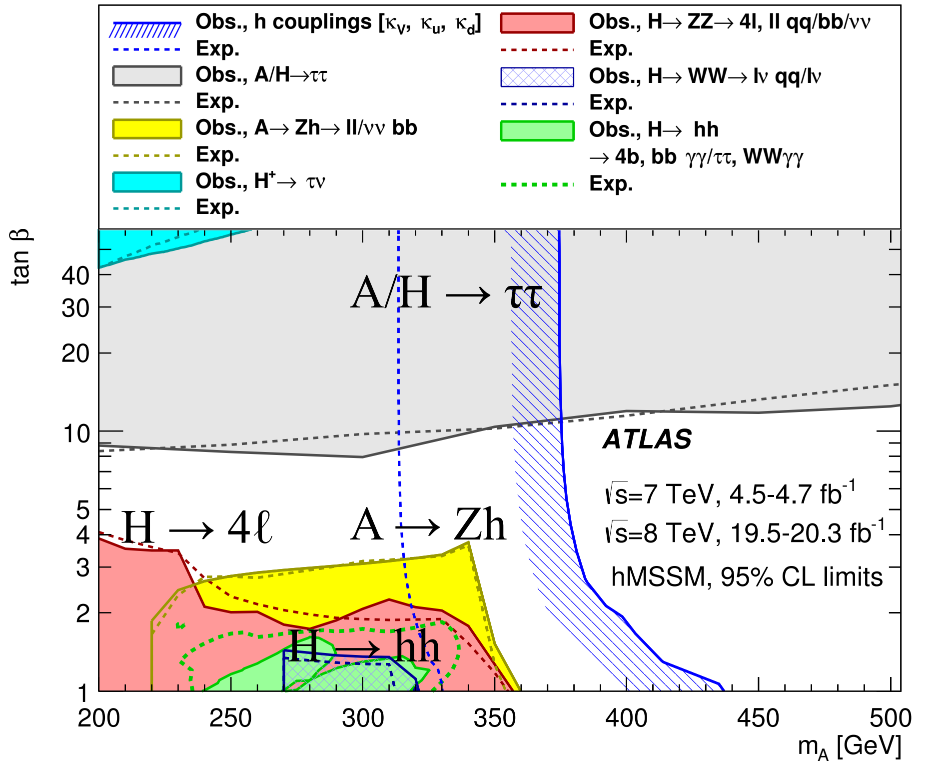
The resonance observed at 125 GeV/c^2 (h) is usually assumed to be the lightest CP-even

Strategy :

→ redundancy : several topologies can cover the same parameter space in given models

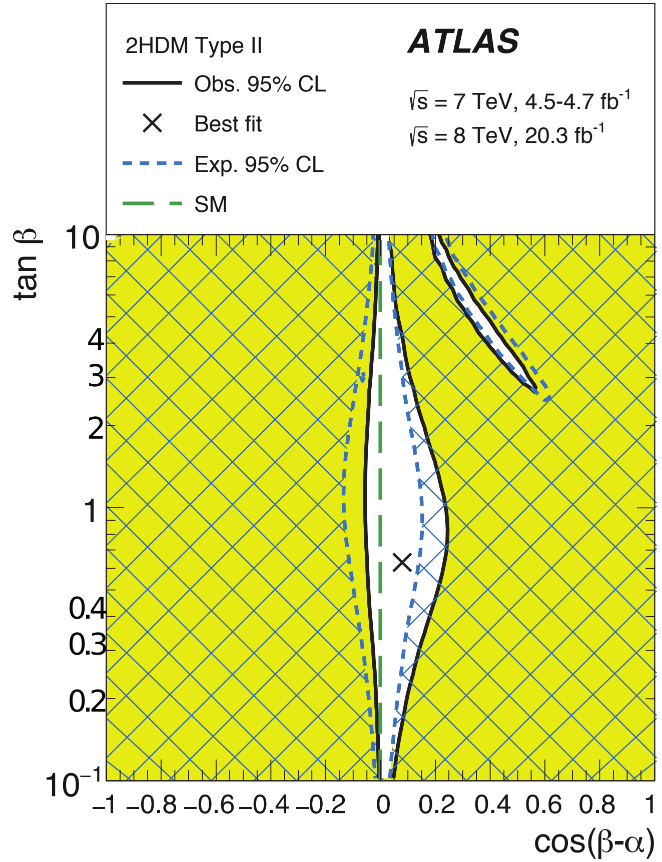
→ stay as model independent as possible (e.g. α is often a free parameter, $m_{H^\pm} \neq \sqrt{m_A^2 + m_W^2}$ ...)

Particular attention to 2HDM-type II (interpretation in the MSSM within the most recent benchmarks)

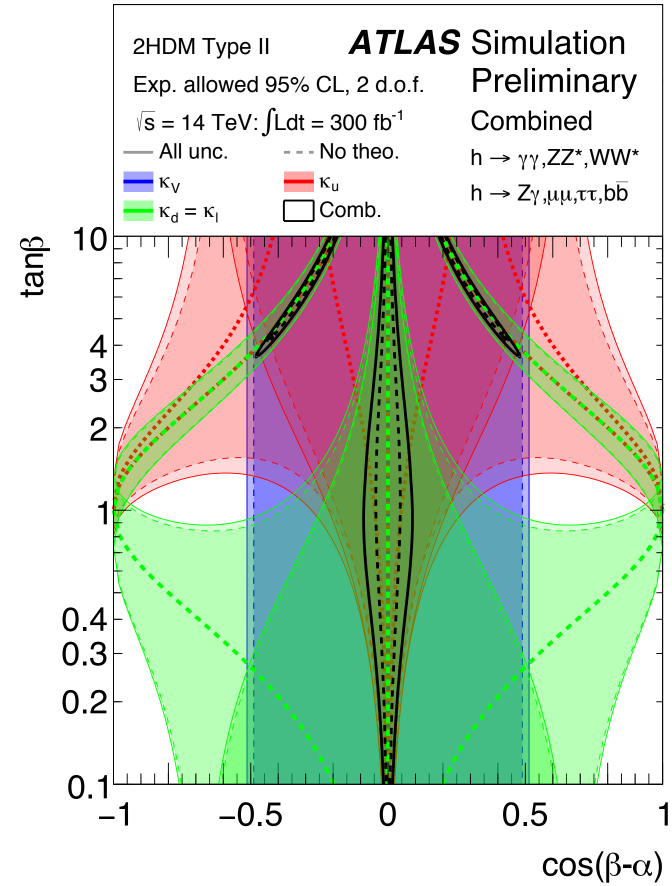


The importance of the h_{125} measurements : example of constraints in the (cos(β-α),tanβ) plane

Run I legacy



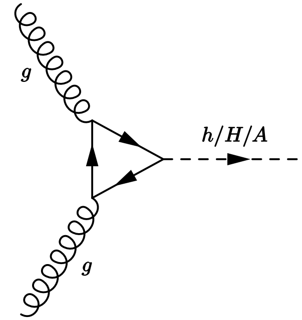
Extrapolation to 300 fb^{-1}
(at 14 TeV)

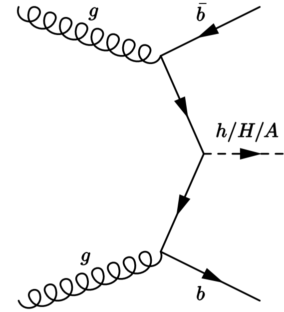


Indirect constraints very powerful :

- Almost independent on A/H/H$^{\pm}$ masses
- $\kappa_V \sim 1 \Leftrightarrow$ cos(b-a) ~ 0 but soon limited by systematic uncertainties
- in very constrained models (e.g. hMSSM) strong lower limit on heavy scalar masses

The high tanβ region : $A/H \to \tau\tau$ (example of ATLAS analysis)



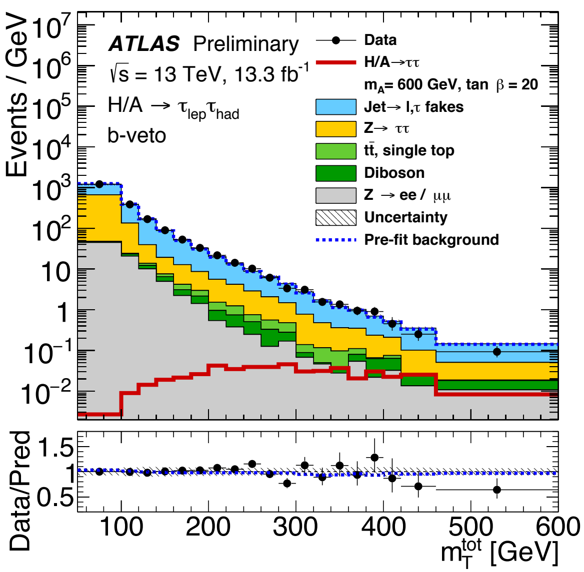


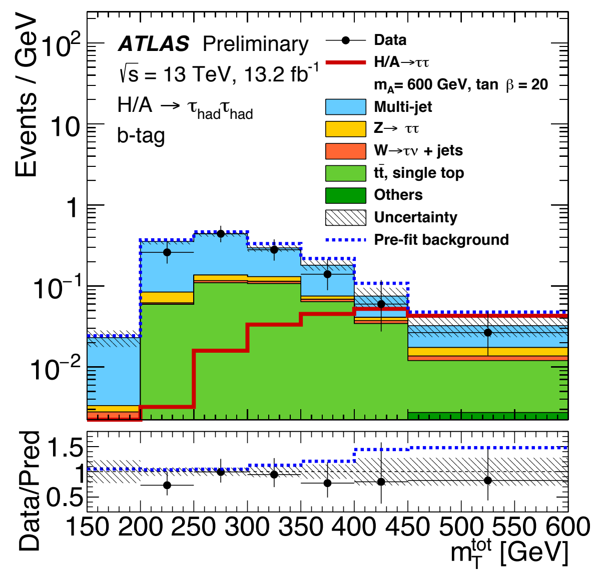
* Two main production mechanisms :
gluon fusion (low tanβ) and b-associated (high tanβ)
⇒ b-tag and b-veto categories

* Two di-tau categories : $\tau\tau \to$ hadrons + 2ν : high mass
$\to \ell\nu\nu$ + hadrons ν : low (but > 200 GeV/c^2) mass
(CMS also includes $\tau\tau \to \ell\ell 4\nu$, very important for even lower masses)

* Backgrounds : true hadronic τ decays and lepton faking τ from MC (Drell-Yan, ttbar)
Multijet from data , jet faking τ from corrected MC (had-had) or data (lep-had)

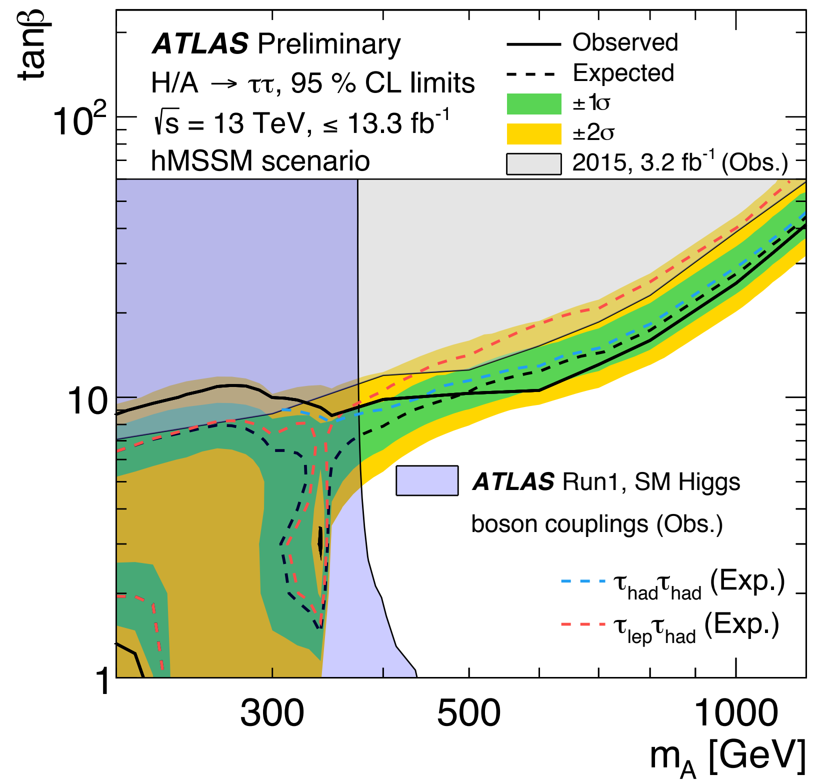
* Fit $m_T^{tot} = |\, \mathbf{p_T}^{\tau 1} + \mathbf{p_T}^{\tau 2} + \mathbf{E_T}^{miss} |$ (massless 4-momenta in the transverse plane) to extract the signal





Interpretation in the (m_A,tanβ) plane :

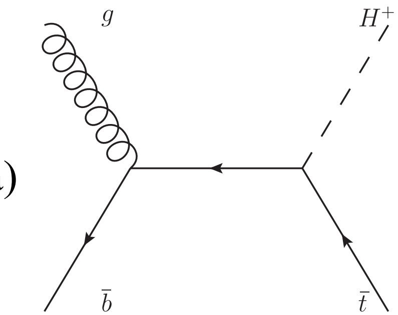
e.g. hMSSM



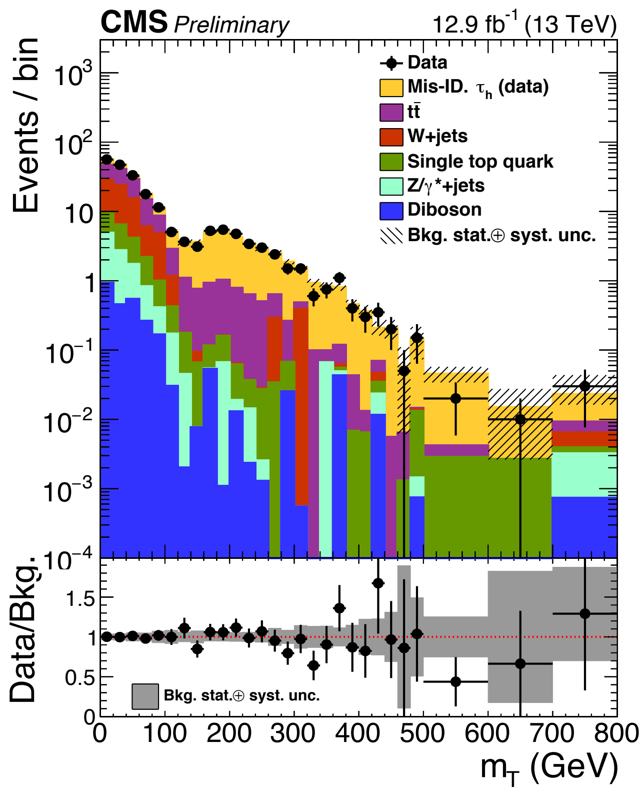
- tanβ > 25 for m_A = 1 TeV/c^2
- Starting to cover the low tanβ, m_A < 2 m_{top} region

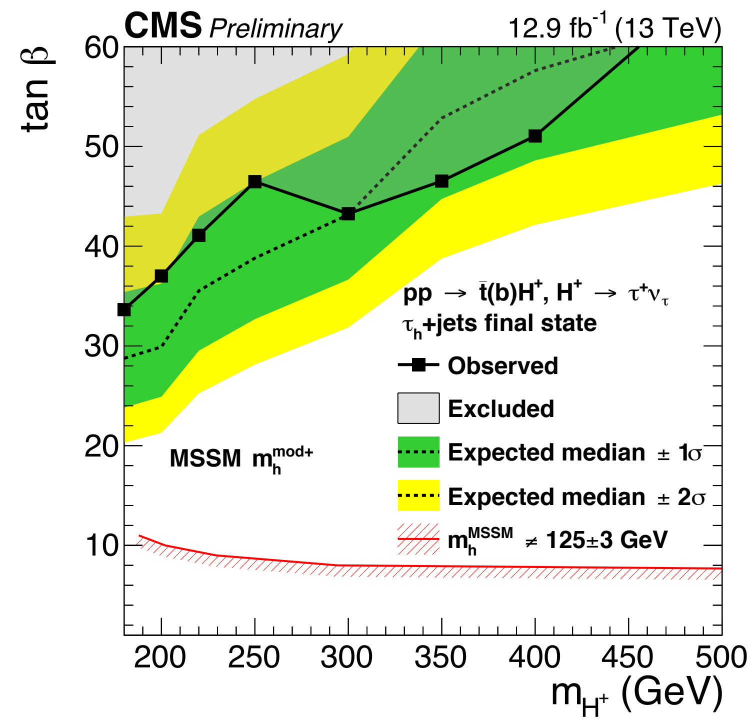
In MSSM or degenerate 2HDM, A/H → ττ sufficient to cover the high tanβ regime
However, with relaxed assumptions, important to directly search for $H^{\pm} \to \tau\nu$

Search produced in association with a top quark $pp \to tH^{\pm}(b)$



Consider hadronic tau decays, high E_T^{miss}, ≥3 jets, ≥ 1 b-tag jet
Background from top processes (MC) and jet faking taus (estimated from data)
Fit $m_T(\tau, E_T^{miss})$ to extract the signal





In MSSM or degenerate 2HDM, $A/H \to \tau\tau$ sufficient to cover the high $\tan\beta$ regime
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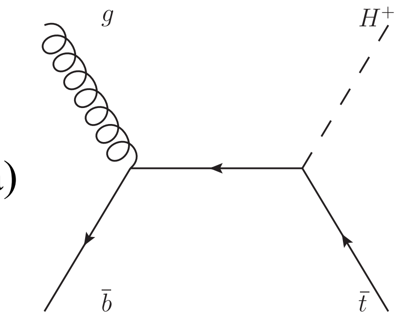

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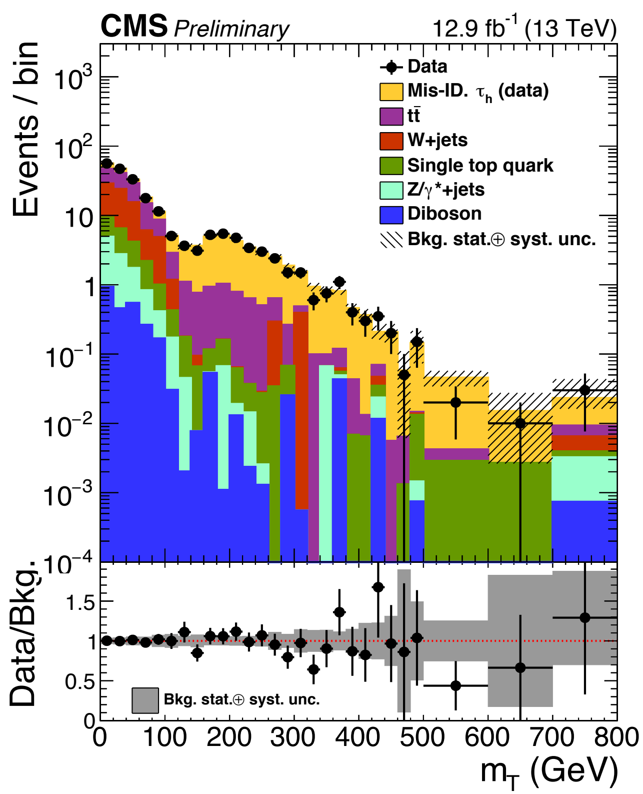
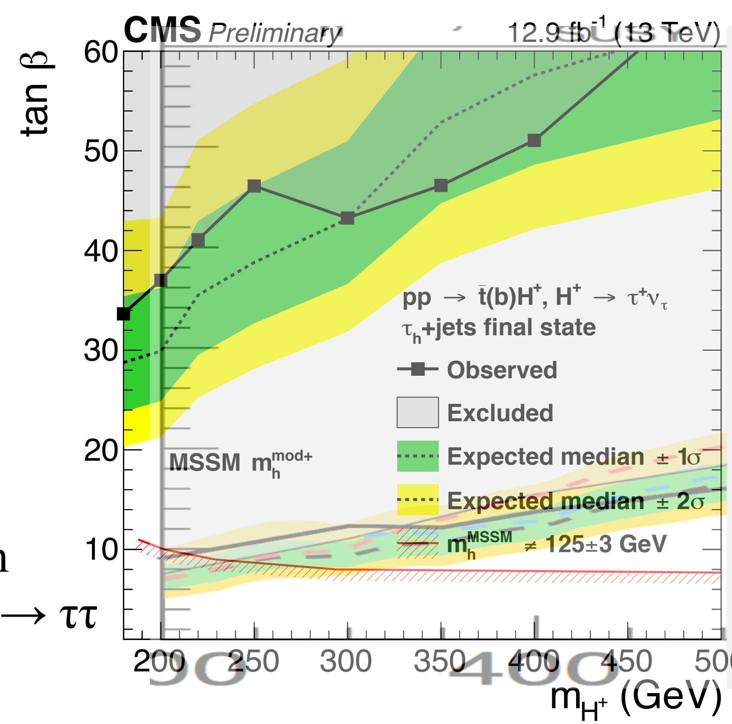




From
$A/H \to \tau\tau$

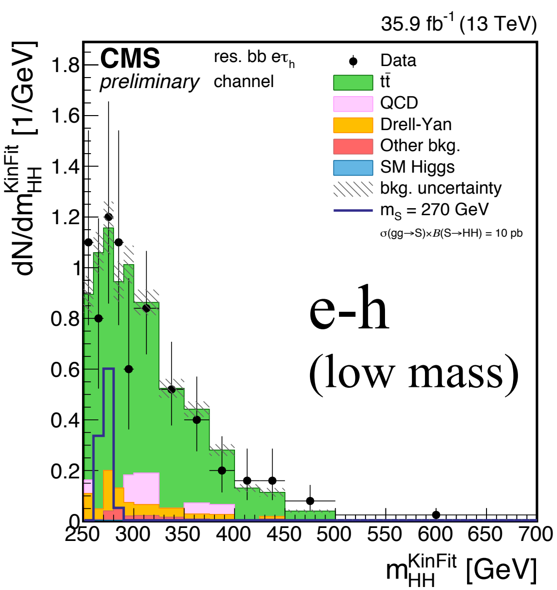
The low tanβ, low $m_{A/H}$ region : several relevant channels : $H \rightarrow 4\ell$, $A \rightarrow Zh$, $H \rightarrow hh$

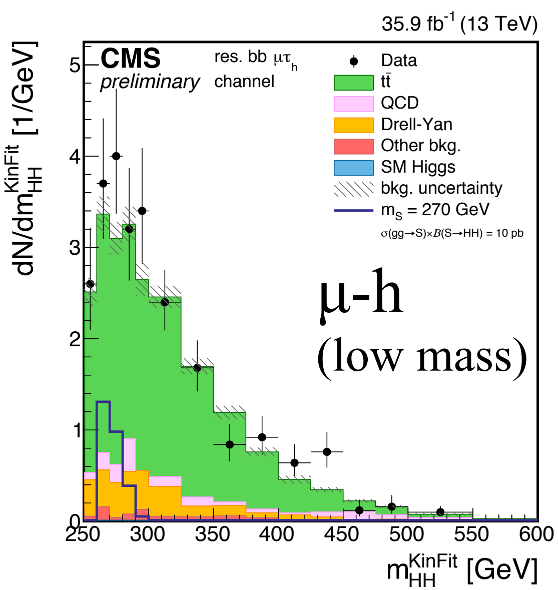
Example of CMS $H \rightarrow hh \rightarrow b b\tau\tau$, 35.9 fb^{-1}

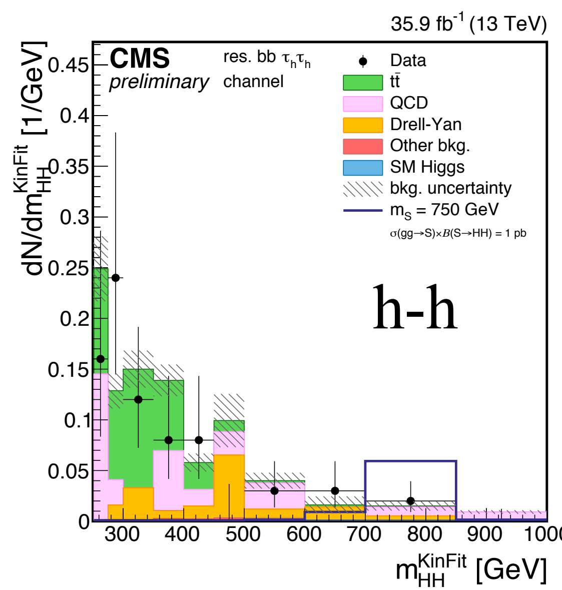
- 3 di-tau-decay channels (ℓ(e, μ)-h(hadron), h-h) x (2 small jets, 1 fat jet)
  (The fat-jet category improves the sensitivity for $m_H > 700$ GeV/c^2)
  In the two small jet category, use of 1 and 2 b-tag categories

- BDT (ℓ-hadron channel) to reject tt background
  use reconstructed di-Higgs invariant mass (from a kinematic fit) distribution to extract signal

- Backgrounds :
  multijet from same-sign taus scaled using anti-isolated tau regions,
  Drell Yan from MC + correction, tt (and other minor) from MC

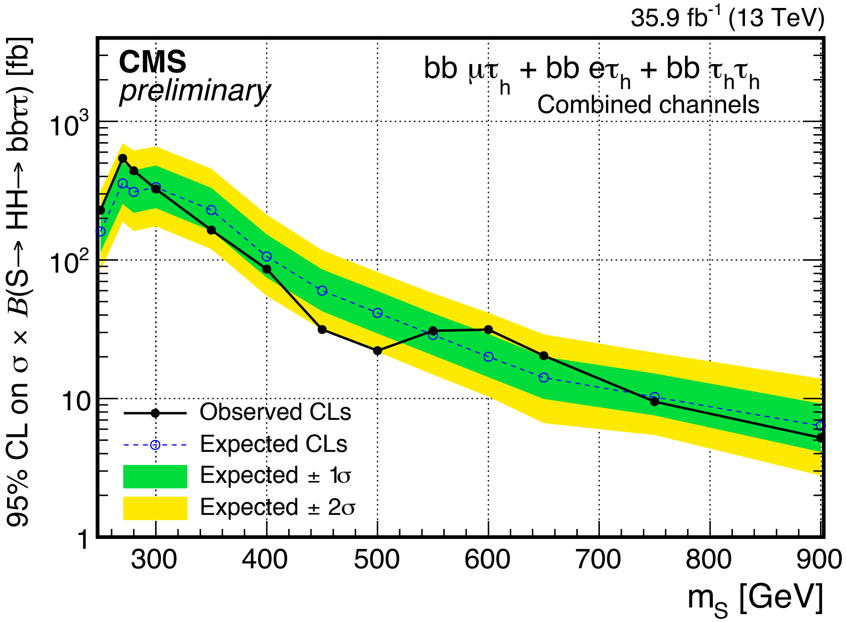




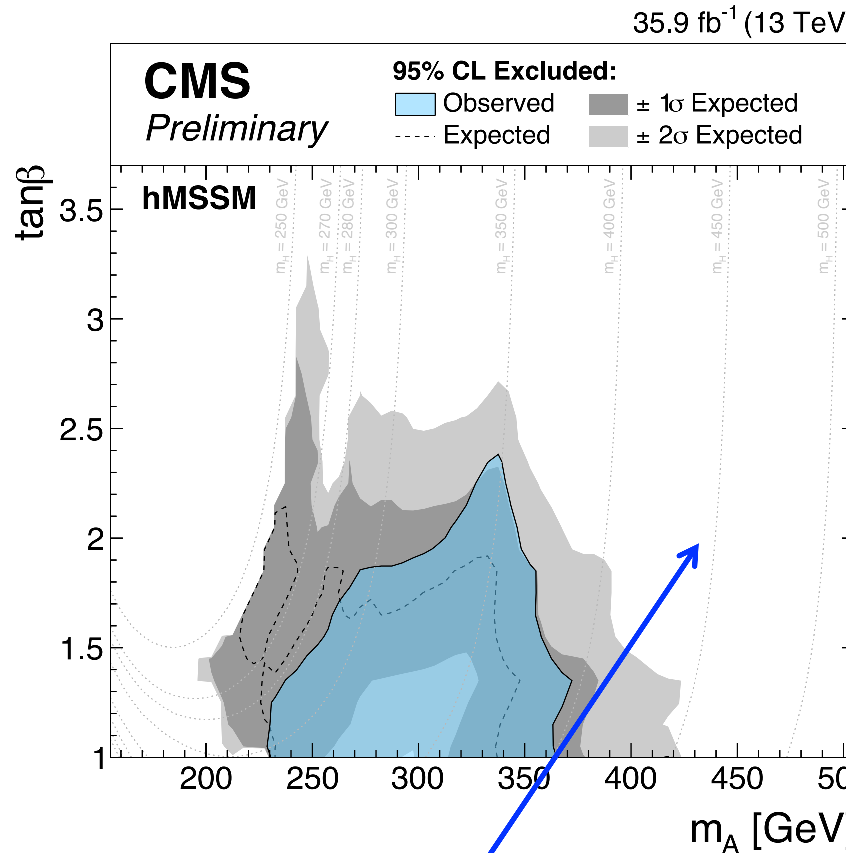


No significant excess unfortunately

Model-independent limit vs m_H



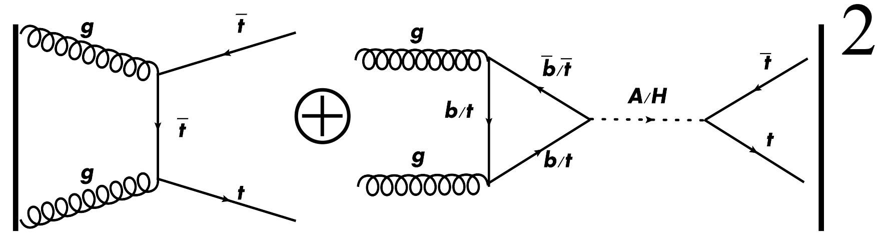
And in the hMSSM (m_A,tanβ) plane



H → hh → bbγγ also very relevant at low mass
(4b at high mass)

Now need to attack the wedge (intermediate tanβ) and $m_A > 2\ m_{top}$ …

Cornering the low tanβ, $m_A > 2m_{top}$ region : $A \to tt$

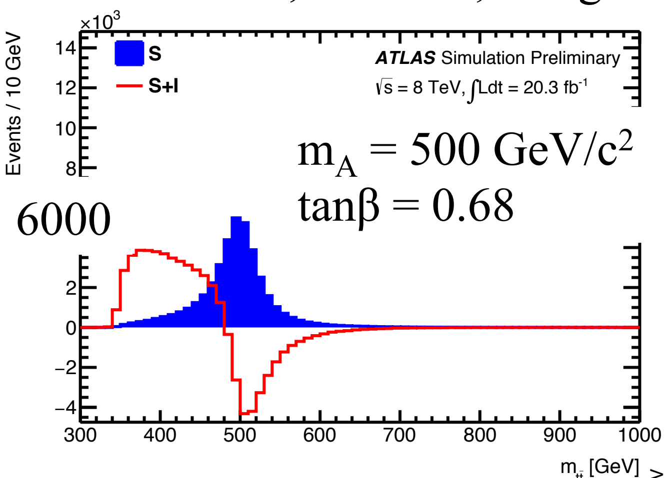


Huge tt background + same initial / final state

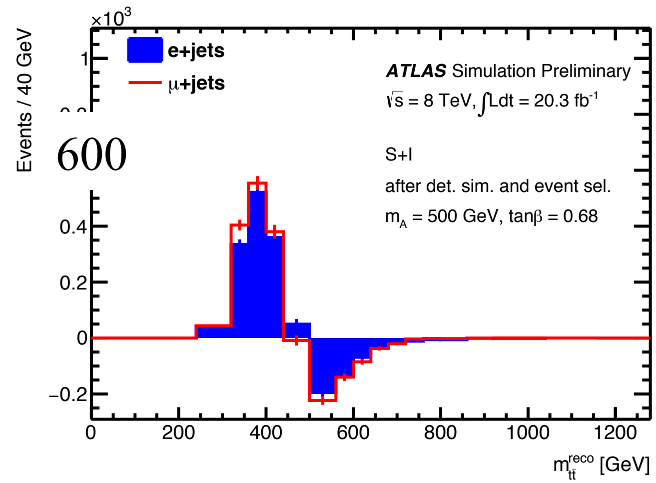
⇒ very large interference effects

⇒ peak-dip structure in tt invariant mass distribution (different for H and A)
(or even only a dip, e.g. m_A = 500 GeV/c^2, tanβ = 9)

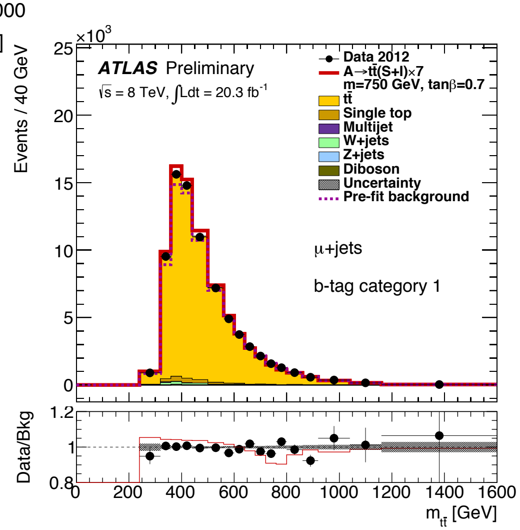
ATLAS 8 TeV, 20.3 fb^{-1}, using usual "1-lepton, 4 jets, E_T^{miss} and ≥ 1 b-tag" tt selection



Including simulation…



And including backgrounds :



First attempt :
expect many improvements soon
- 13 TeV data
- refined methods
- go closer to tt threshold
  (need to include off-shell top
  and higher order effects in A/H decay)

The wedge (intermediate tanβ) :

ATLAS-CONF-2016-104 (13 TeV, 13.2 fb^{-1})

Promising (?) $pp \to ttH/A \to$ tttt (4 tops), ttbb

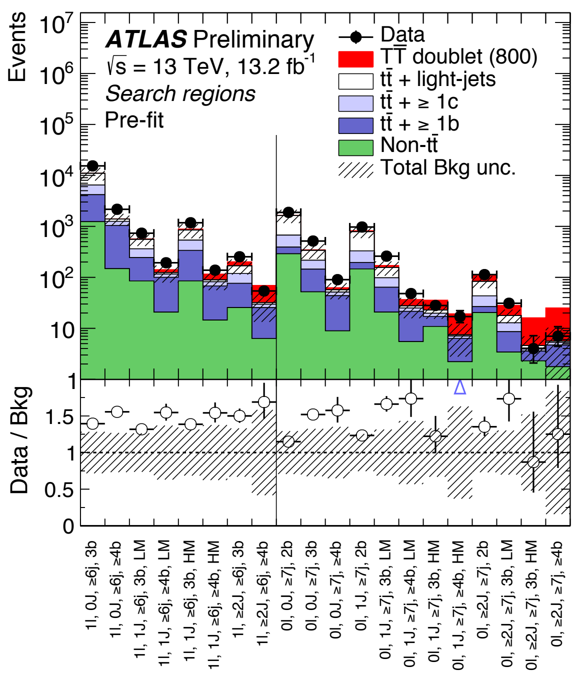
$pp \to bbH/A \to$ bbtt

(including non resonant, e.g. $pp \to Wb\, t\, H/A$)

⇒ tt + heavy flavour topologies (similar to $tth_{125} \to ttbb$ but with higher p_T objects)

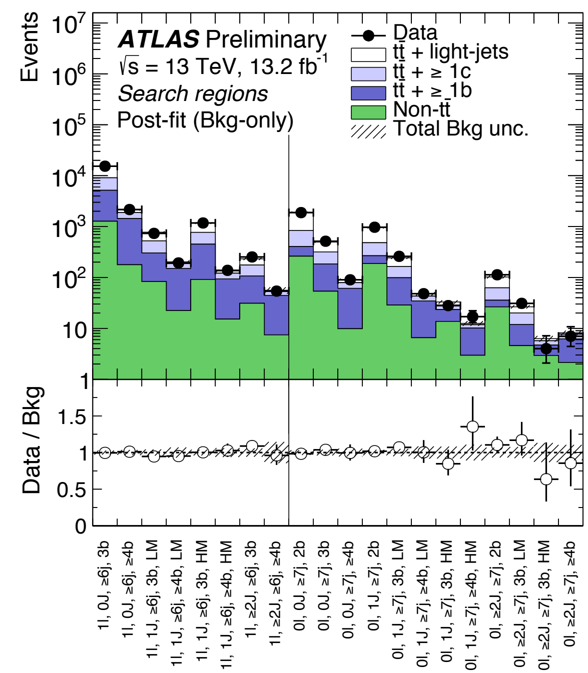
0/1 lepton, many jets, many b-jets, 0/1/2 fat jet(s) : 20 search regions

⇒ However, rather low yields and very difficult tt + heavy flavour background :



Many categories
to constrain tt + ≥ 1b

Fit :



No sensitivity in the wedge yet, more work is needed…
(many possible improvements in the pipeline)

Attacking Triplets

Various "motivations" (neutrino masses, fermio-phobic scalars…).
Naïve models very constrained by $\rho = m_W^2 / m_Z^2 \cos^2\theta_W = 1.00040 \pm 0.00024$

Prototype with built-in $\rho = 1$: Georgi-Machacek

- 1 doublet, 1 real and 1 complex triplets : 10 scalars
  ⇒ 1 doubly charged, 2 singly charged, 4 neutrals

- Scalar potential tuned…
  ⇒ The custodial five-plet $H_5^{\pm\pm}$, $H_5^{\pm}$, H_5^{0} couples only to EW gauge bosons V at tree level (fermio-phobic scalars)

Naïve model accepting tuning :

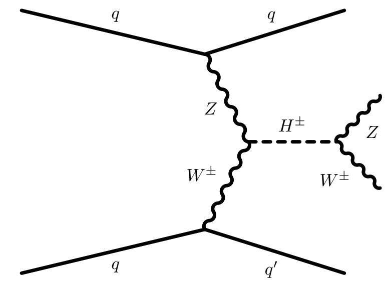
- Adding a single triplet (7 scalars in total) requires a very small vev v_t

- Very different phenomenology, dependent on the value of v_t
  e.g. spectacular final state with resonant same sign lepton pairs

The importance of VBF

In addition to $H^0 \to VV$ via VBF , search for $H^\pm \to WZ$ (= 0 in doublet models), via VBF

Very clean $WZ \to \ell' \nu \ell\ell$ 3-lepton signatures + VBF jets



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

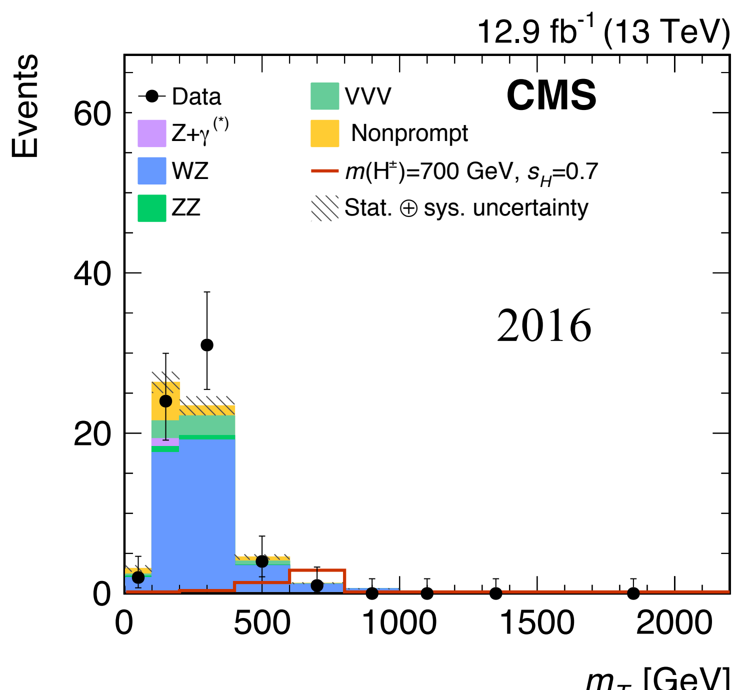
used for signal extraction ($E_T(W) = p_T(\ell') + E_T^{miss}$, $\mathbf{p_T}(W) = \mathbf{p_T}(\ell') + \mathbf{E_T^{miss}}$)

Backgrounds :

80% QCD (norm. from data side band) + EW WZ

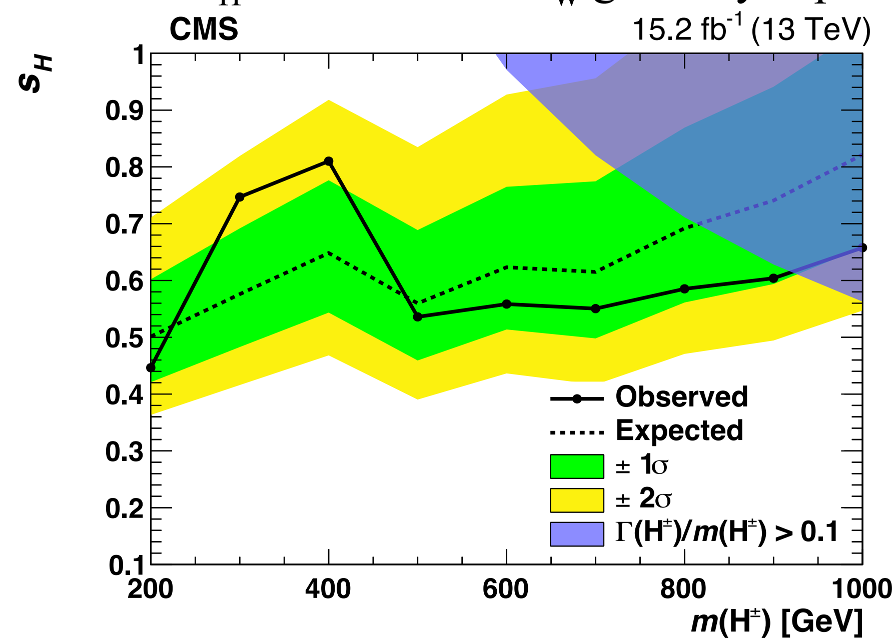
~ 10% ZZ, VVV (MC),

~ 10% non prompt (Z, tt; from data)



$\Rightarrow$ limit in the (m_{H+} , $\sin\theta_H$) plane

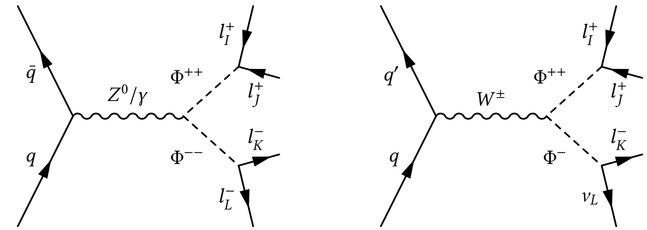
$\sin\theta_H$ = fraction of m_W given by triplets



A global combination of VBF searches for neutral, singly and doubly charged scalars can be done to better corner the model

Doubly charged Higgs boson in the lepton channels

In simple heavy triplet model, assuming $m_{H^{\mp}} = m_{H^{\mp\mp}}$



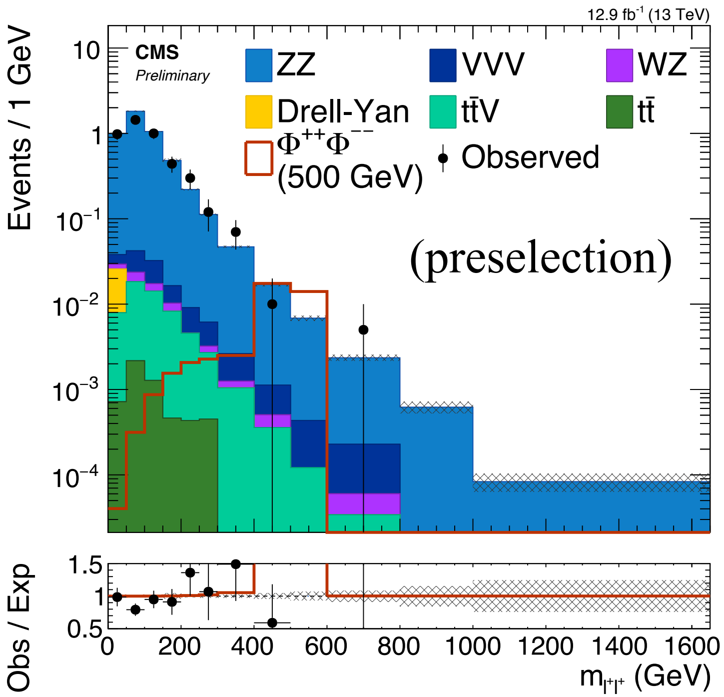
At very small v_t, suppressed $H^{\mp\mp}$-$W^{\pm}$-$W^{\pm}$, $H^{\mp}$-$W^{\pm}$-Z couplings

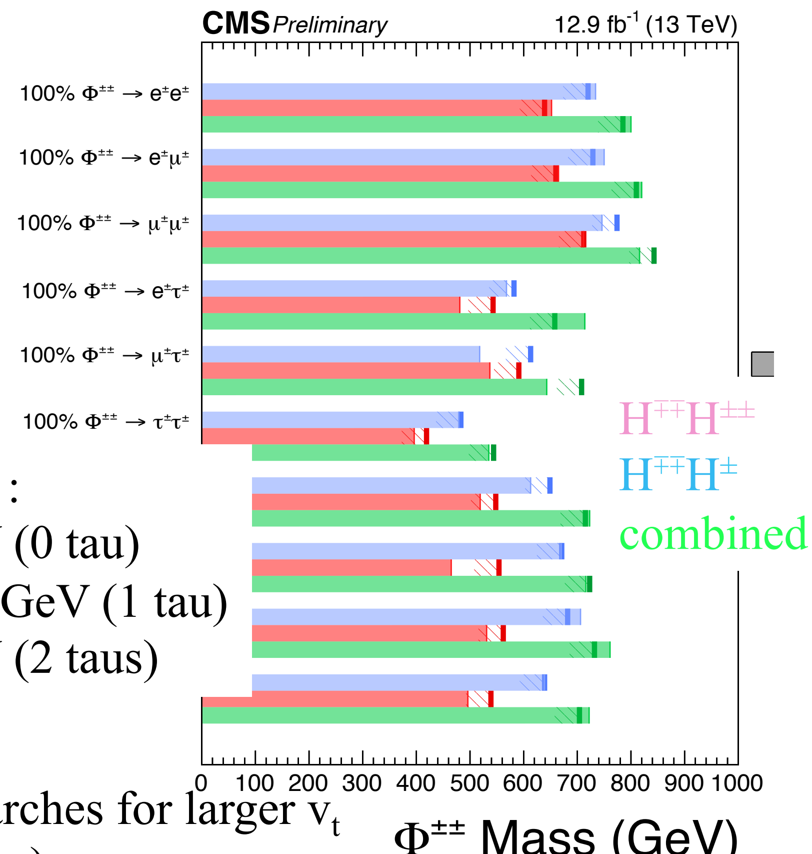
$\Rightarrow$ search for $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$, $H^{\pm} \rightarrow \ell\nu$ in Drell-Yan pair and associated productions

$\Rightarrow$ 3ℓ and 4ℓ channels, for all possible lepton and relevant charge combinations using $m(\ell^{\pm}\ell^{\pm})$ as discriminating variable

Sliding $m_{H^{\mp\mp}}$ - dependent analysis, simulation and data-driven (side-band of $m(\ell^{\pm}\ell^{\pm})$) bkg

$m(\ell^{\pm}\ell^{\pm})$ in the 4ℓ-0 tau channel





Sensitivity :

~ 800 GeV (0 tau)

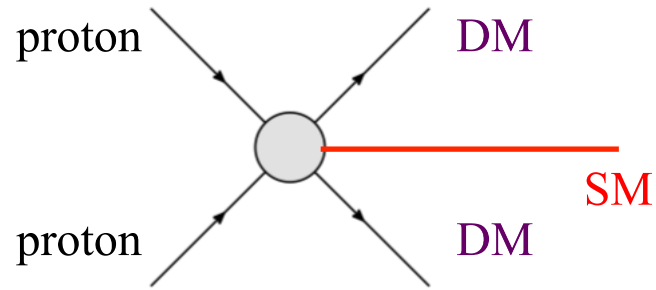
~ 650-700 GeV (1 tau)

~ 550 GeV (2 taus)

On going searches for larger v_t ($W^{\pm}W^{\pm}$ decays)

125 GeV/c^2 Higgs boson and dark matter

Search for dark matter (DM) at LHC :
e.g. pair produced DM particles (invisible)
tagged by accompanying SM particle(s)



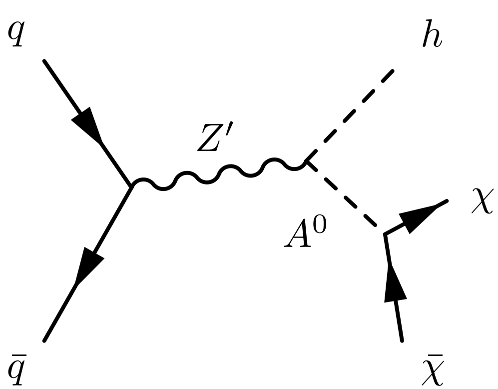
Tons of mono-X (jet (g), photon, Z, W, h_{125}, top-quark, b-jet) searches at the LHC in the previous year
Special role of mono-h_{125} :

→ negligible coupling to incoming partons : not from ISR (contrary to e.g. gluon or photon)

⇒ direct probe of the dark sector interactions

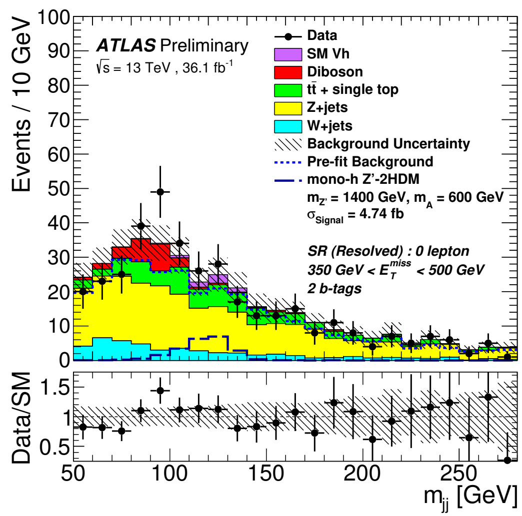
→ interpretation in benchmark simplified models designed to cover a large wealth of topologies

e.g. the Z'-2HDM model
CP-odd couples to DM



Searches targeting specific modes : e.g. largest BR : h → bb
2 jets or 1 fat jet (with b-tag) + E_T^{miss}

similar to SM VH, H → bb search

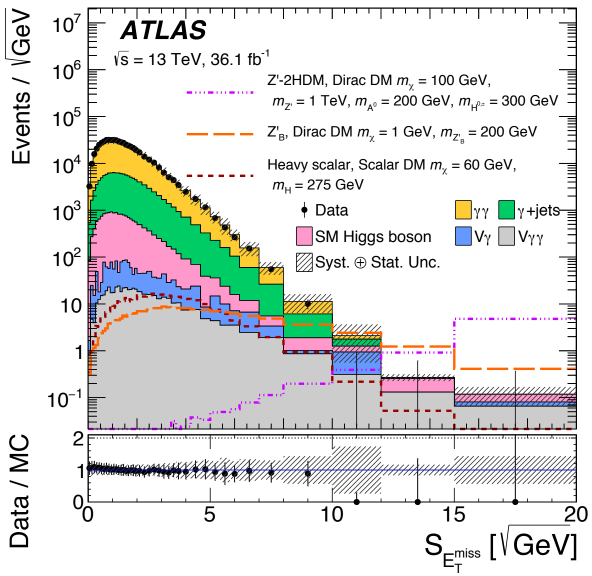


Range in E_T^{miss}/GeV	$\sigma^{obs}_{vis,h+DM}$ [fb]	$\sigma^{exp}_{vis,h+DM}$ [fb]	$\mathcal{A}\times\varepsilon$ %
$[150, 200)$	19.1	$18.3^{+7.2}_{-5.1}$	15
$[200, 350)$	13.1	$10.5^{+4.1}_{-2.9}$	35
$[350, 500)$	2.4	$1.7^{+0.7}_{-0.5}$	40
$[500, \infty)$	1.7	$1.8^{+0.7}_{-0.5}$	55

The mono-h, $h \to bb$ search is limited below E_T^{miss} = 150 GeV by the trigger

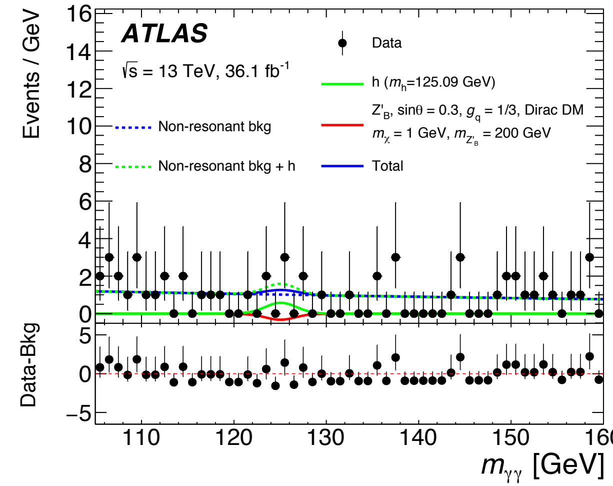
⇒ recover sensitivity with the cleaner and easier-to-trigger-on $h \to \gamma\gamma$ channel

2 high p_T (> 0.35(0.25) $m_{\gamma\gamma}$) photons, with large $p_T(\gamma\gamma)$ and E_T^{miss} significance



Extract signal by un-binned fit to the $m_{\gamma\gamma}$ distribution

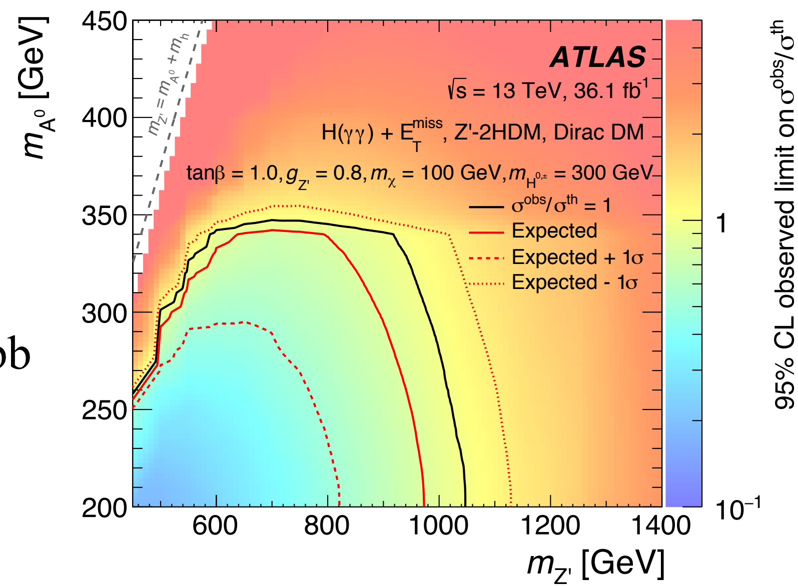
(several categories depending on benchmarks)



Interpretation in the ($m_{Z'}$,m_A) plane

for fixed couplings and H, $H^{\pm}$ masses

Relevant at low m_A when combined with $h \to bb$



Conclusions

- The discovered Higgs-like particle is ***very*** SM like

- No sign of BSM physics in the Higgs sector yet…

- Both experiments are becoming smarter and smarter
  (trigger, new tools, better multivariate techniques)

$\Rightarrow$ Try to leave no stone unturned in the scalar sector !

References :

➢ CMS :

- h125 invisible JHEP02(2017)135 (7 / 8 / 13 TeV , 5.1 / 19.7 / 2.3 fb^{-1})
- H4ℓ (125 GeV) : PAS-HIG-16-041 (13 TeV, 35.9 fb^{-1})
- Singlet Run 1 combination : JHEP10(2015)144 (7 / 8 TeV, 5.1 / 19.7 fb^{-1})
- H4ℓ (heavy) : PAS-HIG-16-033 (13 TeV, 12.9 fb^{-1})
- $H^+ \rightarrow \tau\upsilon$: PAS-HIG-16-031 (13 TeV, 12.9 fb^{-1}) (ATLAS : ATLAS-CONF-2016-088)
- $H \rightarrow hh \rightarrow bb\tau\tau$: PAS-HIG-17-002 (13 TeV, 35.9 fb^{-1})
- $H^+ \rightarrow WZ$: 1705.02942 (13 TeV, 15.2 fb^{-1})
- $H^{++} \rightarrow \ell^+\ell^+$: PAS-HIG-16-036 (13 TeV, 12.9 fb^{-1}) (ATLAS : ATLAS-CONF-2016-051)

➢ ATLAS :

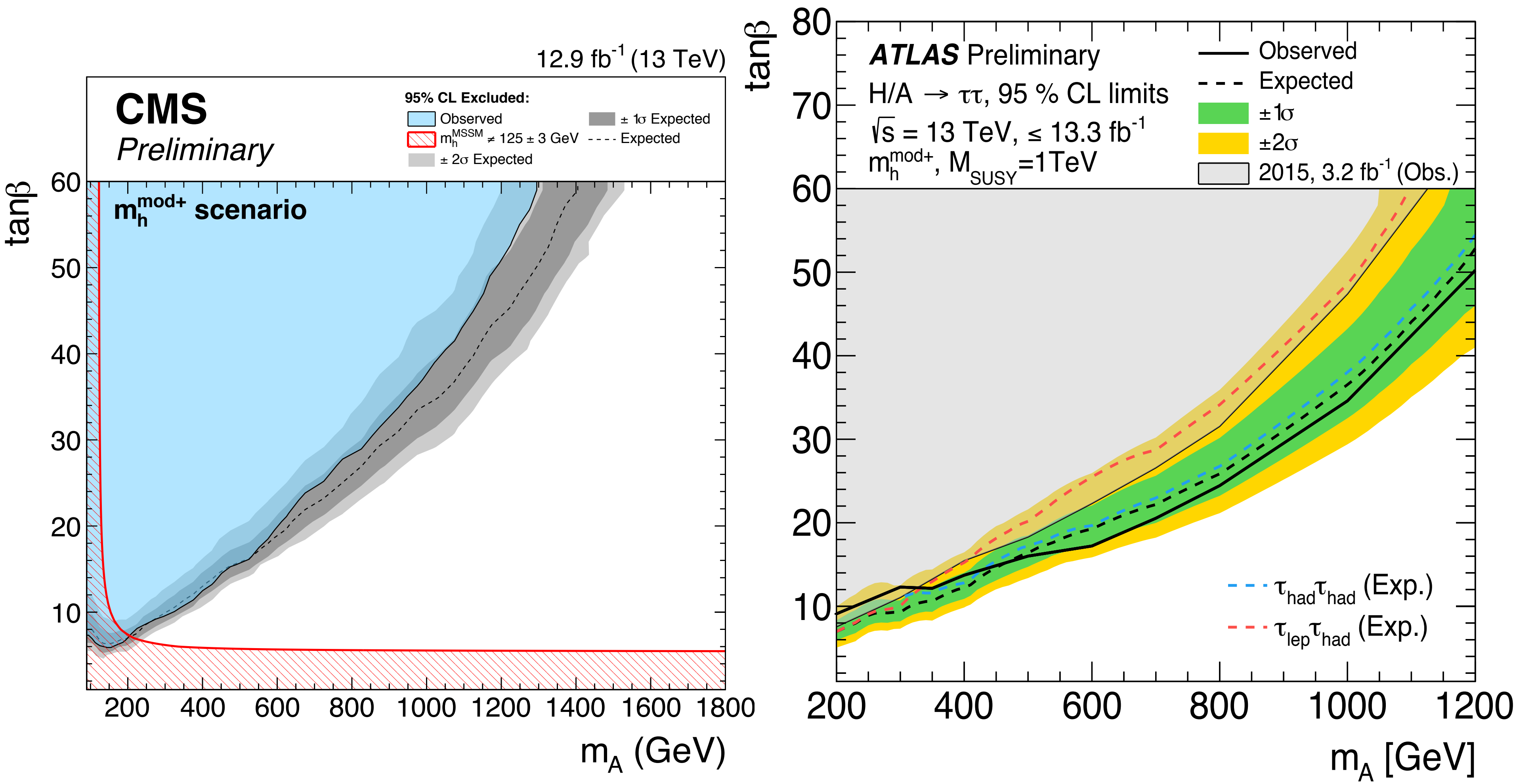
- H4ℓ (125 GeV) : ATLAS-CONF-2016-079 (13 TeV, 14.8 fb^{-1})
- constraints on new phenomena via h125 : JHEP11(2015)06 (7 / 8 TeV, 4.7 / 20.3 fb^{-1}) (PAS-HIG-16-007)
- $H \rightarrow \upsilon\upsilon\ell\ell$: ATLAS-CONF-2016-056 (13 TeV, 13.3 fb^{-1}) (CMS PAS-HIG-16-001)
- Prospect for constraints from h125 : ATL-PHYS-PUB-2014-017 (Run III, HL-LHC)
- $A/H \rightarrow \tau\tau$: ATLAS-CONF-2016-085 (13 TeV, 13.3 fb^{-1}) (CMS PAS-HIG-16-037)
- $A/H \rightarrow tt$: ATLAS-CONF-2016-073 (8 TeV, 20.3 fb^{-1})
- mono H, $H \rightarrow bb$: ATLAS-CONF-2017-028 (13 TeV, 36.1 fb^{-1}) (CMS comb. 1703.05236
- mono H, $H \rightarrow \gamma\gamma$: 1706.03948 (13 TeV, 36.1 fb^{-1}) 2.3 fb^{-1})

➢ ATLAS+CMS H125 combination : JHEP08(2016)045 (7 / 8 TeV, 10 / 40 fb^{-1})

ATLAS : https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CMS : http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

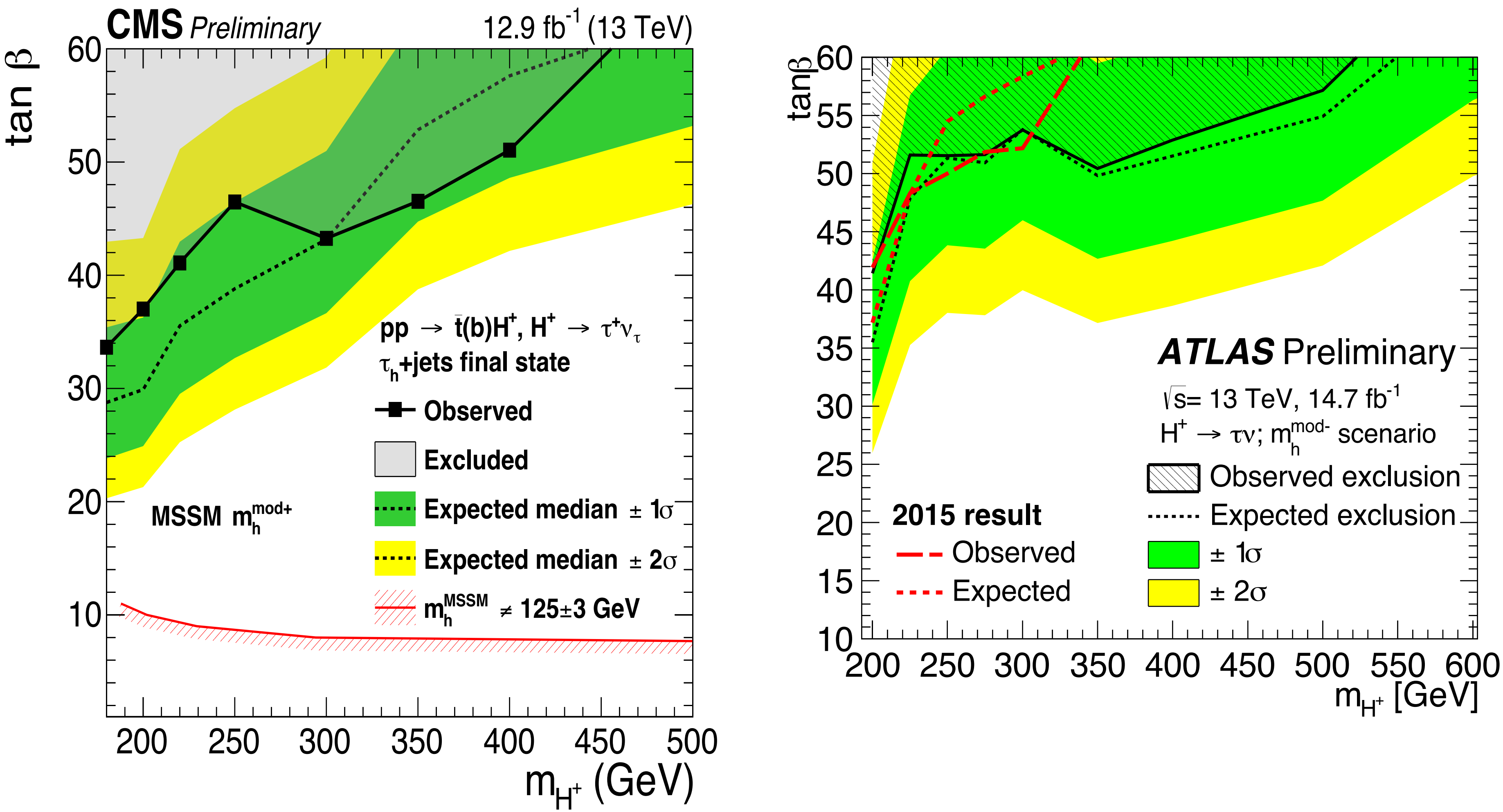
Back-up

$A/H \rightarrow \tau\tau$ CMS vs ATLAS, example of m_h^{mod+} scenario



Very similar sensitivity, e.g. expected exclusion for m_A = 1 TeV/c^2 : tanβ > 34 / 36
CMS search cover also the low mass [90,200] GeV/c^2

$H^+ \rightarrow \tau\nu$ CMS vs ATLAS, example of m_h^{mod+} scenario



Similar sensitivity, e.g. expected exclusion for $m_A = 400$ GeV/c^2 : $\tan\beta > 58 / 52$

Back-up

(from run 1 analyses)

Indirect limit on the invisible (/undetected) branching ratio can be determined from the coupling fits. In the most generic model tested, the

$$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_\tau, \kappa_{Z\gamma}, \mathcal{B} = \mathrm{Br}(H \rightarrow inv)$$

model, and assuming $\kappa_W, \kappa_Z < 1$ to lift the model degeneracy

$\mathcal{B} < 0.49$ @ 95% CL (assuming $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$ gives $\mathcal{B} < 0.68$)

Direct search for invisible decay $H \rightarrow \chi\chi$, where χ is a generic (quasi-) stable neutral and weakly interacting particle (e.g. the lightest neutralino in R_p-conserving SUSY)

⇒ use Higgs boson associated production VBF or VH, V = W/Z
(ttH might also be used)

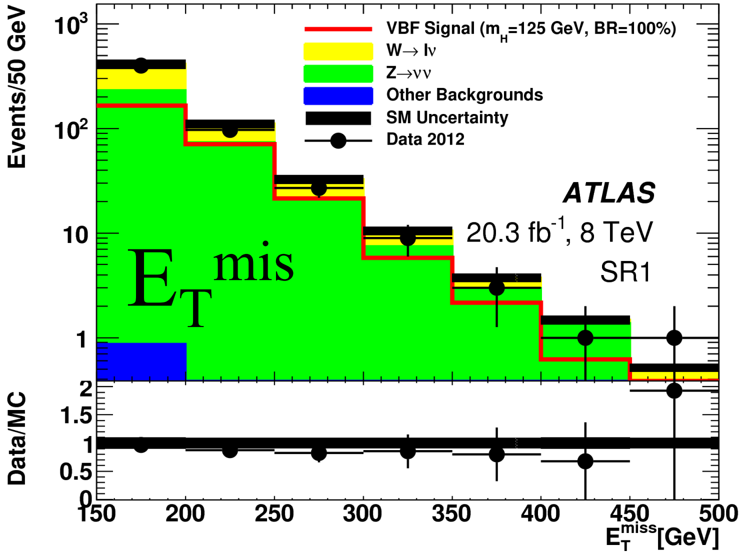
⇒ or single production, relying on ISR tagging
(smaller sensitivity, from mono-jet or mono-V tagging *(unresolved W : fat jet)* since not specifically designed towards Higgs production)

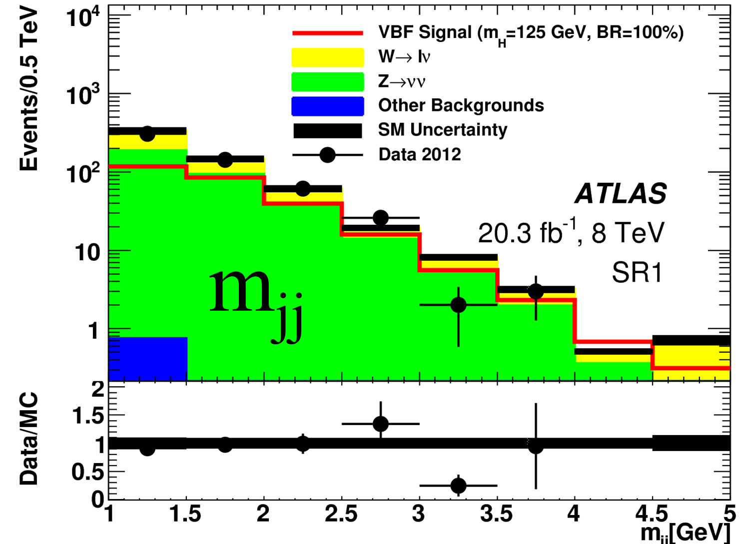
All results quantified in term of $\xi = \dfrac{\sigma \times \mathcal{B}_{inv}}{\sigma_{SM}}$ or $\mathcal{B}$ assuming SM production

Search in VBF production

combine three analysis categories SR1 and SR2a,b which add a 10% sensitivity to SR1

Typical VBF signature : 2 high p_T jets with high m_{jj} (> 1 TeV in SR1), large $\Delta\eta_{jj}$ (> 4.8 in SR1), 3rd jet veto + large E_T^{mis} from $H \rightarrow inv$ (>150 GeV in SR1) (+ anti-QCD cuts)





Control region dedicated to Z+jets and W+jets used with together with Signal region in final fit (using 1/2 lepton events, adding lepton in E_t^{mis})

In the most sensitive signal region :

Sig($\mathcal{B}$=1) : N = 306 ± 59 (7% ggH)

Bkg : N = 577 ± 62 (59% Z+jets, 41% W+jets)

N(data) = 539

Combining the three : $\mathcal{B} < 0.28$ (0.31 exp.)

[SR1 alone : 0.30 (0.35 exp)]

The sensitivity in the invisible decay search is a great achievement : before data taking, it was not clear if VBF would be useable at such a large instantaneous luminosity

Combining with (much less sensitive) dedicated VH searches using $Z \to \ell\ell$ and $W/Z \to qq$:

$\mathcal{B} < 0.25$ (0.27 exp.)

The indirect limit ($\mathcal{B} < 0.49$) assumes $\kappa_W, \kappa_Z < 1$

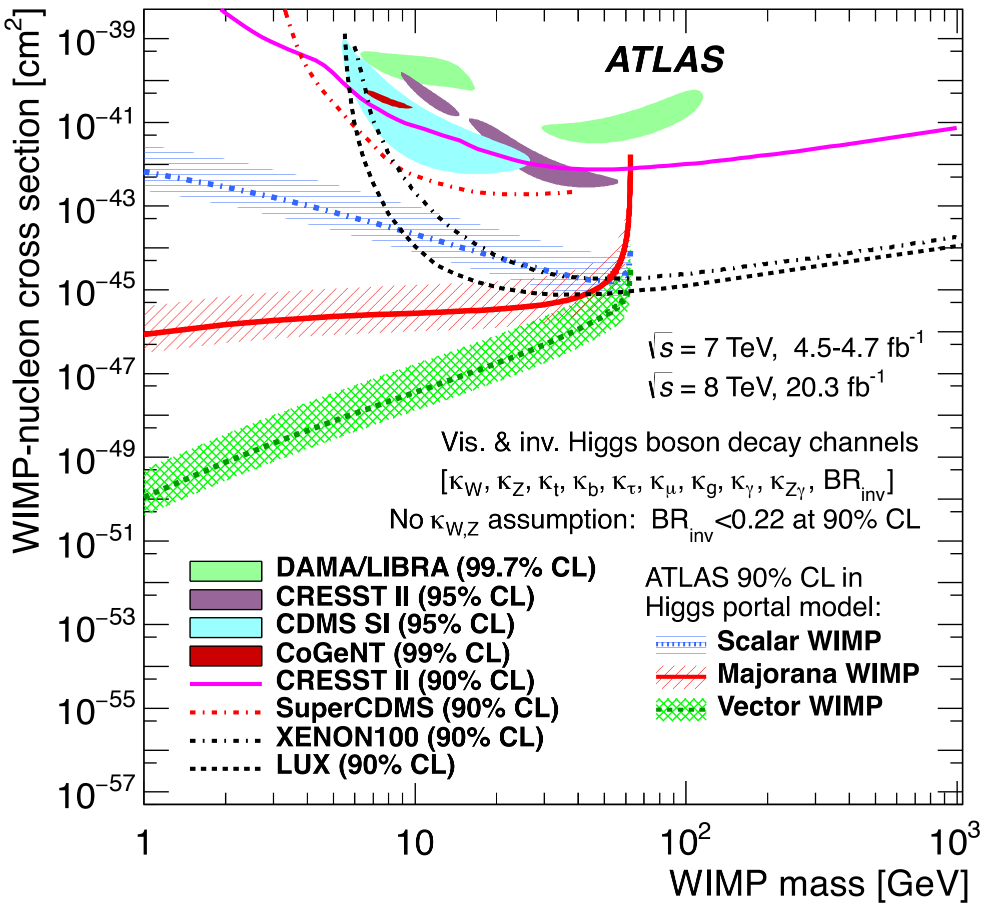
The direct limit ($\mathcal{B} < 0.25$) assumes $\kappa_W = \kappa_Z = \kappa_g = 1$

$\Rightarrow$ Combine both and remove these assumptions !

$\mathcal{B} < 0.23$ (0.24 exp.)

Interpreted as a limit on σ(DM-nucleon)

$\Rightarrow$ very powerful at low DM mass which is very tough for direct detection



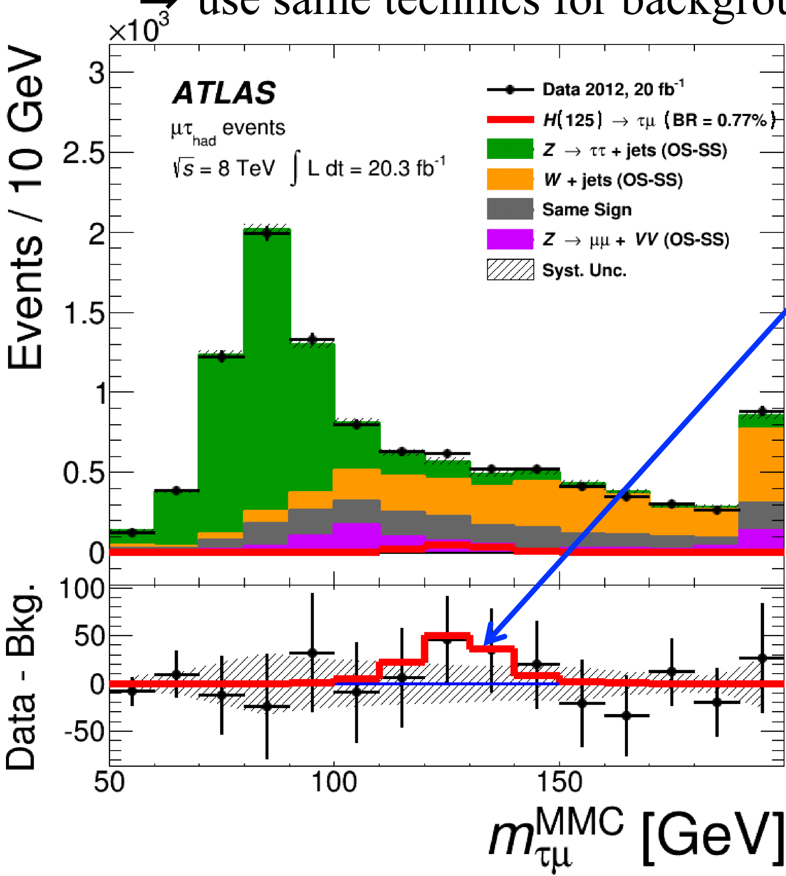
Lepton Flavour Violation $H \to \tau\mu$

- Limits from $\mu \to e\gamma \Rightarrow \mathcal{B}(H\to e\mu) \lesssim 10^{-8}$ but much weaker constrains for $\mathcal{B}(H\to \tau\mu/\tau e)$

- In run I, LHC sensitivity not far away from the "*naturalness limit*" (Cheng-Sher ansatz)
  $\lambda_{\tau\mu} \sim (2m_\tau m_\mu)^{0.5}/v \Rightarrow \mathcal{B} = \mathcal{B}(H\to \tau\mu) \sim m_\mu/m_\tau\, \mathcal{B}(H\to \tau\tau) \sim 0.4\%$

- Small (2.4σ) excess seen in CMS : $\mathcal{B} < 1.57\%$ (0.75% exp.), best fit $\mathcal{B} = 0.84^{+0.39}_{-0.37}\,\%$

- ATLAS performed this search in the $\tau_{had}\mu$; similar to standard $H \to \tau\tau$ search :
  $\Rightarrow$ use same technics for background and systematics uncertainties estimation



Using 20 fb^{-1} of 8 TeV data, small 1.3σ excess
$\mathcal{B} < 1.85\%$ (1.24% exp.),
best fit $\mathcal{B} = 0.77\pm0.62\ \%$

An interesting ~ 2.6σ excess (CMS+ATLAS naïve combination !) to be monitored in run II :
Signal and main bkg increase by ~ 2 :
* in ATLAS expected limit could be

$\mathcal{B} \lesssim 0.7\%$ (0.3%) with 20 fb^{-1} (100 fb^{-1})

$\Rightarrow$ sensitivity to "*naturalness limit*" with $\tau_{had}+\mu$ only without major improvement nor combination with $\tau_{lep}+\mu$

Higgs boson Flavour Changing Neutral production $t \rightarrow qH$

Tiny branching ratio in SM : ~ 10^{-15} / 10^{-17} for q = c / u

⇒ Any observation of such processes is a non ambiguous sign of new physics

Some models predict enhancement by several order of magnitude

Benchmark coupling : *Naturalness limit* : $\lambda_{tcH} \sim 0.086$, $\mathcal{B} \sim 0.2\%$

Both ATLAS and CMS searched for this in top-quark pairs :

$$pp \rightarrow t\bar{t} \rightarrow W^{+}b\ Hq + \text{c.c.}$$

No excess has been observed ⇒ limits :

topology	$H \rightarrow \gamma\gamma$ ($W \rightarrow \ell\nu/qq$)		multi-leptons	
(%)	q = c	q = u	q = c	q = u
ATLAS	0.79 (0.51)		0.79 (0.54)	0.78 (0.57)
CMS†	0.47 (0.71)	0.42 (0.65)	0.93 (0.89)	-

† unpublished results with better sensitivity than the published analysis ($\mathcal{B} < 0.56\%$)

- The ATLAS multi-lepton result is a simple re-interpretation of the SM ttH search in the multi-lepton topology : not optimized for this less busy final state but yet very sensitive !

  ⇒ Might hope for great improvement in run II

What about H → bb ? A priori very tough !

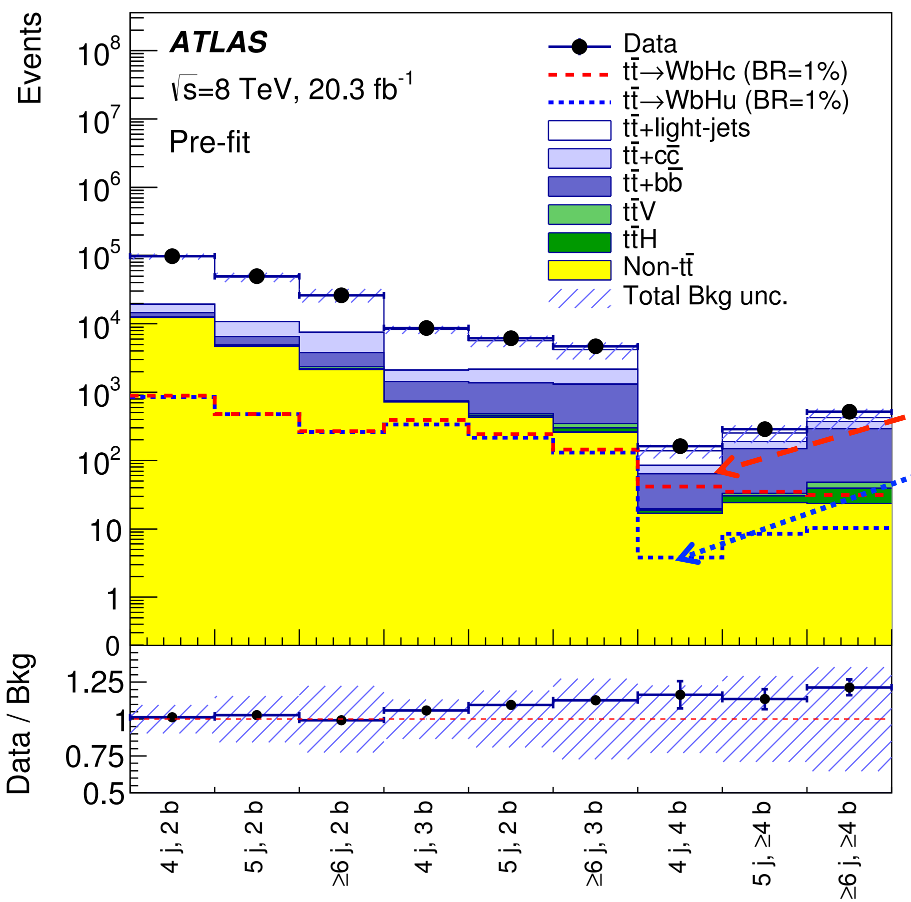
Signal : ℓνb bbq

vs top pair background : ℓνb qqb

- Much higher stat. than γγ (× 250)
- Handles : more b-tags, Higgs boson invariant mass

⇒ Recycle all technics used for ttH, H → bb :

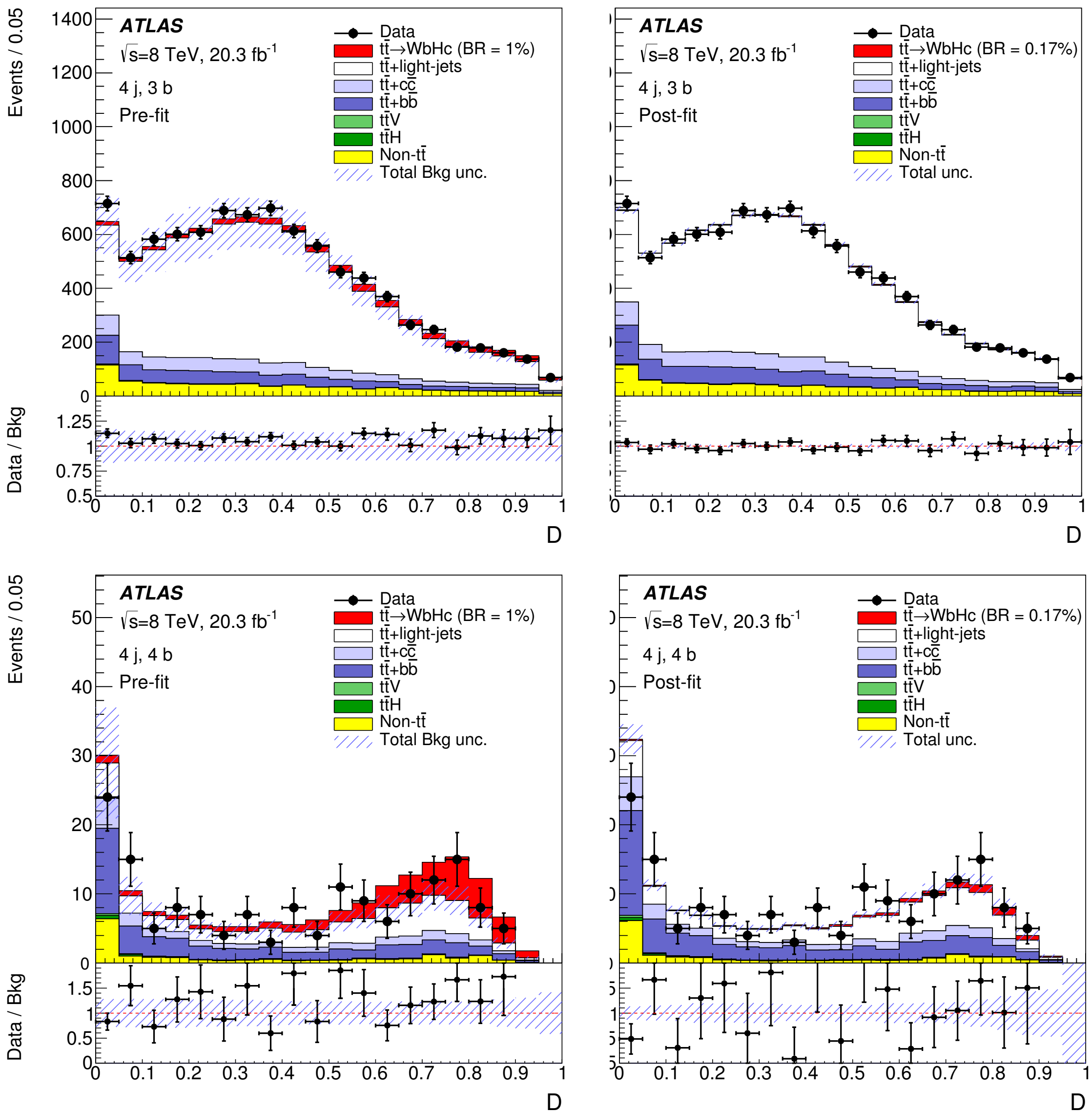
constrain the background from data via simultaneous fit in categories in N_{jet}(4, 5, ≥6) and N_{bjet} (2, 3, ≥4)



✓ Expect most sensitive categories (N_{jet} N_{bjet}) = (4,3), (4, ≥4)

✓ Sensitivity to q= c vs u using ≥4 b categories

✓ Final discriminant combines invariant masses (two tops, a Higgs boson) and b-tagging into a likelihood pre-fit post-fit



No excess :

$\mathcal{B}(t \to cH) < 0.56\%$ (0.42% exp)

$\mathcal{B}(t \to uH) < 0.61\%$ (0.64% exp)

Combination with $\gamma\gamma$ and multi-lep :

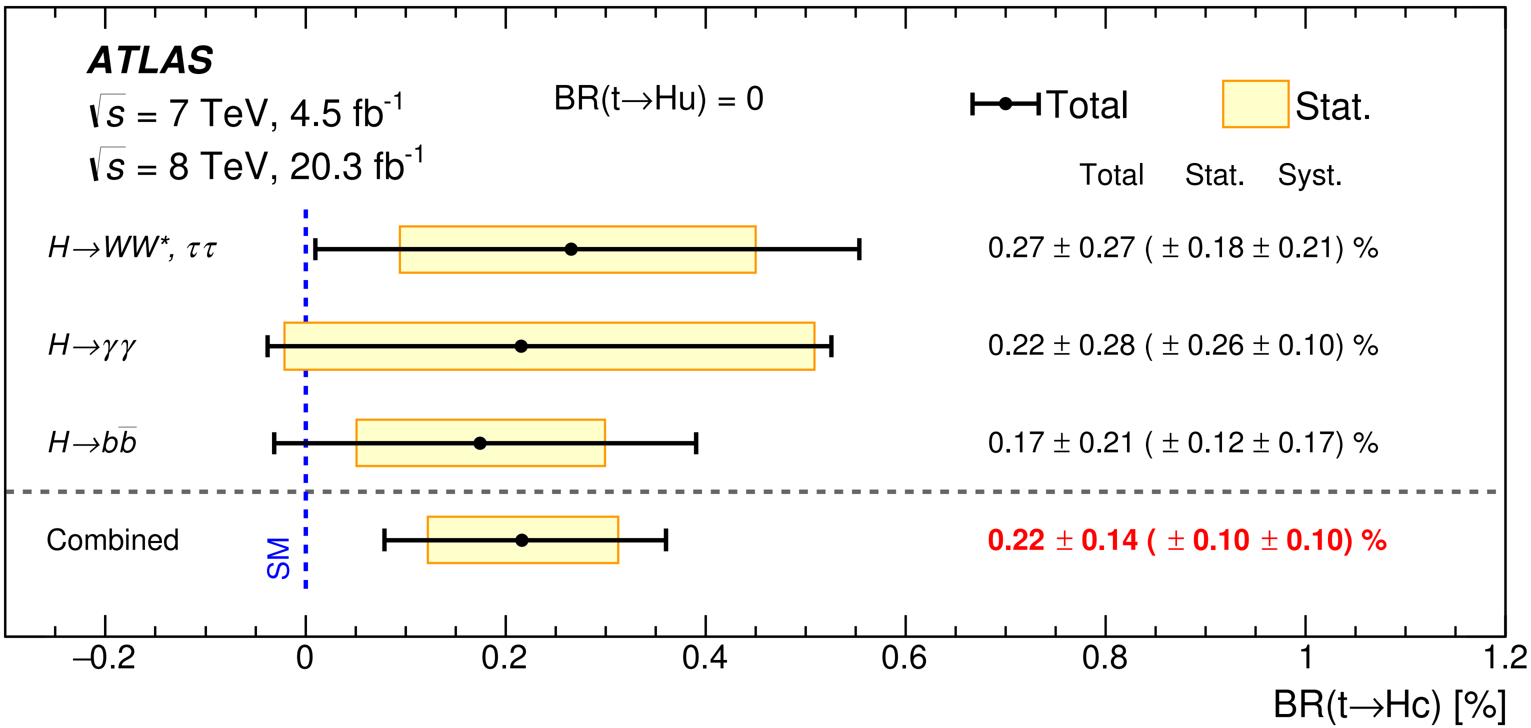
$\mathcal{B}(t \to cH) < 0.46\%$ (0.25% exp)

$\mathcal{B}(t \to uH) < 0.45\%$ (0.29% exp)

Intriguingly the three channels observed a slight excess (and for H → bb, in the t → cH decay) corresponding to a best fit value of

$$\mathcal{B}(t \to cH) \sim 0.2\%$$

which matches the *naturalness limit* …



For run II, in the di-photon channel, expect ~ 3.7 events / fb^{-1} for $\mathcal{B}$ = 0.1% :
sensitivity ~ 0.15% with 30 fb^{-1}
⇒ Adding the multi-lepton and bb final state might allow to probe well below the *naturalness limit* before the end of run II

Details on the search for A → Zh

In the MSSM, especially useful at low tanβ, below the tt threshold

For example in type II, using h → down-type fermion pair, constraining coupling combination :

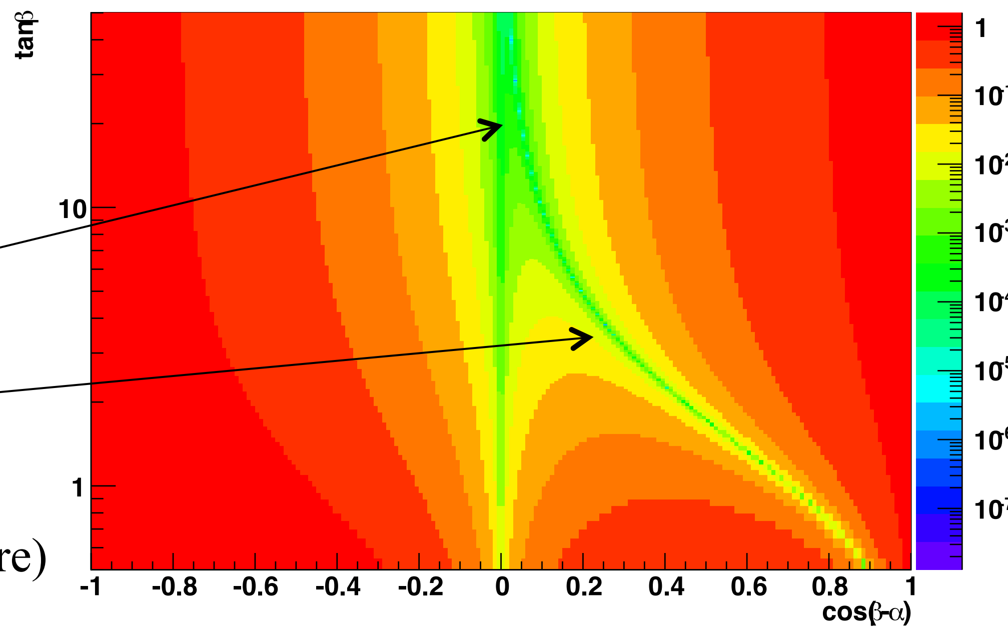
- Gluon fusion : κ = [t-t-A ~ 1/tanβ] x [Z-h-A ~ cos(β-α)] x [h-b-b ~ -sinα/cosβ]

(• b-associated : [b-b-A ~ tanβ] x [Z-h-A ~ cos(β-α)] x [h-b-b ~ -sinα/cosβ])

In the (cos(β-α),tanβ) plane,
for ggA :

Z-h-A ~ 0

h-b-b ~ 0



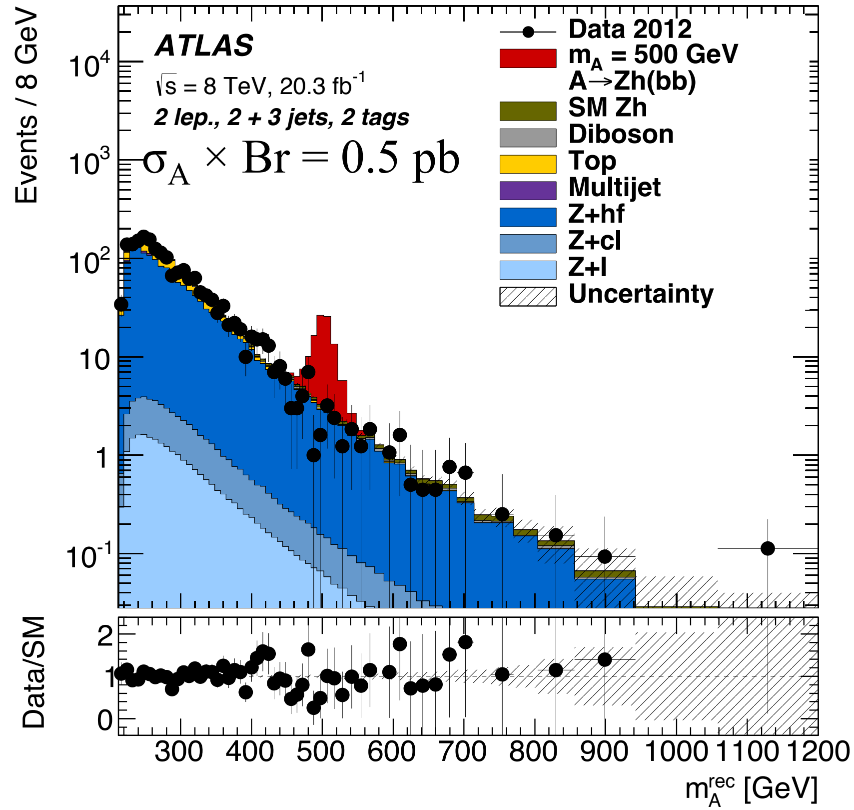
Most promising channels :

- Z → $\ell^+\ell^-$ h → ττ (not described here)
- Z → $\ell^+\ell^-$ h → bb

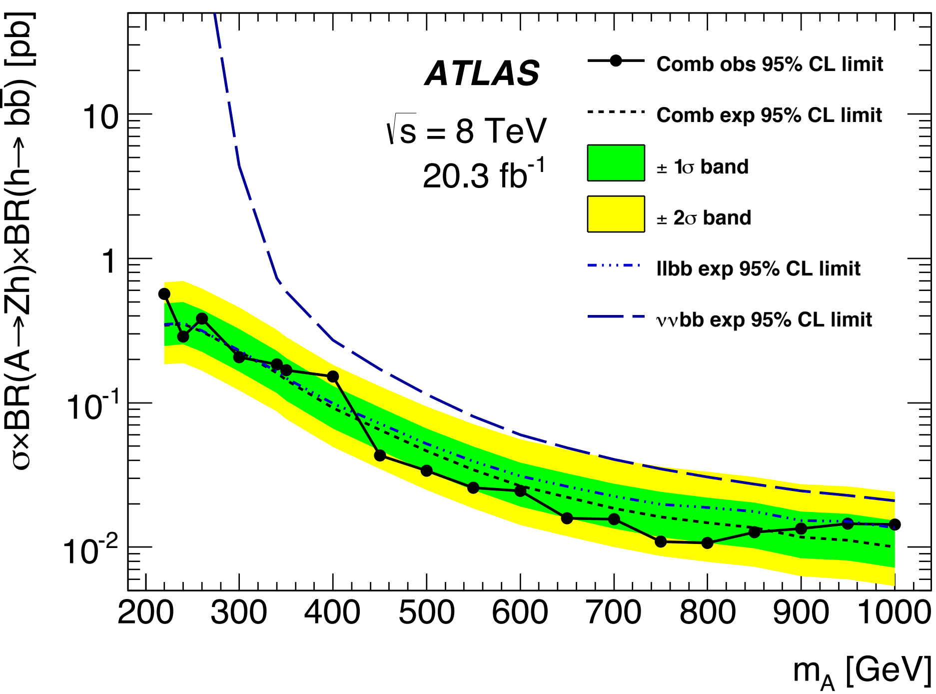
The h → bb case profits from the background understanding acquired in the SM associated Zh, h → bb production study, especially Z + jets

The $\ell^+\ell^-$ bb channel

Very good four body invariant mass resolution, ranging from 2% to 3% for $m_A \in [0.22,1]$ TeV/c^2



Adding the νν bb channel :
3× yields (before cuts),
but no mass peak, only transverse mass
⇒ add ~ 10% to the combined sensitivity at ~ 500 GeV/c^2 but 50% at 1 TeV/c^2
(assuming narrow width…)

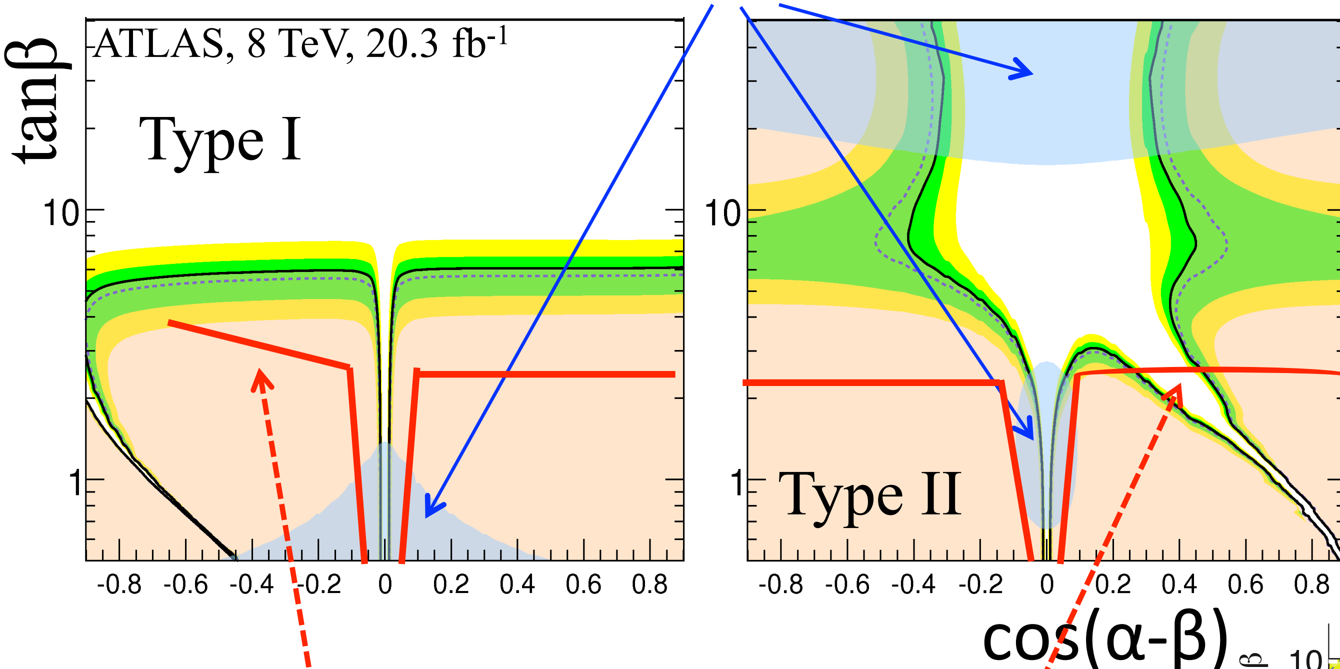


⇒ (almost*) model-independent limit on $\sigma\times B(A \to Zh) \times B(h \to bb)$ between 570 and 14 fb

(* : above the top threshold, the width can vary a lot and a large width degrades the limit)

Interpretation : example of 2HDM I and II, $m_A = 300$ GeV/c^2
(no combination AZh / Aττ / Hhh)

$A \to \tau\tau$ (bbA production included)



Nice complementarity between

$A \to Zh$ and $A \to \tau\tau$

in 2HDM II

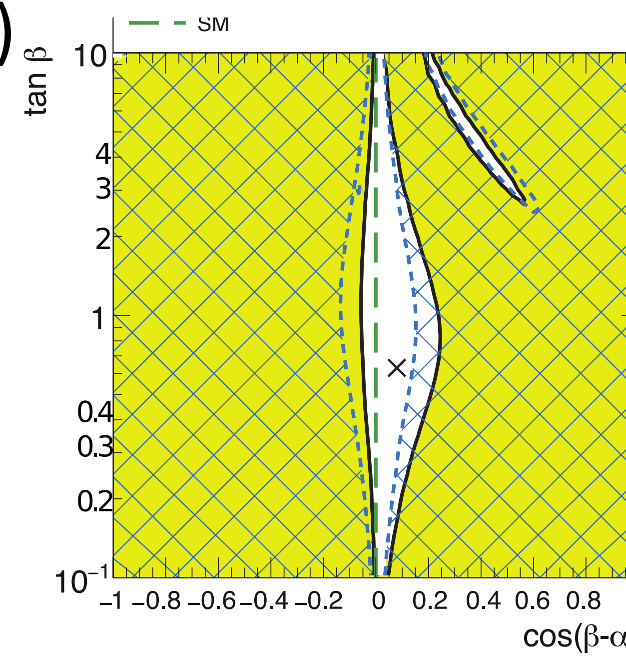
CMS also looked at multi-lepton (≥ 3 including at most 1 τ_{had}) and γγ decays searching for $H \to hh$ and $A \to Zh$

⇒ very important to fill the holes when h-b-b ~ 0

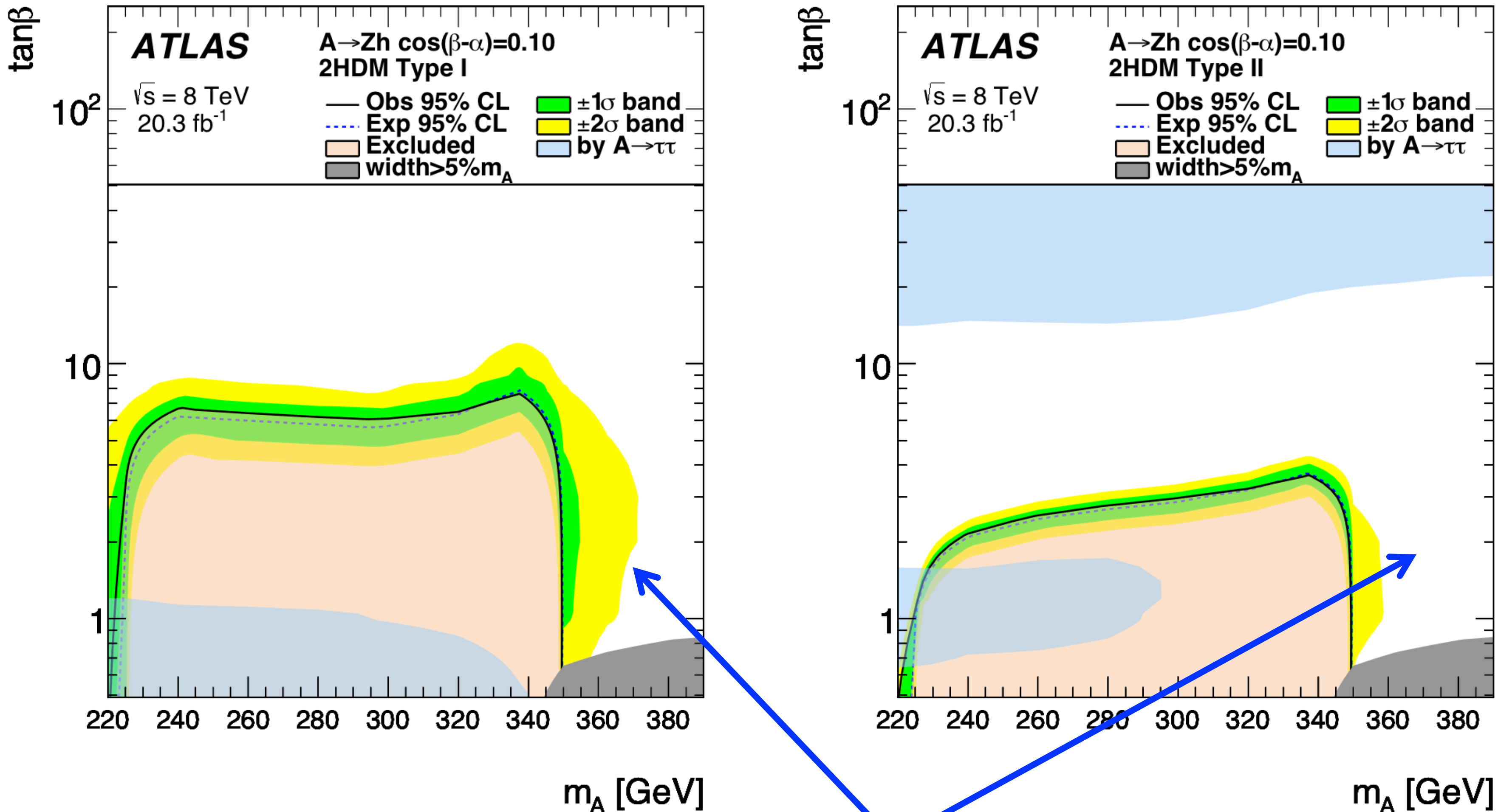
(~ h-τ-τ for 2HDM I,II)

(mainly from AZh so only slightly worse if assumption $m_H = m_A$ is relaxed)

Example for 2HDM II
from h coupling measurements
$h \to ZZ^*, WW^*, \gamma\gamma, \tau\tau, bb$



In the (mA,tanβ) plane, for cos(β-α) = 0.1 :



Opening of A → tt

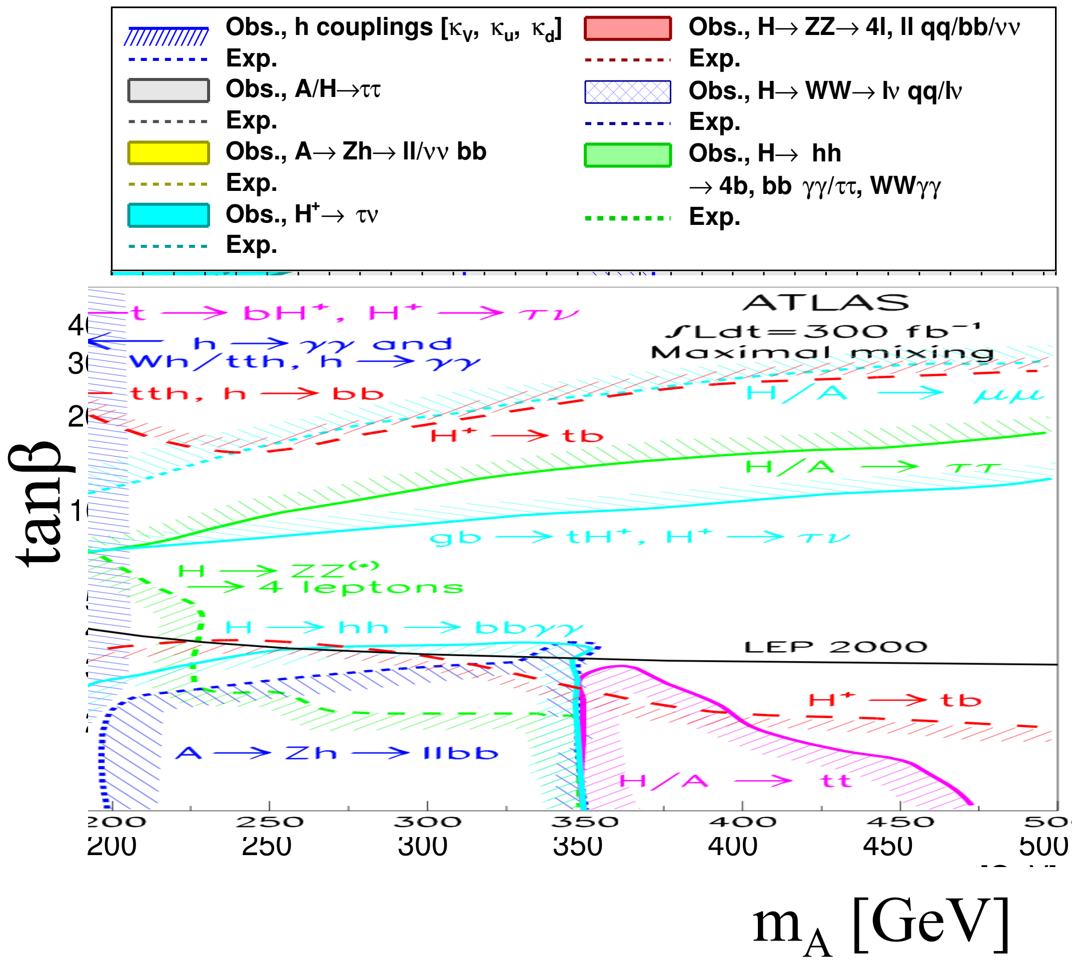
Interpretation in the simplified MSSM

(using m_H = 125.1 GeV/c^2 to estimate radiative corrections to effective couplings)

A simple overlay of all constrains,
not yet a global combination

Run I analyses not all done yet !
Work in progress for some missing channels

e.g. $pp \rightarrow (b)tH^{\pm}, H^{\pm} \rightarrow tb$ at high $m_{H\pm}$



More channels should be covered
in run II benefiting from better tools,
e.g. :

$A \rightarrow tt$ for $m_A > 2\, m_{top}$

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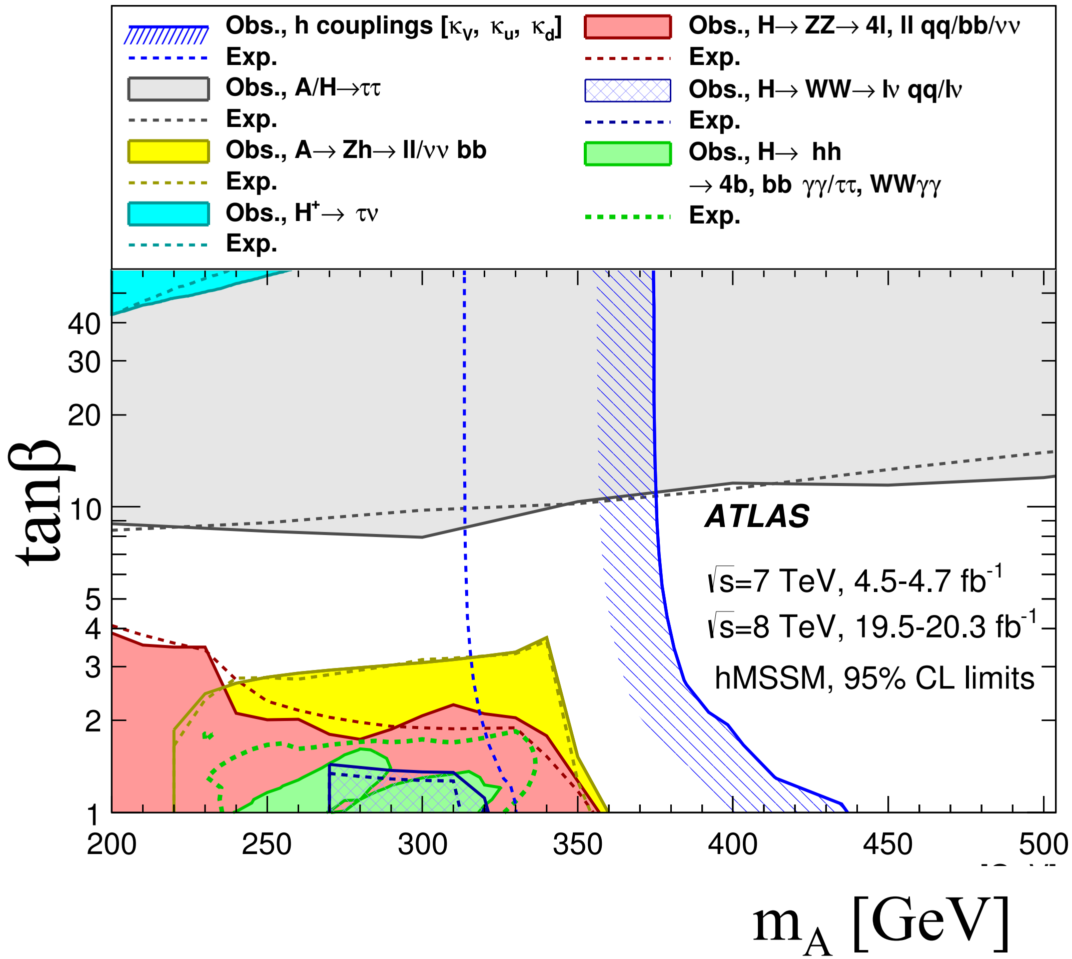

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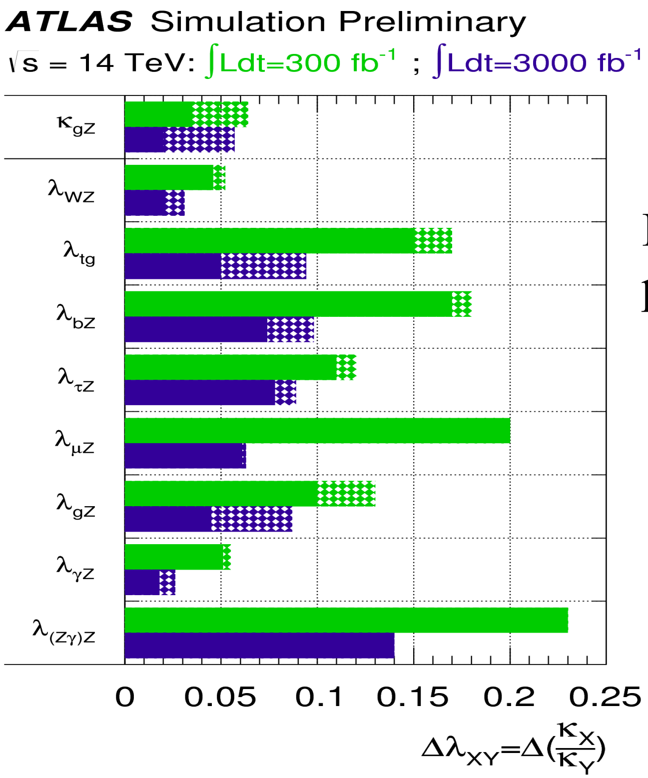
$A \to tt$ for $m_A > 2\ m_{top}$

Some expectations for beyond run II

→ most prospects have been considering integrated luminosities of 0.3 or 3 ab^{-1}…



In particular for 0.3 ab^{-1} factor ~ 2 gain on precision for $\lambda_{\gamma Z}$: ~ 5% accuracy assuming 2014 theory uncertainties

⇒ sensitivity to new charged particles in the loop ?

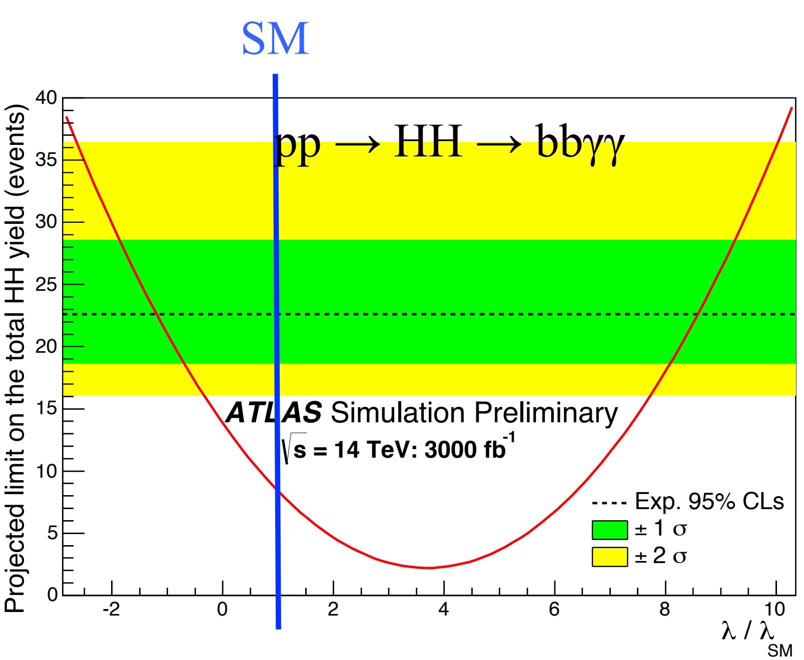
- What about the trilinear λ_{3H} coupling ?

$$V_{SM}(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

$\lambda = m_H^2 / 2v^2 \sim 0.13$, $\lambda_{3H} = 3m_H^2 / 2v \sim 191$ GeV

Very very hard, needs HL-LHC : e.g. in $bb\gamma\gamma$

$S \sim 8.4$, $B \sim 47.1$, $\lambda/\lambda_{SM} \in [-1.3, 8.7]$ @ 95%CL



Work in progress to include more final states…