Search for BSM Higgs Phenomena at the LHC

What have we learned from the newly discovered particle?
What are potential BSM Higgs signatures?
What have we done in searching those signatures?

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University of Michigan

Oskar Klein Center, Stockholm, Sweden, May 20, 2014

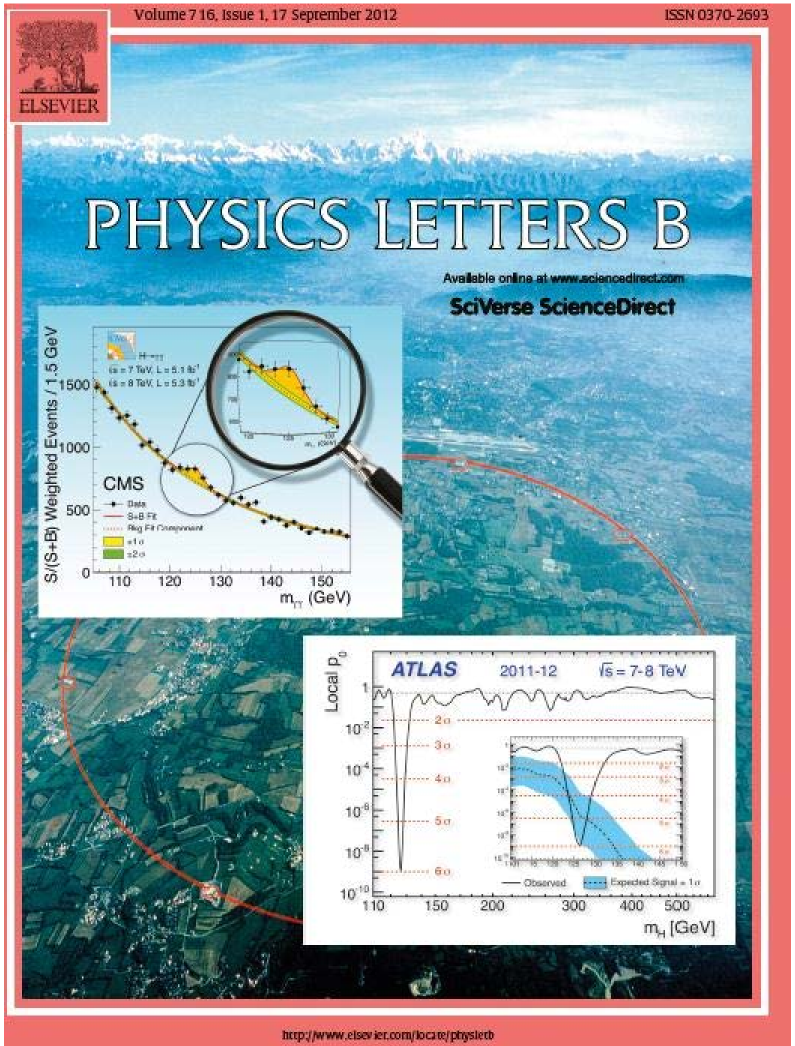
Oskar Klein

In 1923, he received a professorship at University of Michigan in Ann Arbor and moved there with his recently wedded wife, Gerda Koch from Denmark.

http://en.wikipedia.org/wiki/Oskar_Klein

What Now?

Discovery has been made…



Nobel prize has been awarded

But one question remains:

Is the new boson solely responsible for the electroweak symmetry breaking?

Two-pronged approaches

A precision program

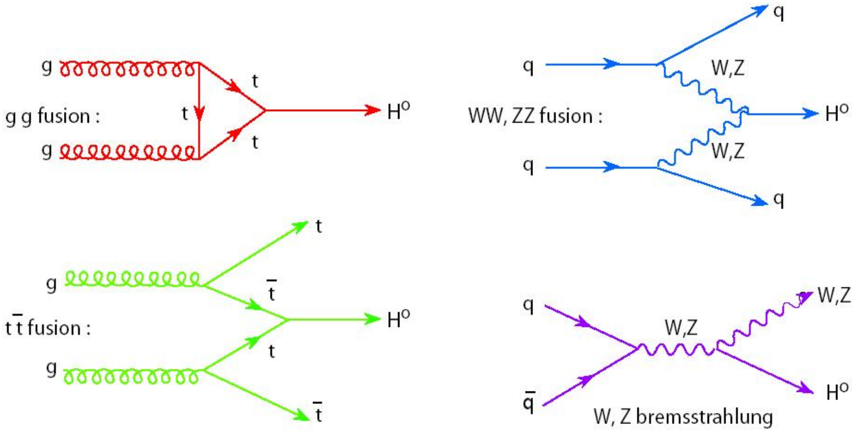
measurements of h(125) Higgs properties

A search program

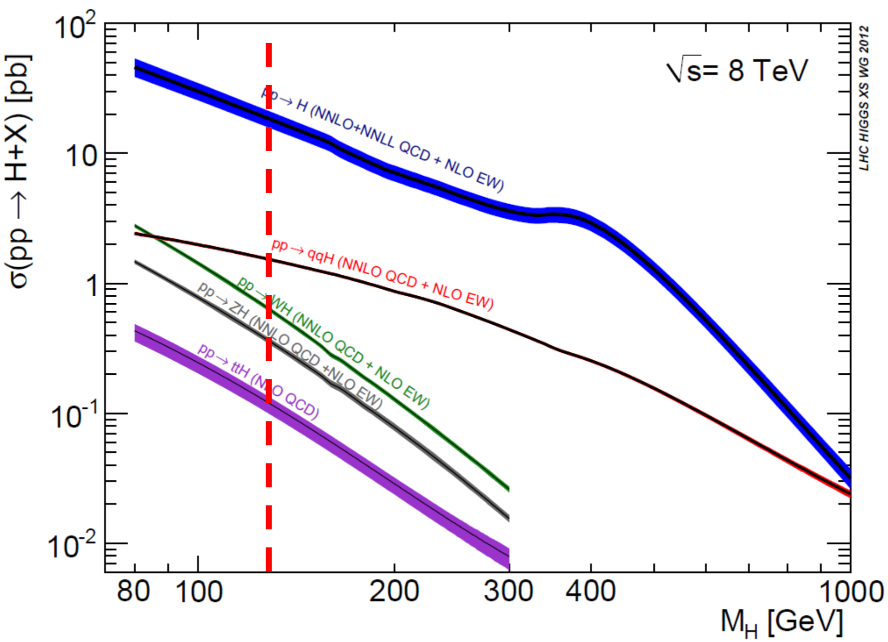
searches for additional Higgs bosons, use the newly discovered particle as a tool to explore potential new physics

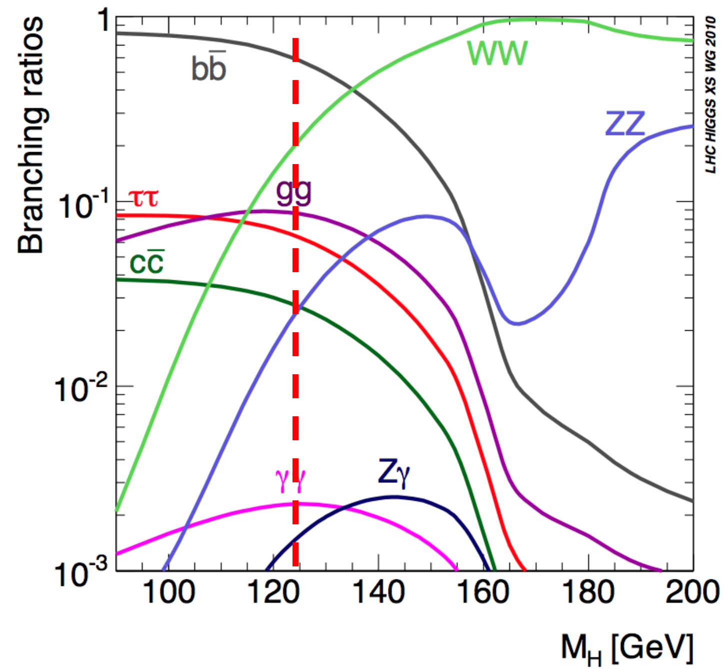
Productions and Decays

$m_H = 125 \text{ GeV} \quad \sigma_H = 22.3 \text{ pb}$



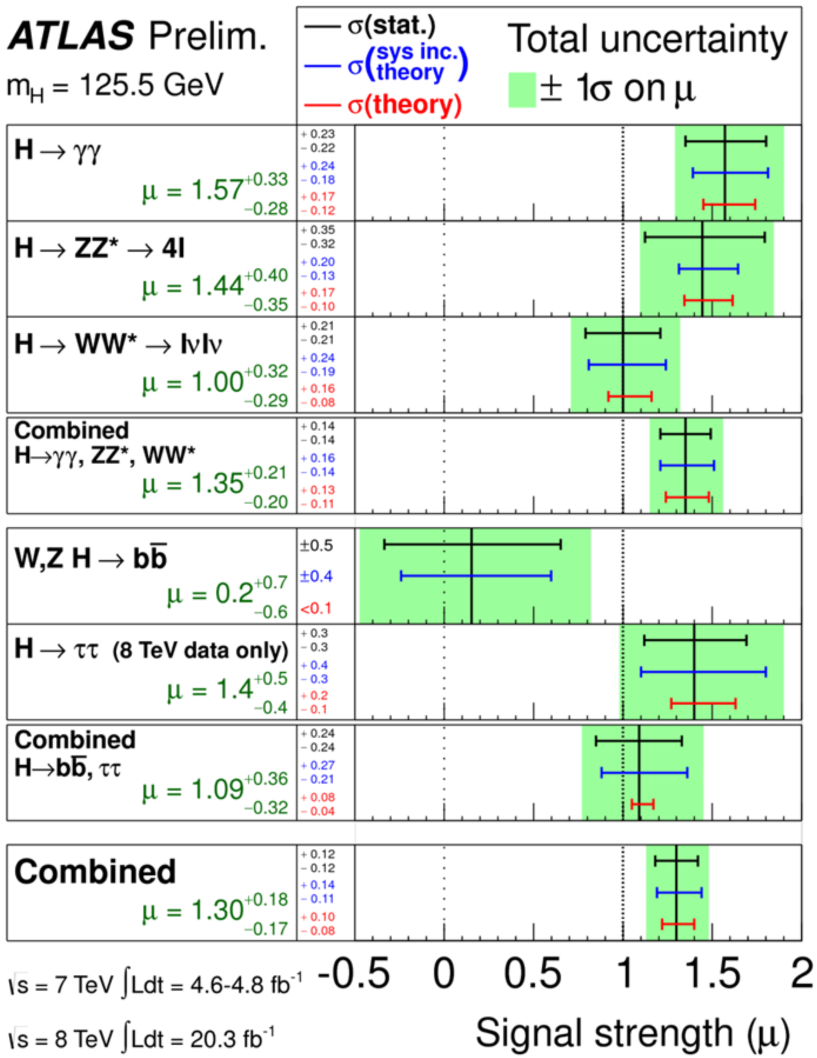
Branching ratio	
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%





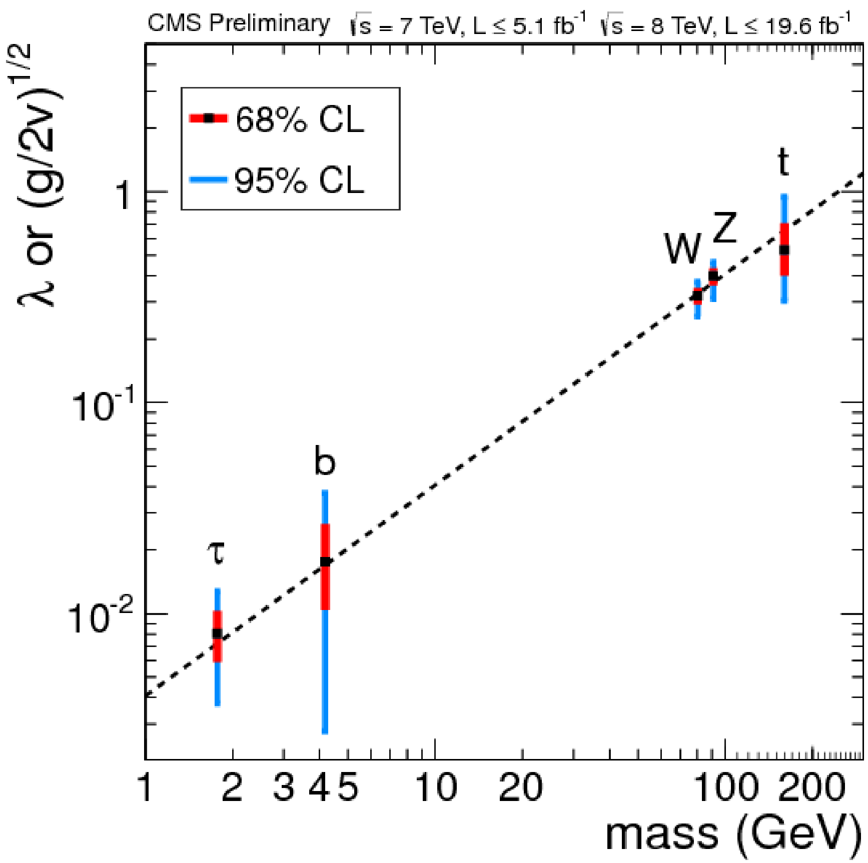
Over 1,000,000 Higgs bosons “produced” at LHC in Run 1!

H(125): Rates and Couplings



SM: $\lambda \propto m$ (fermions)

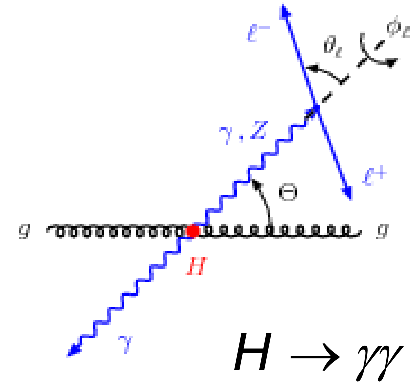
$g \propto m^2$ (bosons)

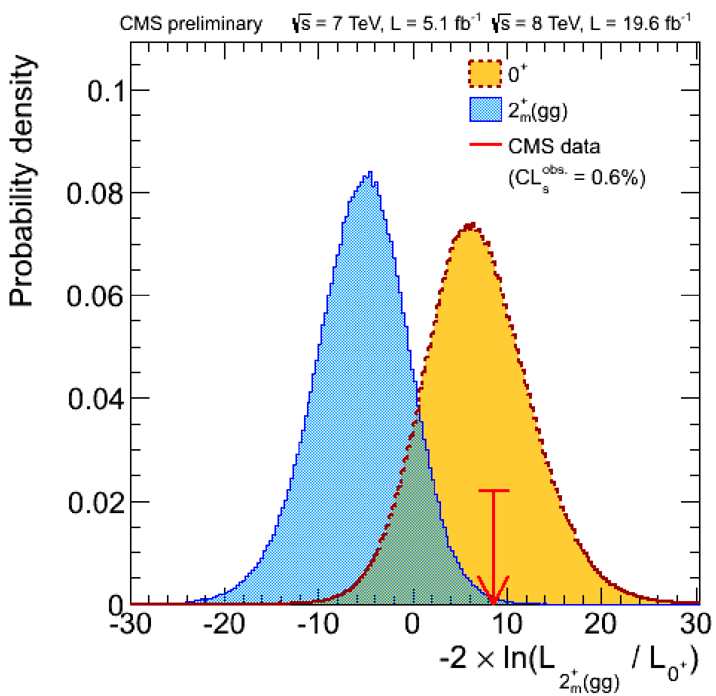


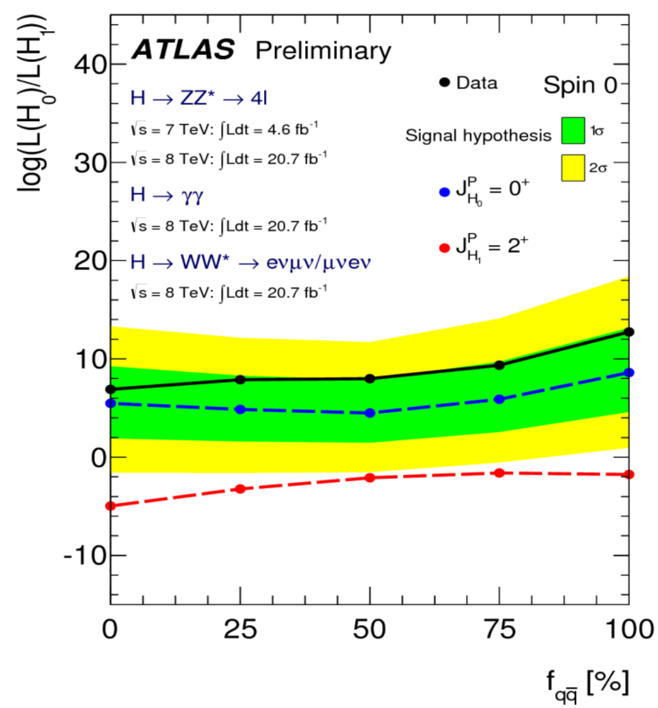
Rates and couplings are very Standard Model like

H(125): Spin and CP

Higgs decay kinematics depends on its properties of spin and parity. $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ final states have been analyzed to determine these properties.







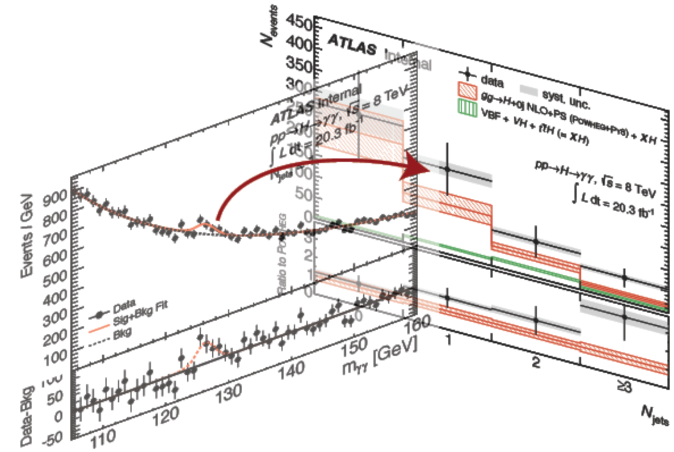
SM prediction of $J^p=0^+$ is strongly favored,
most alternatives studied are excluded @ 95% CL or higher

$H \rightarrow \gamma\gamma$: Differential Distributions

Study kinematics of candidate events:

- fit $m_{\gamma\gamma}$ distributions into bins of kinematic variables such as N_{jet} and $p_T^{\gamma\gamma}$,

- unfold to particle-level cross sections



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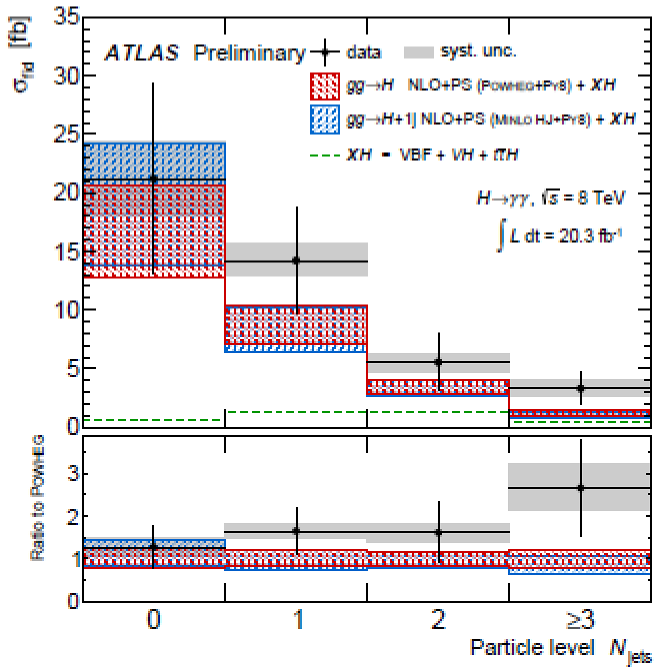
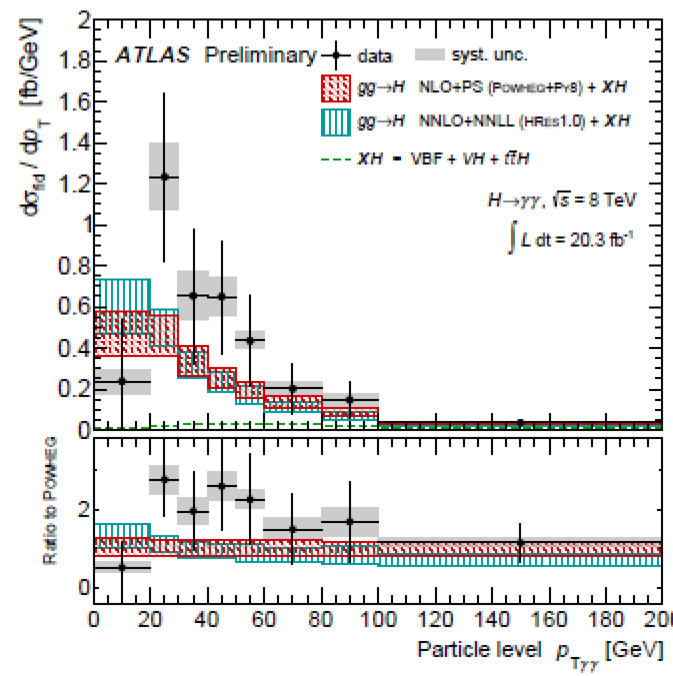




Good agreements between data and the SM expectations (within statistics)

Beyond the Standard Model

The Standard Model Higgs sector consists of one $SU(2)$ Higgs doublet field

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Natural extensions to the SM Higgs sector:

- SM + a singlet S (real or complex);
- SM + an additional Higgs doublet, known as 2 Higgs doublet model (2HDM);
- 2HDM + a singlet S;
- Higgs triplet model; ......

Why extensions?

May provide a dark-matter candidate (Higgs portal model);

May offer explanation for the electroweak phase transition; ......

Phenomenological and experimental consequences:

Non-SM-like Higgs bosons $\Rightarrow$ coupling modifications;

Additional neutral and/or charged Higgs bosons;

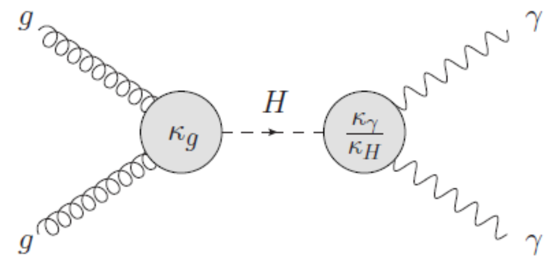
New production processes and decay modes; ....

Coupling Parametrization

Parametrizing deviations from SM using scale parameters: κ $(\text{SM: } \kappa = 1)$

$$g_{hff} = \frac{\sqrt{2}m_f}{\upsilon}, \qquad g_{hVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}, \quad g_{hVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$



For example: $(\sigma \cdot BR)(gg \to h \to \gamma\gamma) = \left[\sigma(gg \to h) \cdot BR(h \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_h^2}}$

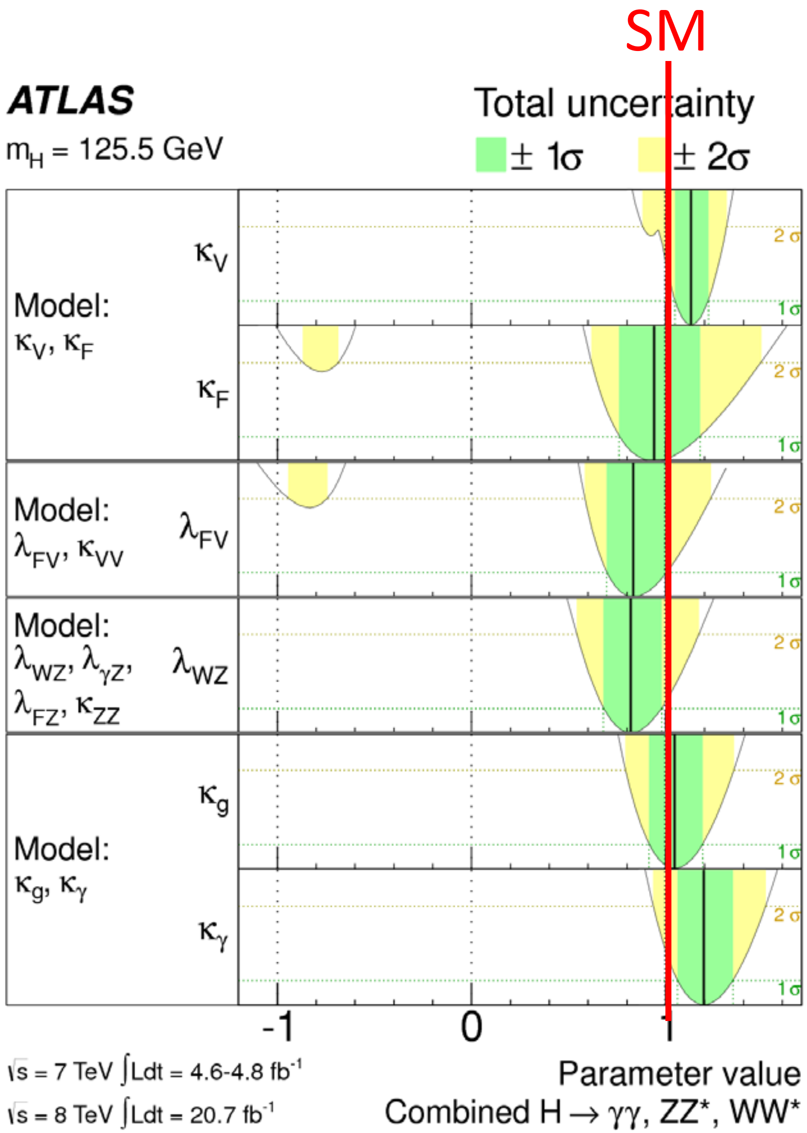
assuming there is no new production processes.

κ_h^2 is the scale factor to the total Higgs decay width

$$\kappa_h^2 = \sum_x \kappa_x^2 \cdot BR(h \to xx) \xrightarrow{\text{No BSM decays}} \kappa_h^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(h \to xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_h^2 = \sum_x \kappa_x^2 \cdot \frac{BR_{SM}(h \to xx)}{1 - BR_{new}}$$

Summary of Coupling Fits



Coupling parameters are determined with precisions ~10%.

Fits to different models are not independent, they often represent different parameterizations of the same information with varying assumptions.

The bottom line is that the data is consistent with the SM expectation at ~10% level.

Expected Coupling Deviations

Typical effect on coupling from heavy state (or new physics scale) M:

$$\boxed{\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 6\% \text{ @ } M \sim 1 \text{ TeV}}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

Typical sizes of coupling modification from some selected BSM models

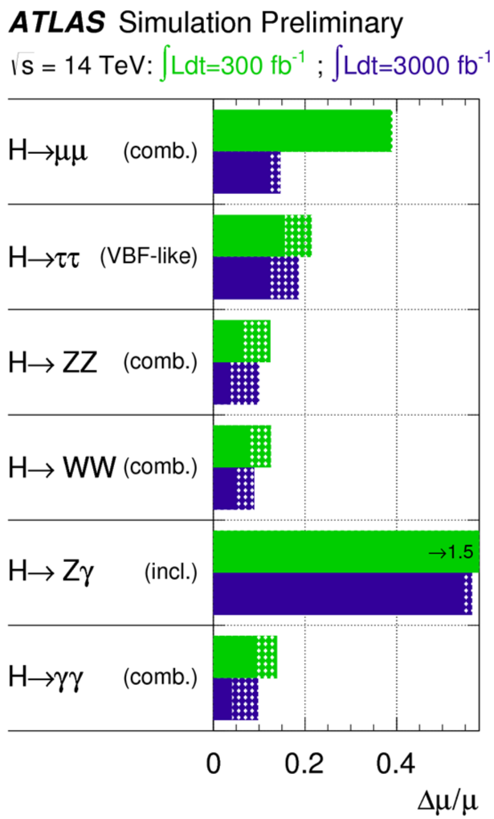
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Snowmass Higgs report, arXiv:1310.8361

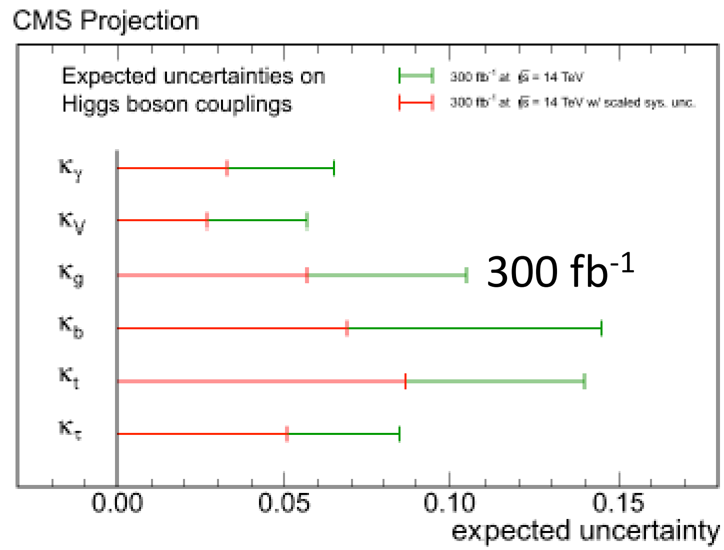
The precisions of the current coupling fits are insensitive to new physics at TeV scale…

Coupling Projections

Many studies done for US Snowmass process, Europe ECFA studies.



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Even with the projected precisions at HL-LHC, the couplings are not expected to be constrained better than ~ 5%.

SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi, S) = \left\{\mu^2 \phi^\dagger \phi + \lambda\left(\phi^\dagger \phi\right)^2\right\} + \left\{m_S^2 S^2 + \rho S^4\right\} + \kappa\left(\phi^\dagger \phi\right) S^2$$

Interesting phenomenology depends on whether $\langle S \rangle = 0$.

If $\langle S \rangle \neq 0$, in general the singlet scalar and the "SM" Higgs boson can mix to form two mass eigenstates: $(h,\ H)$ assuming $h = h(125)$:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} \begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

and new decay $H \to hh$ opens up if kinematically allowed.

If $\langle S \rangle = 0$, there will be no mixing and the physical scalar $\boxed{S}$ can be stable and is therefore a dark matter candidate.

SM + Singlet

Scenario 1: *h(125)* is the heavier one

If $m_s < m_h/2$, then $h \to ss$ decay opens up. If there is no mixing, a stable s will lead to $h \to ss \to$ invisible decay.

Otherwise $s \to f\bar{f} \Rightarrow$ similar final states as $h \to aa \to f\bar{f}\, f^{'}\bar{f}^{'}$.

Scenario 2: *h(125)* is the lighter one

H is the heavier one. Assuming mixing, h and H have similar decay mode $\Rightarrow$ "SM-like" high mass searches such as $H \to WW, ZZ$.

If $m_h < m_H/2$, the decay $H \to hh$ opens up $\Rightarrow$ Higgs pair production.

The coupling measurements can constrain the model which are described by 3 additional parameters:

- $\cos\theta$: mixing angle,
- $m_{s/H}$: mass of the other Higgs,
- BR_{new}: $\mathrm{BR}(H \to hh)$ or $\mathrm{BR}(h \to ss)$

Constraints on the Heavy Higgs

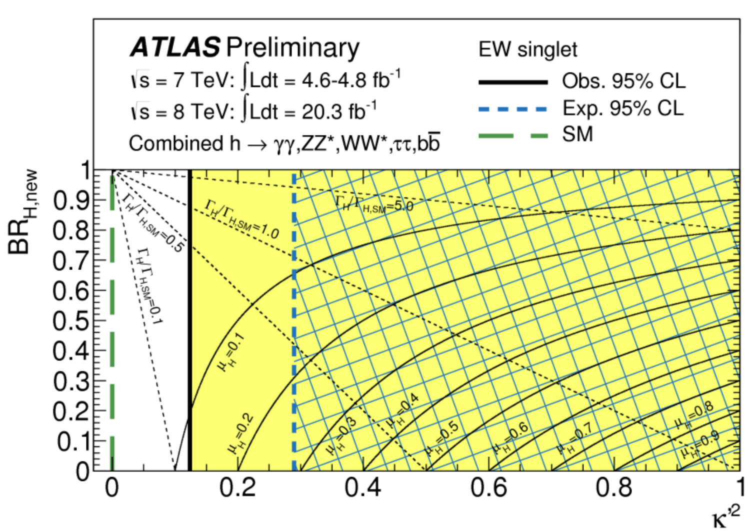
The mixing of H_{SM} and S leads to the modifications $\left(\kappa^2 = \cos^2\theta \text{ and } \kappa'^2 = \sin^2\theta\right)$

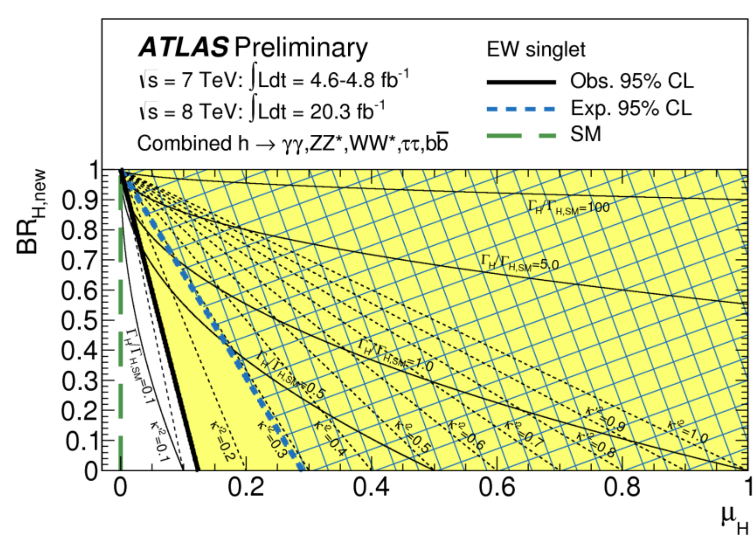
$$\sigma_h = \kappa^2 \times \sigma_h^{SM}, \qquad \Gamma_h = \kappa^2 \times \Gamma_h^{SM}, \qquad \mathrm{BR}_h = BR_h^{SM},$$

$$\sigma_H = \kappa'^2 \times \sigma_H^{SM}, \qquad \Gamma_H = \frac{\kappa'^2}{1 - BR_{new}} \times \Gamma_H^{SM}, \qquad \mathrm{BR}_H = \left(1 - BR_{new}\right) \times BR_H^{SM}$$

The measurement of the light Higgs boson can constrain the heavy Higgs boson:

$$\mu_h = \frac{(\sigma \times BR)_h}{(\sigma \times BR)_h^{SM}} = \kappa^2 \quad \Rightarrow \quad \mu_H = \frac{(\sigma \times BR)_H}{(\sigma \times BR)_H^{SM}} = \kappa'^2 \left(1 - BR_{new}\right) = \left(1 - \mu_h\right)\left(1 - BR_{new}\right)$$





independent of the mass of the heavy Higgs boson m_H.

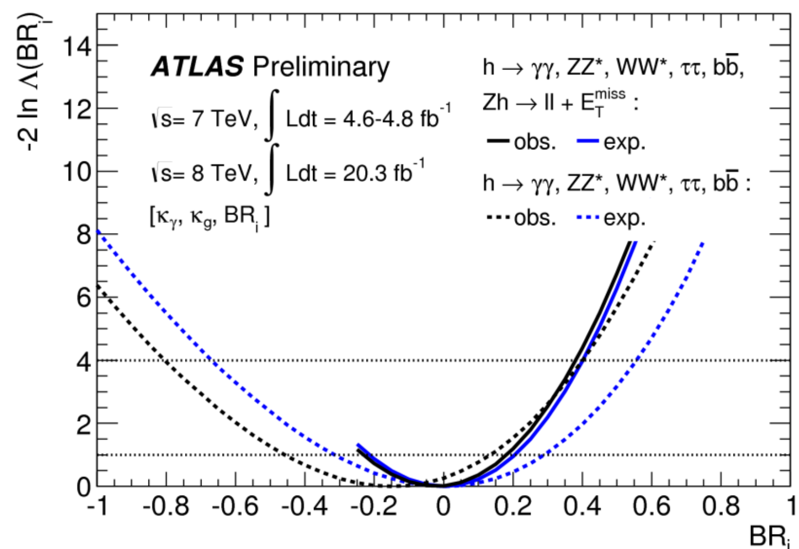
BR_{new} from Coupling Fits

Higgs could have decays that are not accounted for in SM. The decays do not have to be invisible. They could be decays not detectable at LHC.
$\Rightarrow$ modified total Higgs decay width and therefore BRs of other decays, effectively leave the total decay width free.

$$\Gamma_h = \Gamma_h^{SM} \times \frac{\kappa_h^2}{1 - BR_{new}}, \quad BR(h \to xx) = BR_{SM}(h \to xx) \times (1 - BR_{new}) \cdot \frac{\kappa_x^2}{\kappa_h^2}$$

A model allows for potential new physics in vertex loops and additional decays

$$\boxed{\kappa_\gamma, \ \kappa_g, \ BR_{new}}$$



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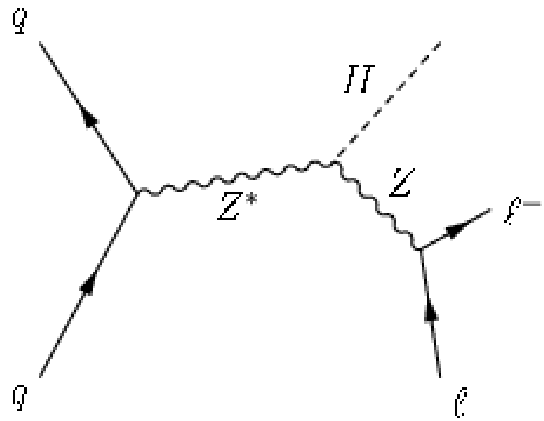
$BR_{new} < 0.41$ (0.55) @ 95% CL
($BR_{inv} < 0.37$ (0.39) combining with $Z + \not{E}_T$ search)

Significant room for potential exotic decays

Search for ZH with Z→$\ell\ell$ and H→invisible



Assuming the SM ZH production, searching for H→invisible decays.

Signature:

dilepton+MET

Main backgrounds:

diboson and top

Two oppositely-charged leptons

e^+e^- or $\mu^+\mu^-$:

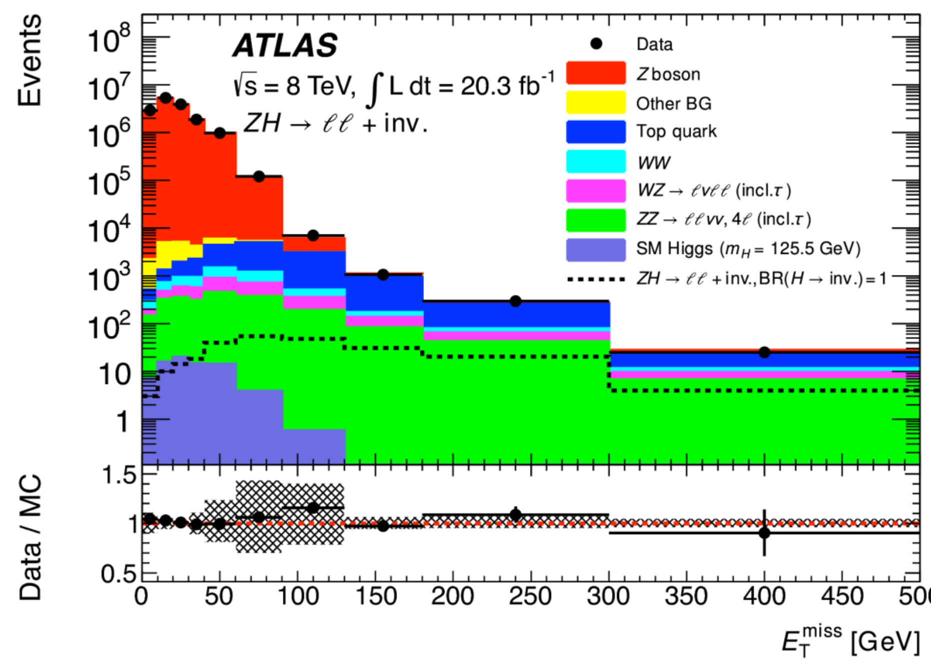
$p_T > 20$ GeV for each lepton

and $76 < m_{\ell\ell} < 106$ GeV

Veto events if having

a 3[rd] lepton with $p_T > 7$ GeV,

jets with $p_T > 20$ GeV and $|\eta| < 2.5$

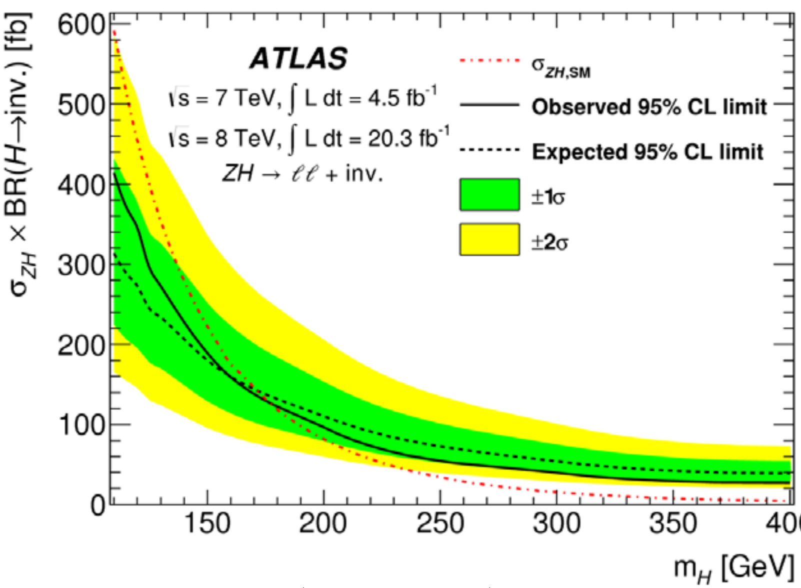


ATLAS: arXiv/1402.3244

Search for ZH with Z→ℓℓ and H→invisible

Angular correlations to further reduce backgrounds. No excess over background.

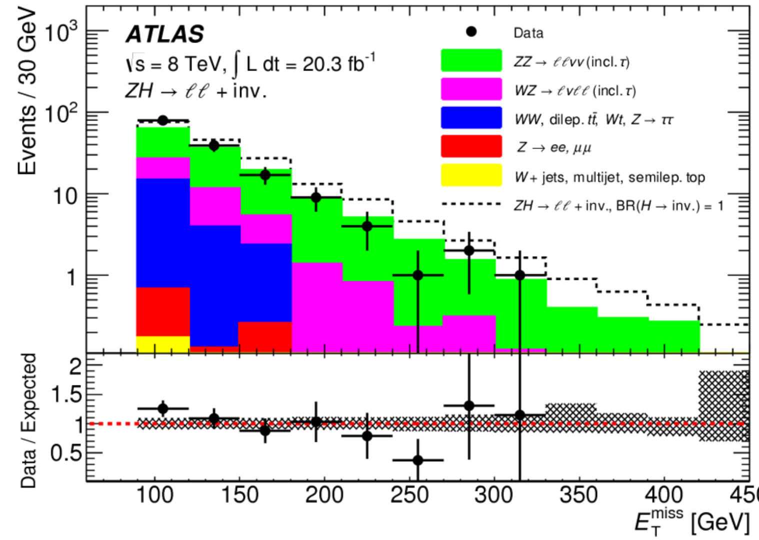
Fit the $\not{E}_T$ distribution to set the upper limit on $\sigma_{ZH} \times \mathrm{BR}(H \to inv)$

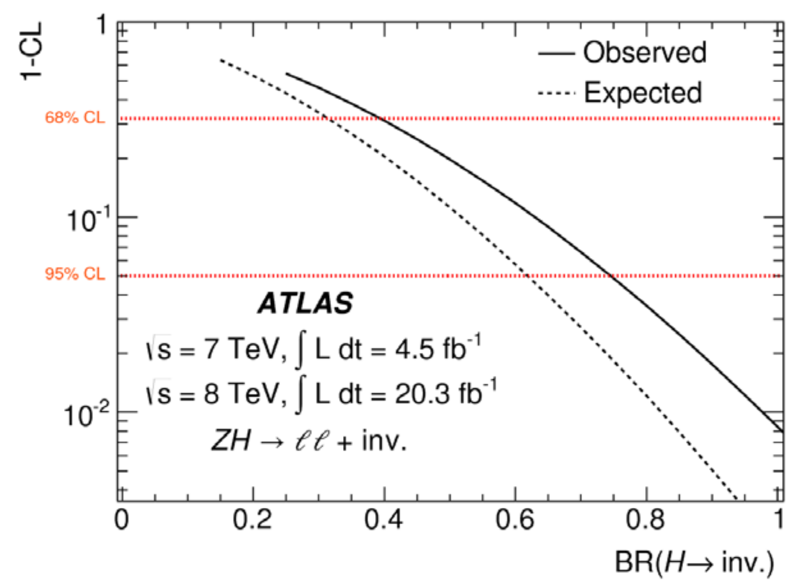


The observed (expected) limits on $\mathrm{BR}(H \to inv)$ at $m_H = 125.5$ GeV is:

75% (62%) at 95% CL

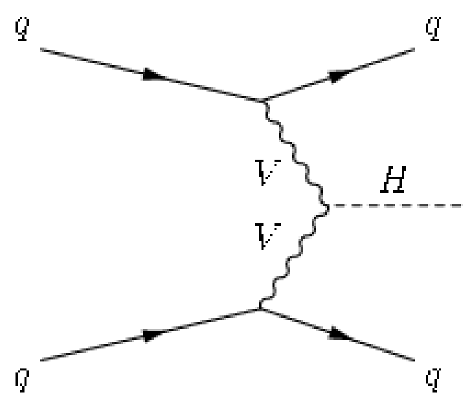
CMS analysis: 83% (86%)





ATLAS: arXiv/1402.3244

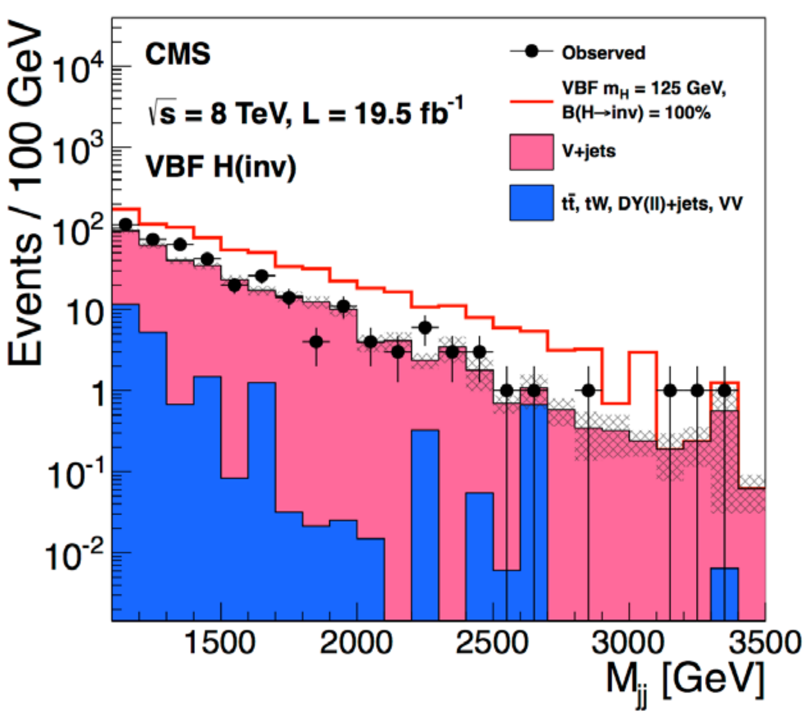
Search for VBF H with H→invisible

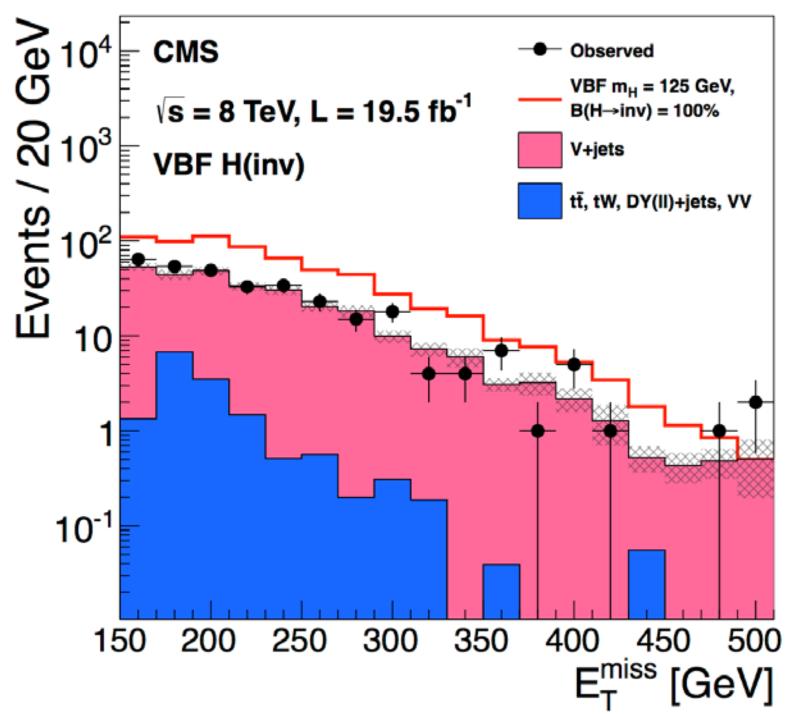


Jet selection: $p_T > 50$ GeV within $|\eta| < 4.7$

Tagging jets selection:
$\eta_1 \cdot \eta_2 < 0$, $\Delta\eta_{jj} > 4.2$, $\Delta\phi_{jj} < 1.0$ and $M_{jj} > 1100$ GeV

$\not{E}_T > 130$ GeV and veto events with
reconstructed e and μ with $p_T > 10$ GeV,
any jet with $p_T > 30$ GeV between tagged jets





CMS: arXiv/1404.1344

Search for H→invisible decays

CMS: arXiv/1404.1344

The observed (expected) 95% CL limit:

$$BR(H \to inv) < 65\% \ (49\%)$$

at $m_H = 125$ GeV.

CMS has combined searches of

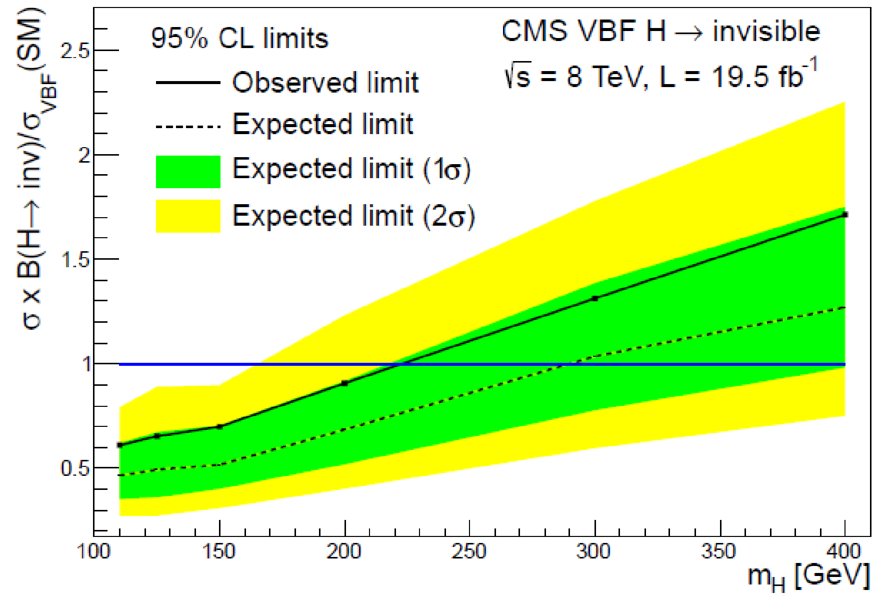
$\mathrm{ZH} \to \ell\ell/bb$ inv

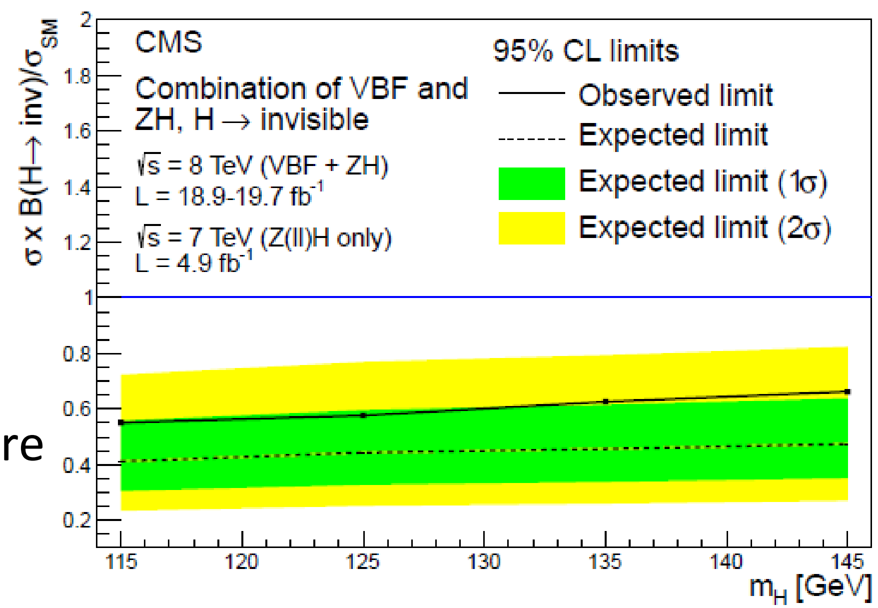
VBF $\mathrm{H} \to$ inv

m_{H} (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(\mathrm{H} \to \mathrm{inv})/\sigma_{\mathrm{SM}}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

At $m_H = 125$ GeV, the combined limits are

$$BR(H \to inv) < 58\% \ (44\%)$$





Dark Matter Interpretation

The constraints on $\mathrm{BR}(h \to inv)$ can be turned into constraints on Γ_{inv}

$$\Gamma_{inv} = \frac{BR(h \to inv)}{1 - BR(h \to inv)} \Gamma_h^{SM}$$

$\Rightarrow$ constrain dark-matter and nucleon interactions

$$\Gamma^{\mathrm{inv}}(h \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128 \pi m_h}$$

$$\Gamma^{\mathrm{inv}}(h \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64 \pi}$$

$$\Gamma^{\mathrm{inv}}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512 \pi m_V^4} \left(1 - 4 \frac{m_V^2}{m_h^2} + 12 \frac{m_V^4}{m_h^4} \right).$$

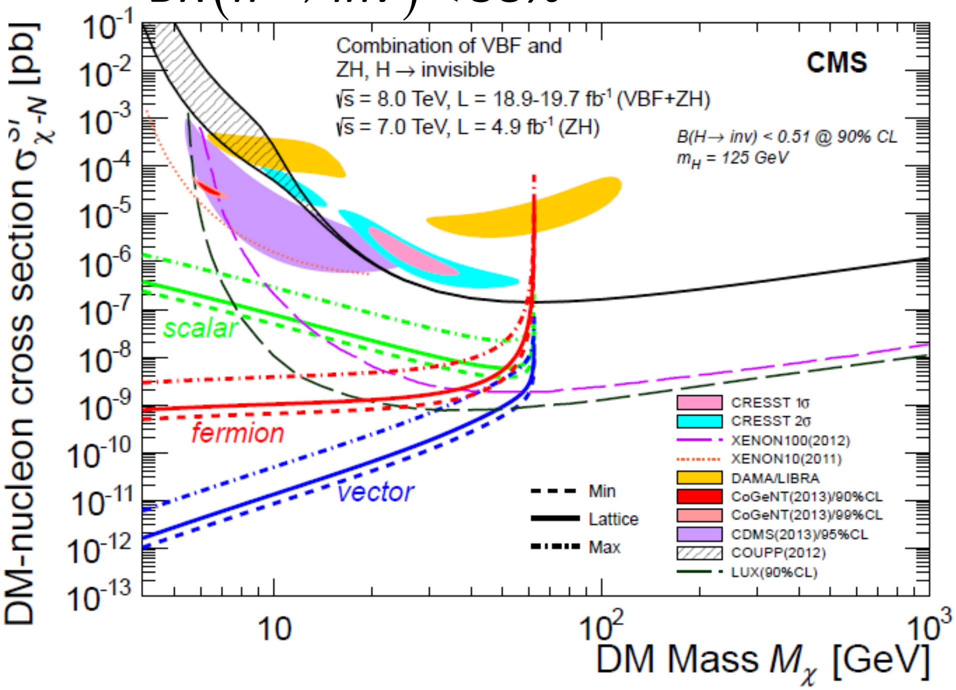
$$\Downarrow$$

$$\sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_S + m_N)^2}$$

$$\sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4 \pi m_h^4 (m_f + m_N)^2}$$

$$\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_V + m_N)^2},$$

$BR(h \to inv) < 58\%$



CMS: arXiv/1404.1344

2 Higgs Doublet Models (2HDM)

2HDM is one of the simplest extensions to the SM Higgs sector. Two Higgs SU(2) doublets are introduced. The most general tree-level Higgs potential of 2HDM has the form

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]$$
$$+\frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2+\frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)+\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+\left\{\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2+\left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right)+\lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right)+\text{h.c.}\right\}$$

It has free 10 parameters and leads to undesirable consequences:

- CP-violating Higgs interactions;
- Tree-level flavor changing neutral currents (FCNCs)

Both are severely constrained by experimental data.

New symmetries can be applied to remove these problems:

- all parameters are real $\Rightarrow$ CP conservation;
- soft-broken discrete Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$)
  $\Rightarrow$ $m_{12}^2 \neq 0$, $\lambda_6 = \lambda_7 = 0$ $\Rightarrow$ no FCNCs

$\Rightarrow$ 8 free real parameters

2 Higgs Doublet Models (2HDM)

These models result in 5 Higgs bosons after the symmetry breaking:

- two neutral CP-even scalars: h and H;
- one neutral CP-odd pseudoscalar: A;
- two charged H^+ and H^- scalars.

and are described by 8 free parameters (2 in SM), often chosen to be

5 mass parameters: m_h, m_H, m_A, $m_{H^\pm}$ and m_{12}^2

2 angular parameters: α and $\tan\beta$

(One more parameter is fixed by W boson mass: $\upsilon = 246$ GeV)

α: mixing parameter of two CP-even Higgs scalars;

$\tan\beta = \dfrac{\upsilon_2}{\upsilon_1}$: ratio of V.E.V. of the two Higgs doublets

2HDMs are classified into 4 types according to Higgs-Fermion couplings

Type	I	II	III	IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2
Also known as	"Fermiophobic"	MSSM-like	Lepton-specific	Flipped

2 Higgs Doublet Models

Coupling modifications relative to SM:

g/g_{SM}	I	II	III	IV
$h\ VV$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$h\ uu$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$h\ dd$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$h\ ee$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
$H\ VV$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
$H\ uu$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
$H\ dd$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
$H\ ee$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
$A\ VV$	0	0	0	0
$A\ uu$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
$A\ dd$	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
$A\ ee$	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Decoupling and Alignment Limits

Typically, the neutral Higgs bosons of 2HDMs have very different properties compared with the SM Higgs boson. However, SM-like Higgs boson can arise from 2HDMs in two ways

Decoupling limit

All but the lightest Higgs boson are heavy: $m_h \ll m_H, m_A, m_{H^\pm} \Rightarrow \boxed{h \approx H_{SM}}$

Integrating out the heavy states yields an effective 1 Higgs doublet theory.

Alignment limit

$$\sin(\beta-\alpha) \to 1$$
$$\cos(\beta-\alpha) \to 0$$
$$\Downarrow$$
$$\boxed{h \approx H_{SM}}$$

Vertex	Type II tree-level coupling factor	
$h\,VV$	$\sin(\beta-\alpha)$	$\longrightarrow 1$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\longrightarrow 1$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\longrightarrow 1$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\longrightarrow 1$

These relations hold true for all 2HDM types

$$g_{hVV} \Rightarrow g_{H_{SM}VV},\quad g_{htt} \Rightarrow g_{H_{SM}tt},\quad g_{hbb} \Rightarrow g_{H_{SM}bb},\quad g_{h\tau\tau} \Rightarrow g_{H_{SM}\tau\tau}$$

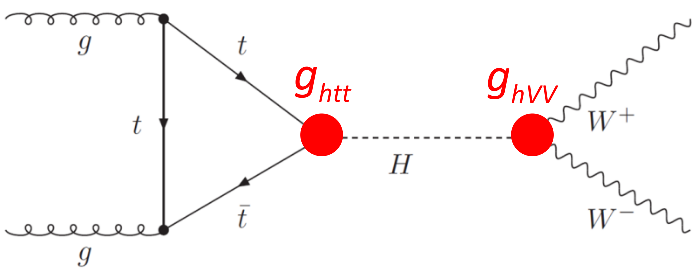
Indirect Constraints from Coupling Fits

Assuming no change in Higgs decay kinematics and no new production process, the measured rates of $h(125)$ can be turned into constraints on the two 2HDM parameters: α and β

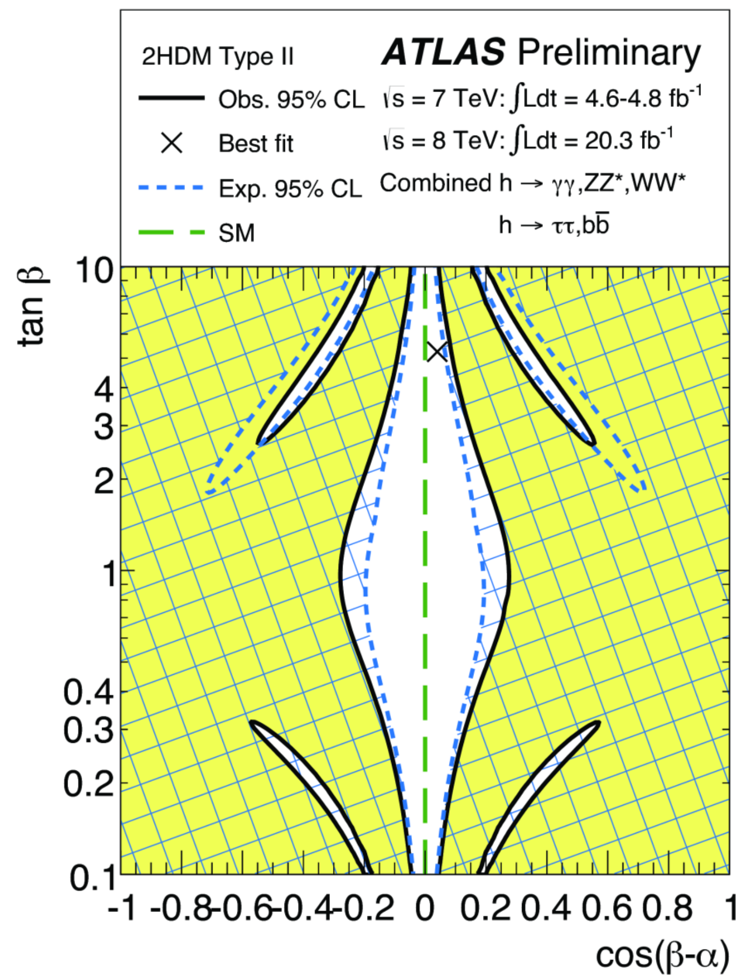
ATLAS-CONF-2014-010

Parametrized using $\tan\beta$ and $\sin(\beta-\alpha)$

Vertex	Type II tree-level coupling factor
$h\,VV$	$\sin(\beta-\alpha)$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$



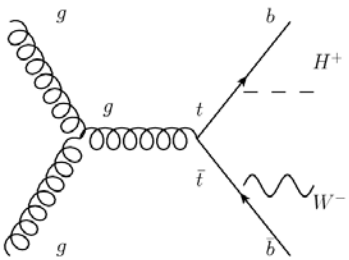
$$\frac{(\sigma\cdot BR)(gg\to H\to WW)}{\left[\sigma(gg\to H)\cdot BR(H\to WW)\right]_{SM}} \approx \left(\frac{g_{htt}}{g_{Htt}^{SM}}\right)^2 \times \left(\frac{g_{hVV}}{g_{hVV}^{SM}}\right)^2$$

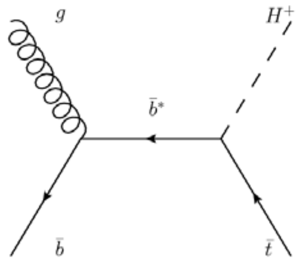


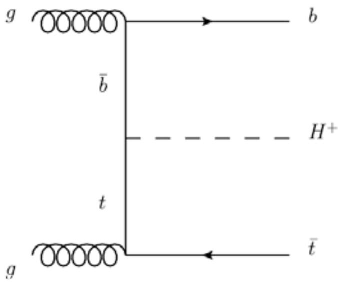
Charged Higgs Boson

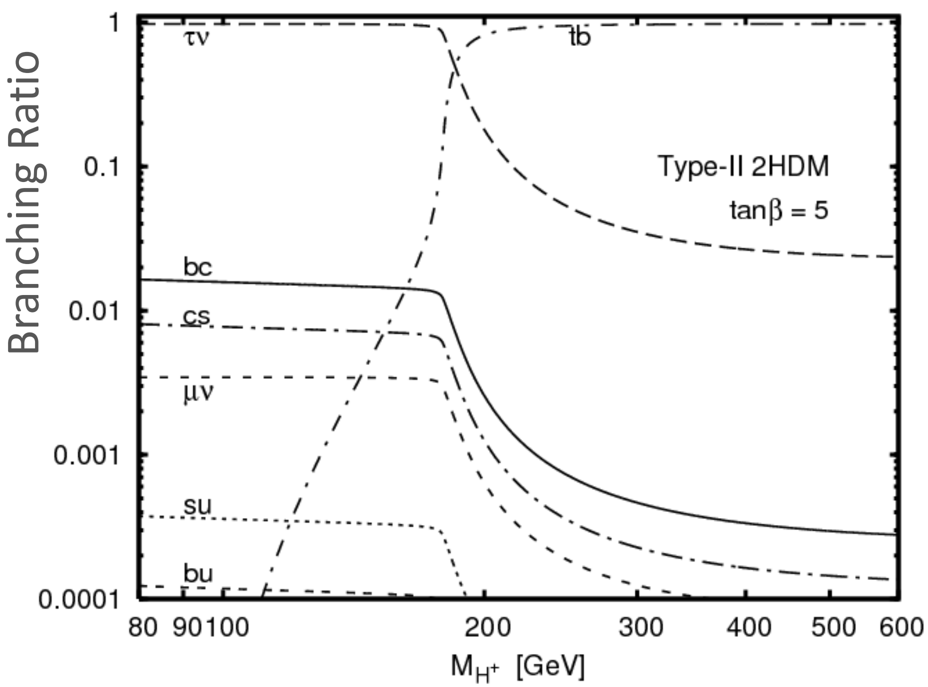
Two main production processes at the LHC:

- light H$^{\pm}$ ($m_{H^{\pm}} < m_t - m_b$): from top quark decay $t \to H^+ b$;
- heavy H$^{\pm}$ ($m_{H^{\pm}} > m_t$): in association with the top quark $tH^+(b)$









Similarly, two dominant decay modes depending on the mass. In much of the parameter space:

Light $H^{\pm}$ ($m_{H^{\pm}} < m_t$):

$$\mathrm{BR}\left(H^{\pm} \to \tau\nu\right) \sim 100\%$$

Heavy $H^{\pm}$ ($m_{H^{\pm}} > m_t + m_b$):

$$\mathrm{BR}\left(H^{\pm} \to tb\right) \sim 90\%$$

$$\mathrm{BR}\left(H^{\pm} \to \tau\nu\right) \sim 10\%$$

Charged Higgs Boson

Two major search signatures:

Light $H^{\pm}$: $pp \to tt \to (Wb)(Hb) \to (\ell \nu b)(\tau \nu b)$

Heavy $H^{\pm}$: $pp \to tH^{\pm} \to t(tb) \to ttb$

$\Rightarrow$ very similar to the SM $pp \to tt$ production

Search for τ excess or tb resonance in tt-like events. The challenge is to reduce and control tt background.

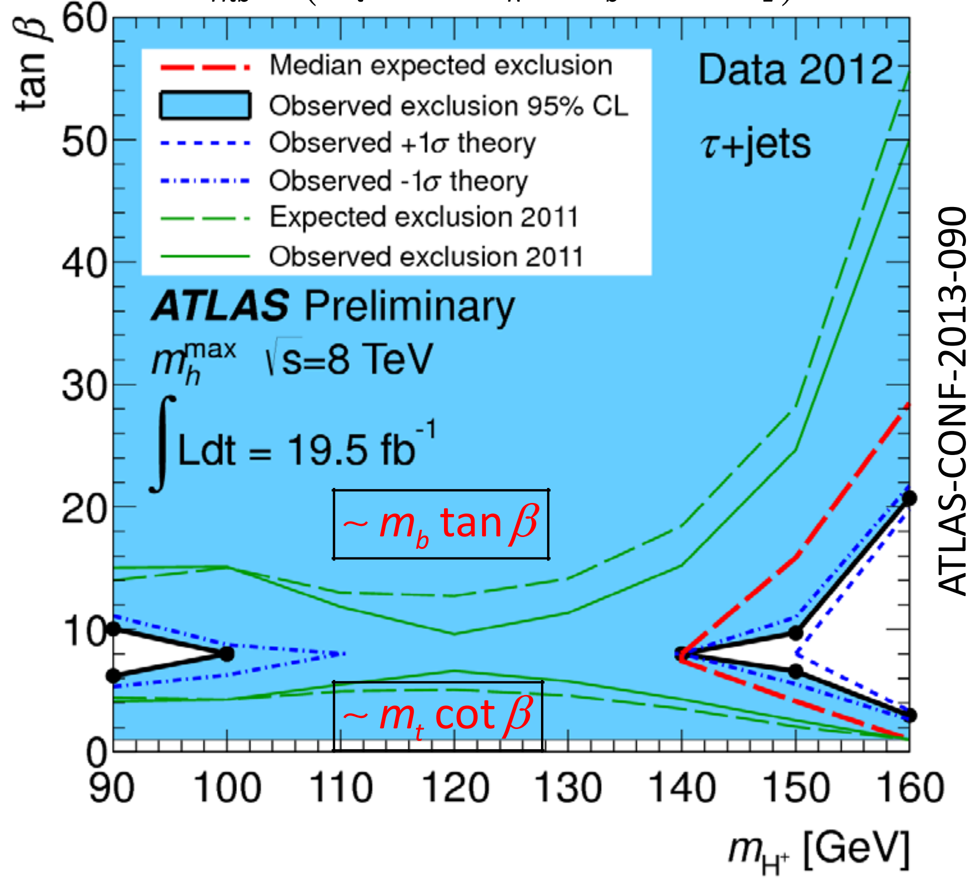
Light H$^{\pm}$:

stringent experimental constraints on most of the parameter space.

Heavy H$^{\pm}$:

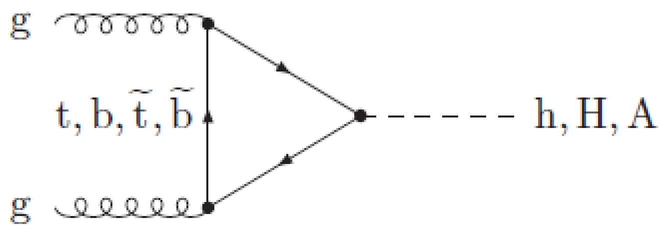
only limited parameter space has been explored.

$g_{Htb} \sim (m_t \cot\beta \, P_R + m_b \tan\beta \, P_L)$

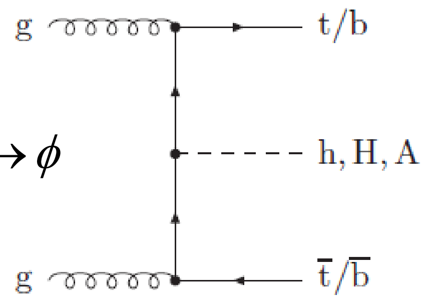


Heavy Neutral Higgs Boson

$gg \to \phi$



$bb \to \phi$



$\phi = A,\ H;\quad g_{\phi bb} \propto \tan\beta,\ \ g_{\phi tt} \propto \cot\beta$

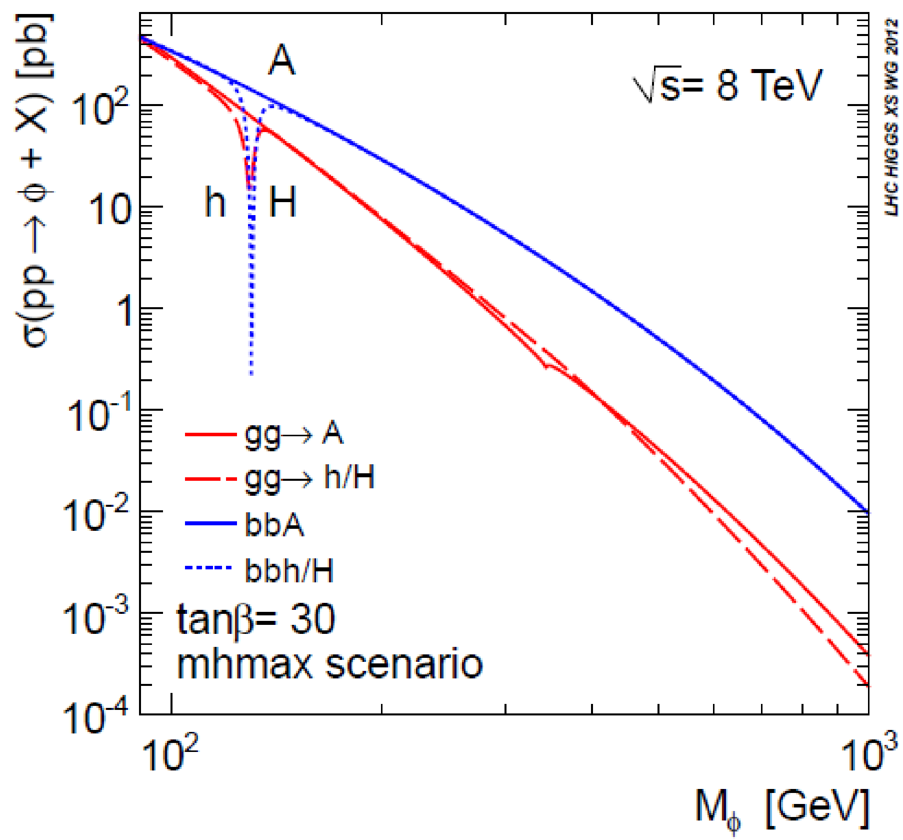
Again two main production processes:

$gg \to \phi$ dominates for $\tan\beta \sim 1$

$bb \to \phi$ dominates for $\tan\beta \gg 1$

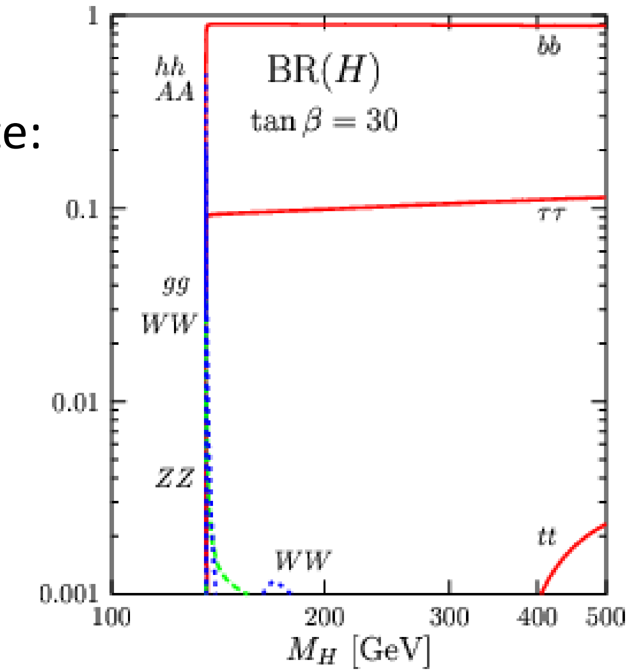
The heavy CP-even Higgs boson *H* has similar decay modes as the SM Higgs boson with modified branching ratios

The CP-odd Higgs boson *A* has no *AVV* coupling at tree-level, thus decays to fermion pairs primarily.

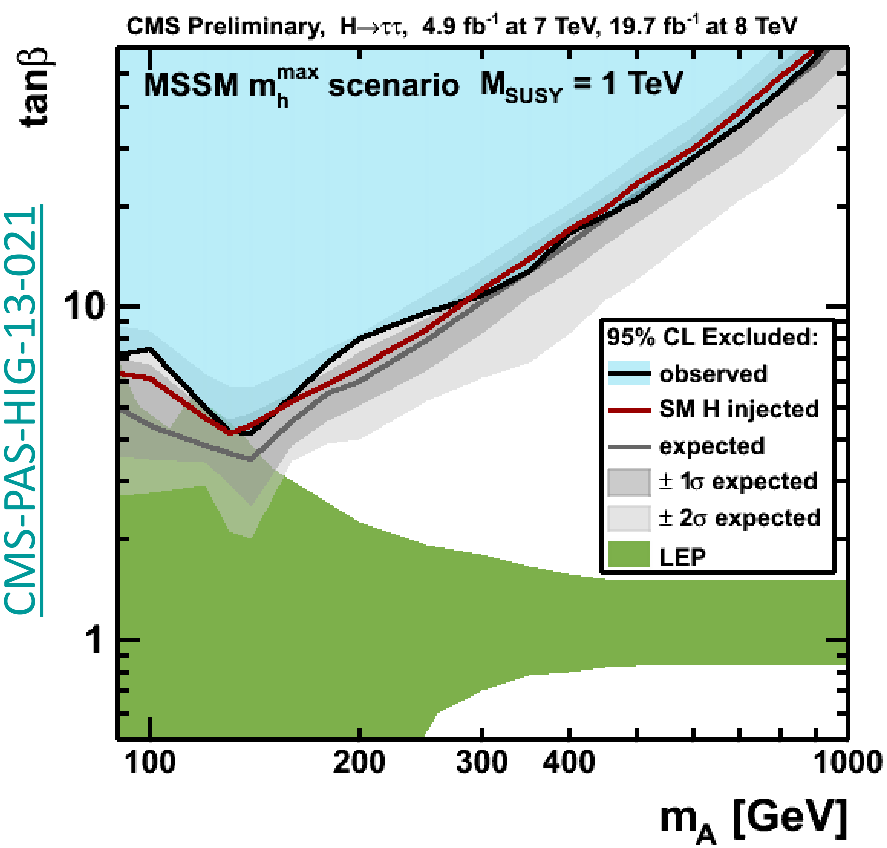


Heavy Neutral Higgs Boson

At $\tan\beta \gg 1$, $\phi(H,A) \to \tau\tau$ and bb decays dominate:
$\mathrm{BR}(\phi \to bb) \sim 90\%$, $\mathrm{BR}(\phi \to \tau\tau) \sim 10\%$



With a leptonic signature, $\phi \to bb$ search is difficult, particularly at low ϕ mass.



CMS-PAS-HIG-13-021

$\phi \to \tau\tau$ search has been the focus at the LHC. Keys to the search:

- identification of τ leptons through $\tau \to e/\mu + \nu$'s and $\tau \to h + \nu$'s decays

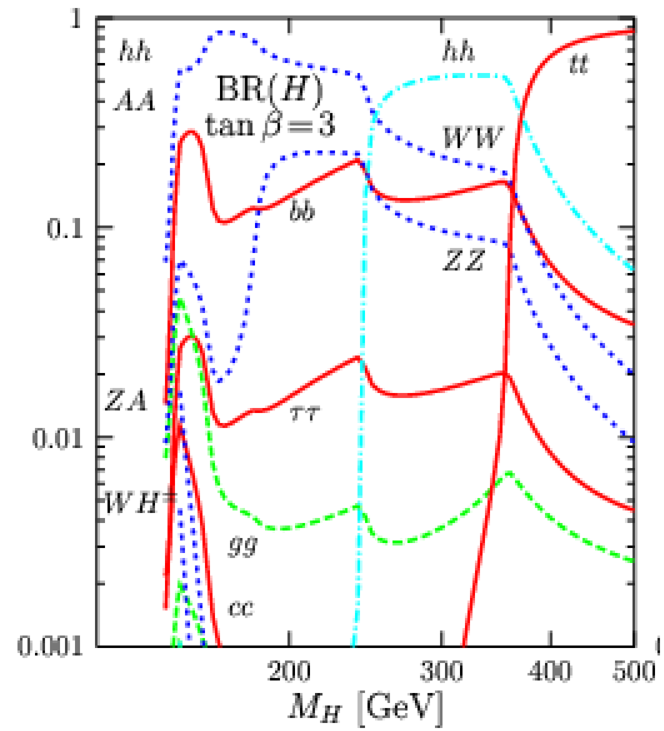
- reconstruction of the $\tau\tau$ invariant mass using methods such as missing mass calculator (MMC). Typical resolution

$$\sigma(m_{\tau\tau})/m_{\tau\tau} \sim 10-20\%$$

Heavy Neutral Higgs Boson

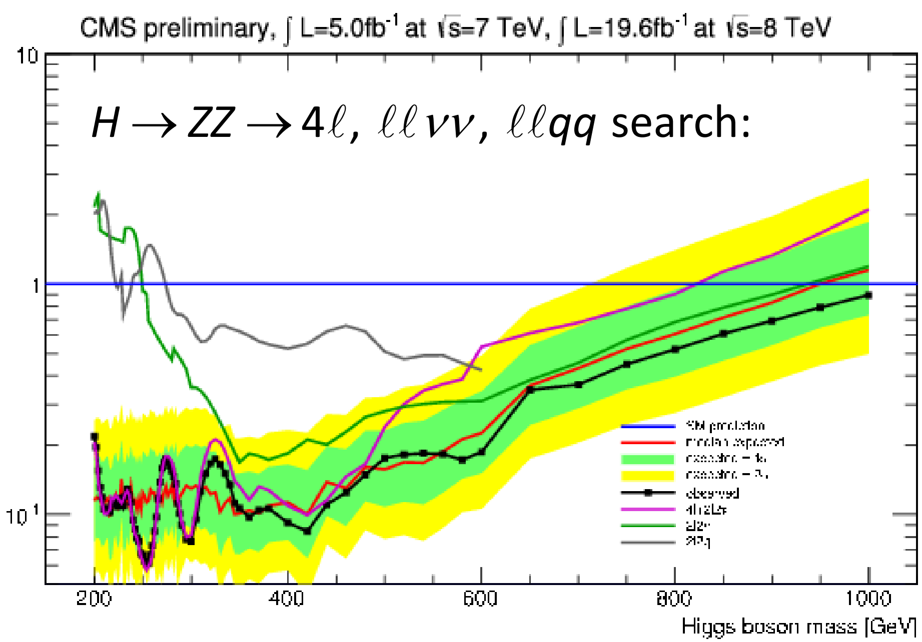
For small tanβ values ~ 1, a diverse of decay modes are available:

$m_H < 2m_t$: sizable $H \to WW, ZZ$ decays
$m_H > 2m_t$: $H/A \to tt$ decay dominates



H → WW, ZZ decays have been searched within the framework of SM, taking into account the effects of large width and inteference.

CMS-PAS-HIG-12-024

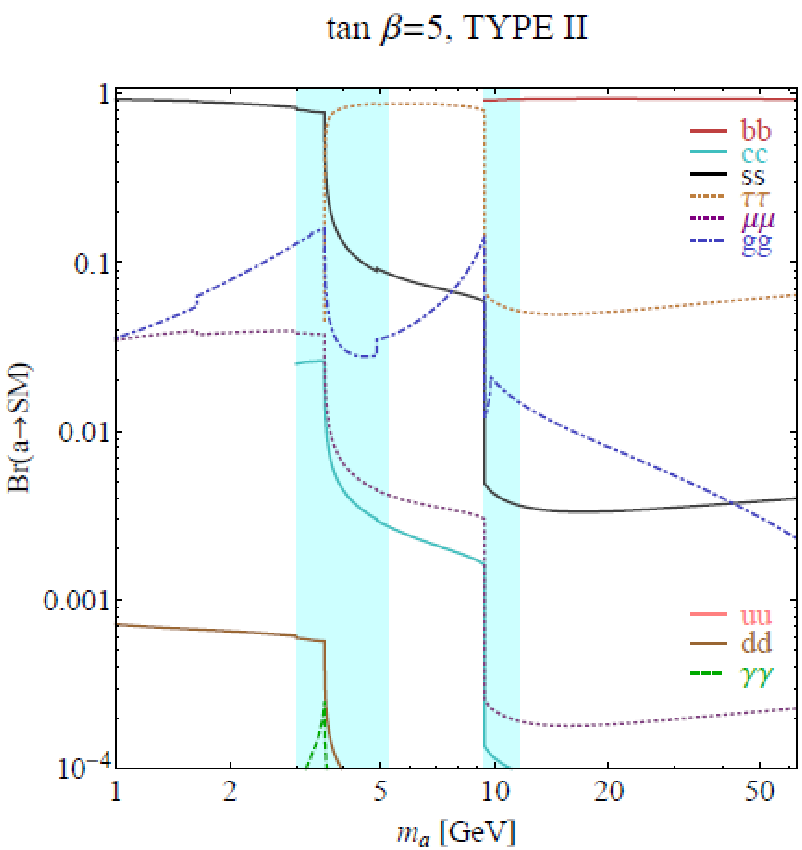


Such a Higgs boson with SM couplings is excluded with its mass up to ~ 1 TeV.

But the couplings in 2HDMs are significantly reduced!

2HDM + Singlet

The 2 Higgs doublet model (2HDM) can also be extended by including a singlet, such as the next-minimal supersymmetric standard model (NMSSM). These models generally predict the existence a light pseudoscalar (a) boson. For a large parameter space, $h \to aa$ decay can lead to interesting signatures.



Curtin et al., arXiv:1312.4992

Dominant/interesting decay modes are:

Low mass: $a \to ee, \mu\mu$

"lepton-jets" analysis

$h \to aa \to 4\mu$

Medium mass (3.5-10 GeV): a $\to \tau\tau$

$h \to aa \to 4\tau$ hard!

$h \to aa \to 2\mu 2\tau$ doable

$h \to aa \to 4\mu$

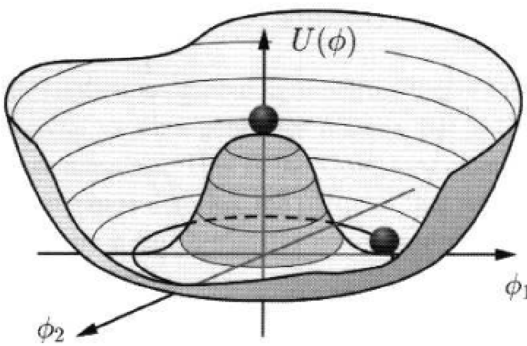
High mass (>10 GeV): $a \to bb$

$h \to aa \to 4b$ hard !

$h \to aa \to bb\tau\tau / bb\mu\mu$ hopeful ?

Higgs Pair Production

Higgs pair productions, both non-resonant and resonant, will be one of the major research areas in the upcoming LHC runs. It is an important final state for both SM physics and BSM phenomena.



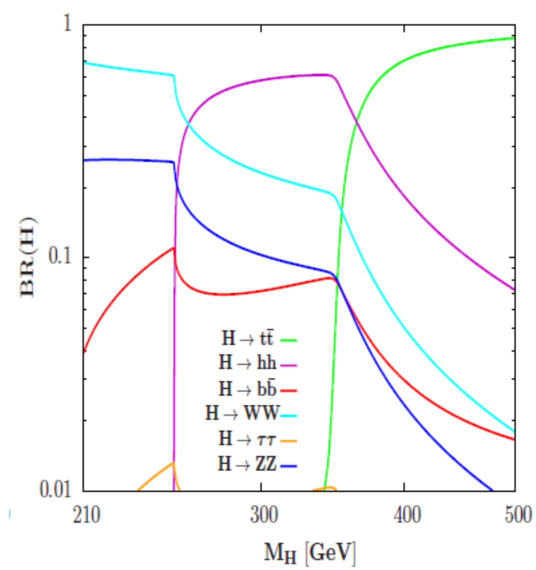
Non-resonant production

offers a direct way to measure the Higgs potential, vital in validating the SM and even our existence

Resonant production

Expected from many extensions of the SM:

2 Higgs doublet models (2HDM);
SM or 2HDM + singlet;
Extra dimensions, …

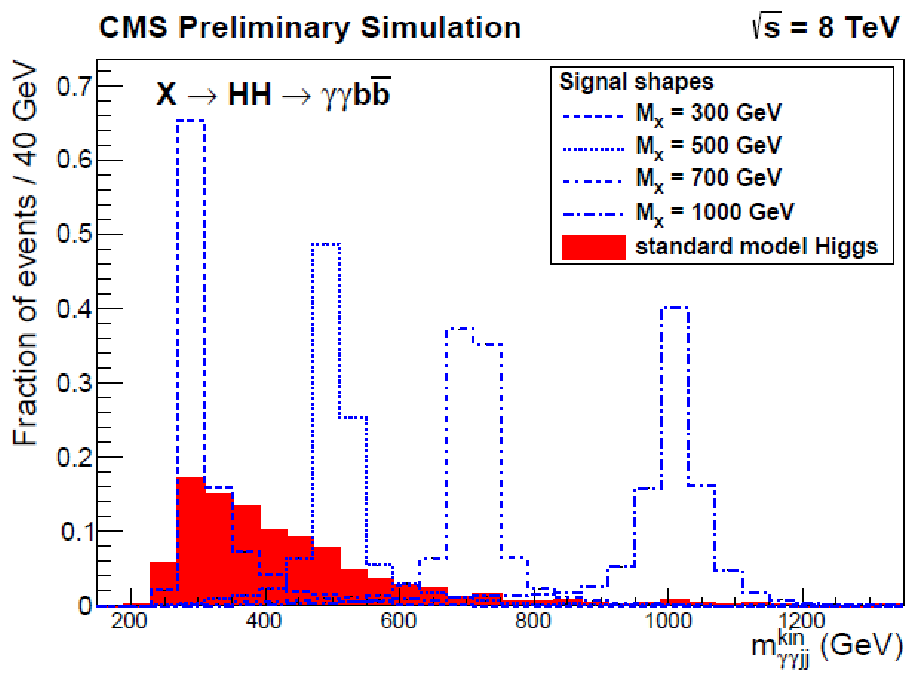


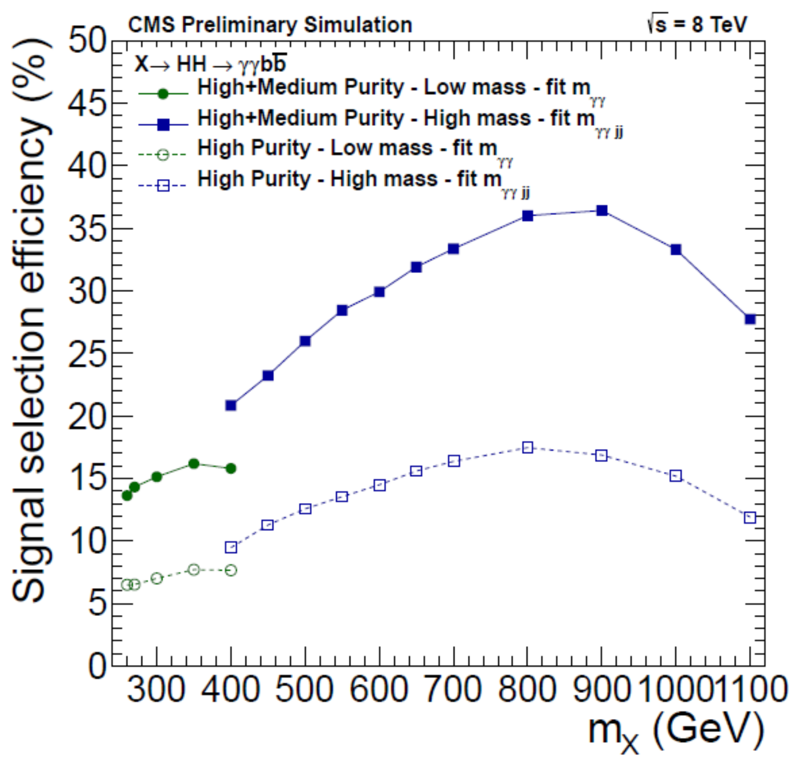
Search for $X \to hh \to bb\gamma\gamma$

[CMS-PAS-HIG-13-031](CMS-PAS-HIG-13-031)

Clear signature with two photons and two b-tagged jets and resonances in 3 mass distributions: $m_{\gamma\gamma}$, m_{jj} , $m_{\gamma\gamma jj}$.

A constant *width of 1 GeV* is assumed for the resonances that are simulated using MadGraph5.





Optimized for two mass regions:

Low mass: $260 \leq m_X \leq 400$ GeV

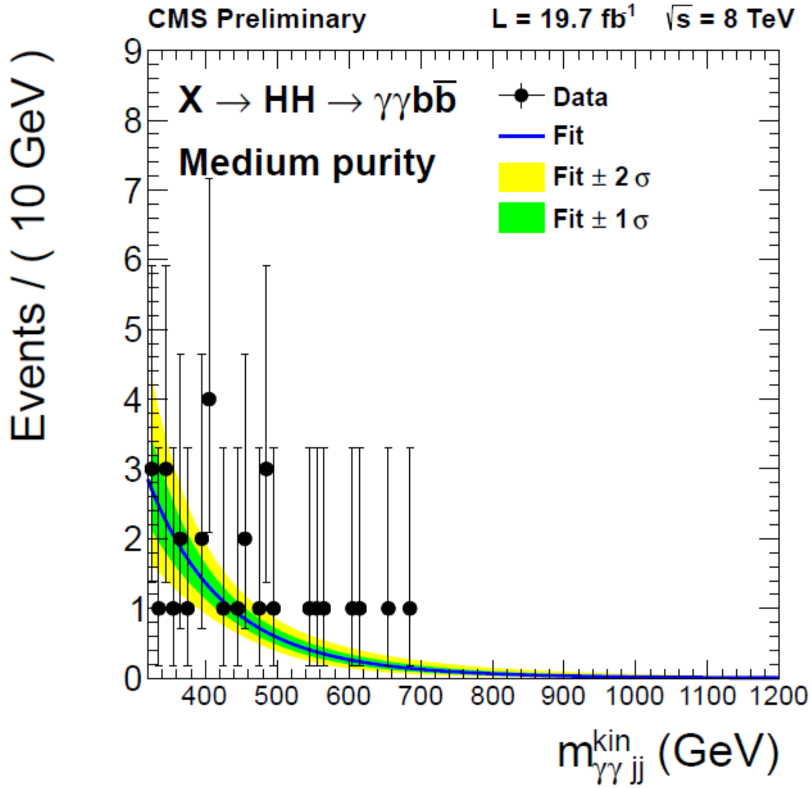
High mass: $400 \leq m_X \leq 1100$ GeV

Jet merging led to efficiency loss for m_X above ~ 800 GeV.

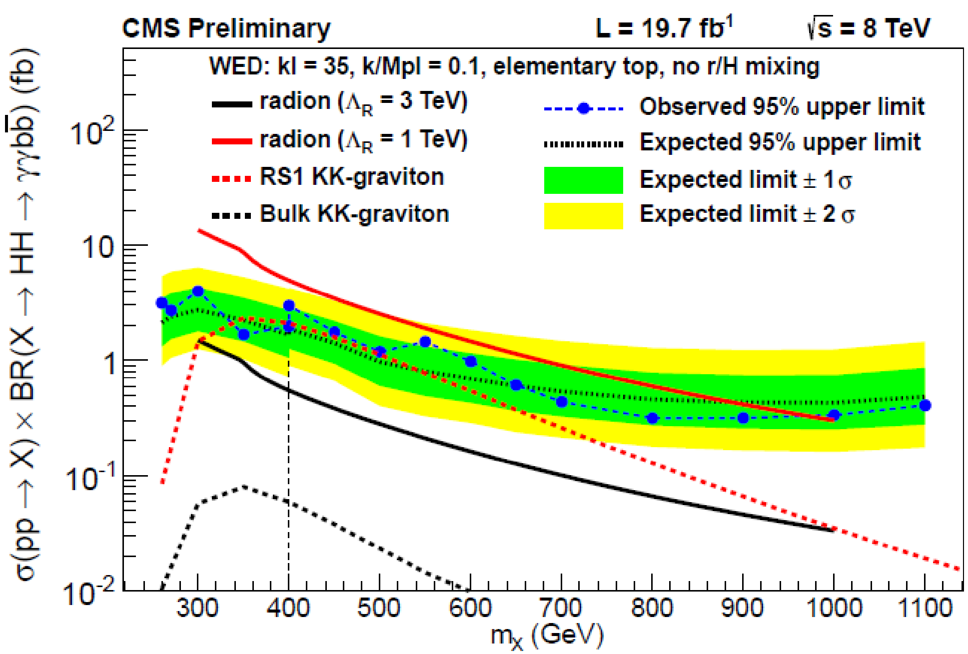
Search for $X \to hh \to bb\gamma\gamma$

Two signal categories:
- medium purity (1 b-tagged jet)
- high purity (2 b-tagged jets)

Fit either the $m_{\gamma\gamma}$ (low mass) or $m_{\gamma\gamma jj}$ (high mass) distribution to extract the $X \to hh$ signal



CMS-PAS-HIG-13-031



Compare to benchmark radion and KK-graviton models

More a proof of principle for now, is getting interesting...

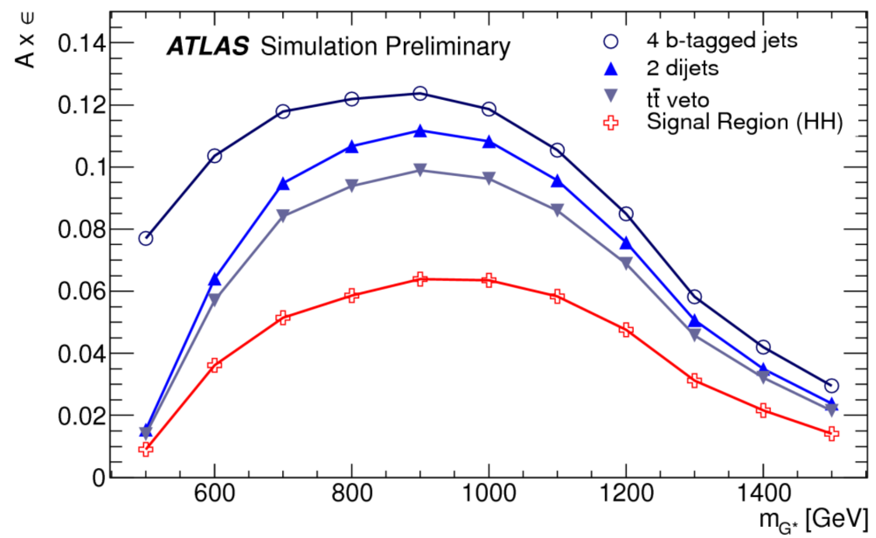
Search for $X \to hh \to 4b$

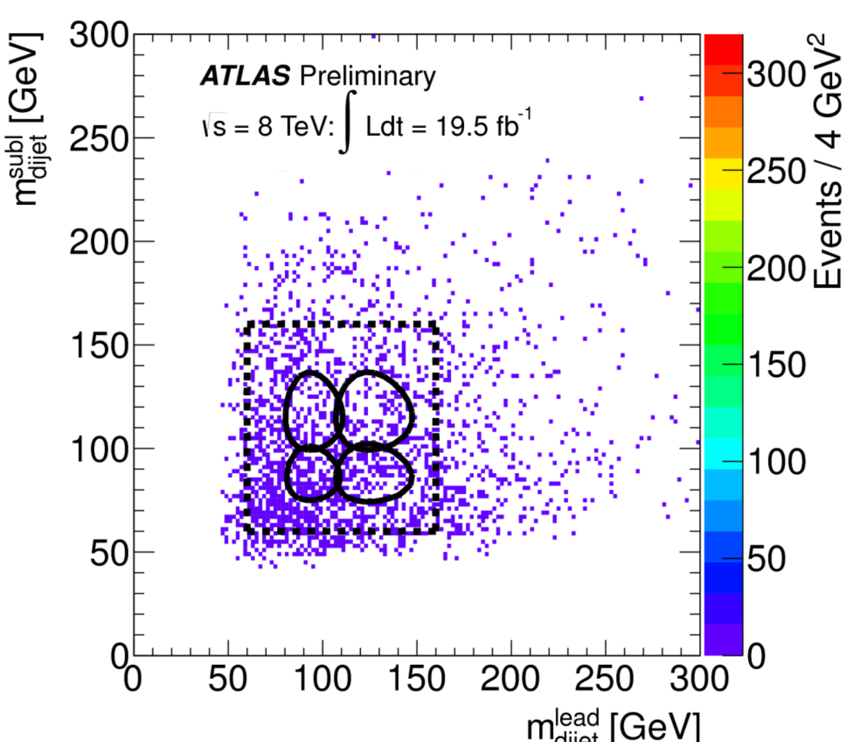
ATLAS-CONF-2014-005

RS graviton with $m_{G*} = 500 - 1500$ GeV and $\kappa / \bar{M}_{Pl} = 1.0$ as the signal model

Trigger: a combination of high E_T jet triggers w/o b-tagging at HLT, $> 99\%$ efficient for $G^* \to hh \to 4b$ stuided.

Offline: two pairs of b-jets with $p_T^j > 40$ GeV and $p_T^{jj} > 200$ GeV, m_{jj} consistent with the mass of the Higgs boson.



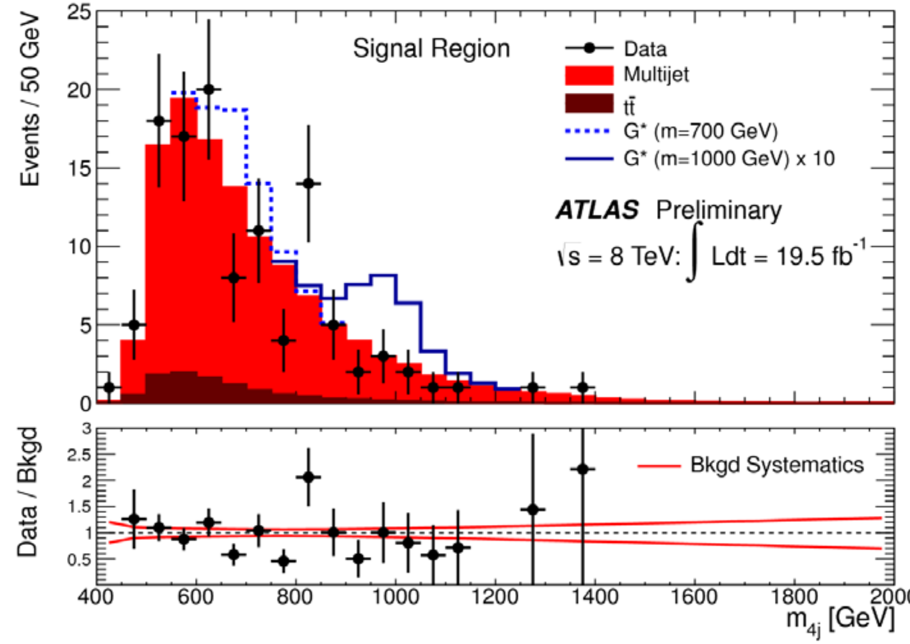


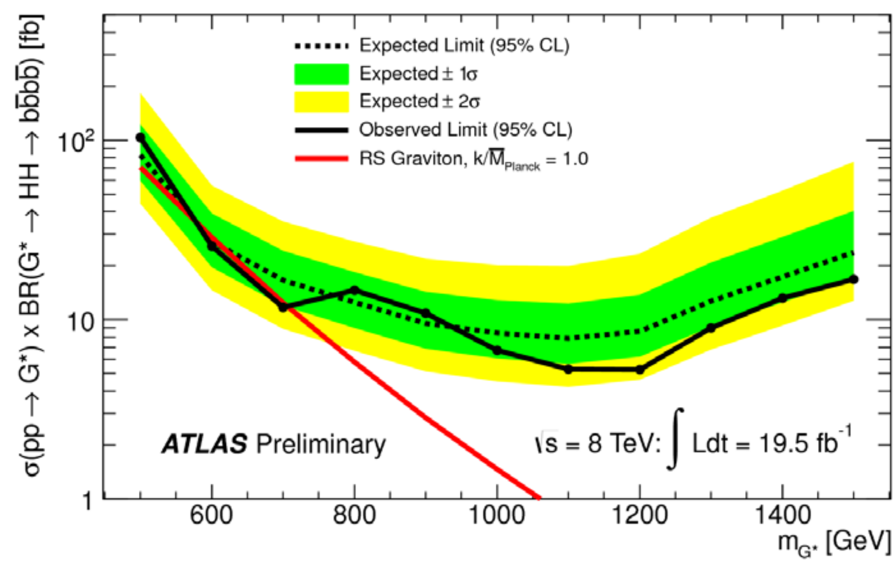
Efficiency loss at high mass due to jet merging.

χ^2 kinematic fitting to reduce ZZ, ZH and top backgrounds

Search for $X \rightarrow hh \rightarrow 4b$

Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114
G^* (m_{G^*} = 500 GeV)	12.5 ± 0.4
G^* (m_{G^*} = 700 GeV)	12.5 ± 0.2

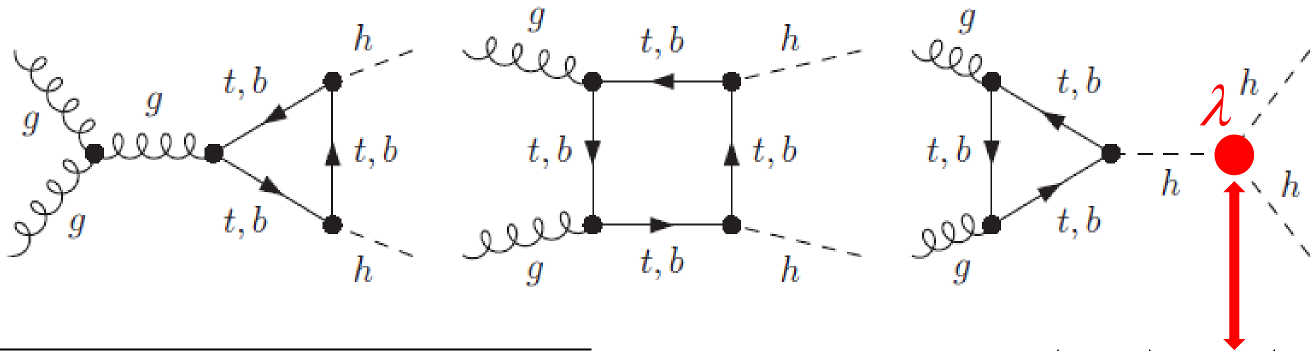




Background dominated by multijets and estimated using data sidebands.

Sensitivity degrades at high mass due to jet merging and systematics.

Higgs Self-Coupling



$\sigma(pp \to hh)$@14 TeV	40.2 fb (NNLO)

$$V(\phi) = \mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

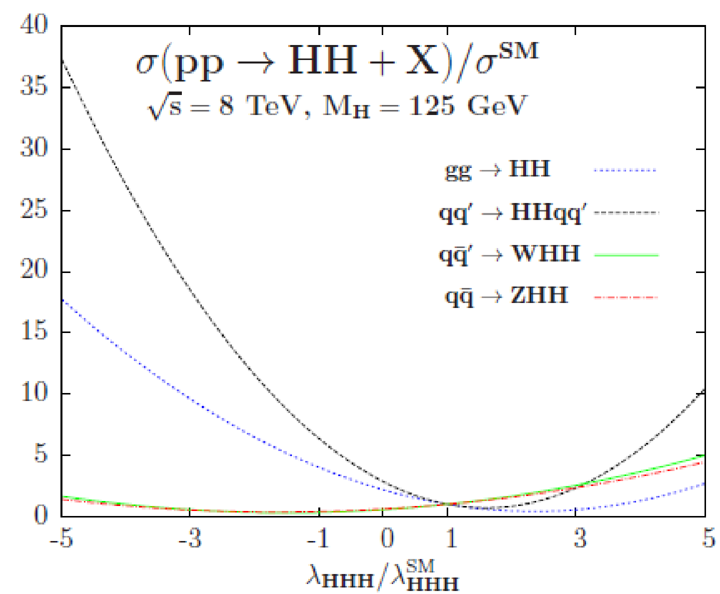
Events in 3000 fb^{-1}	
$hh \to bb\gamma\gamma$	320
$hh \to bb\tau\tau$	8,800
$hh \to bbWW$	29,900
$hh \to bbbb$	40,200

Small cross section and the destructive interference between self- and non-self-coupling diagrams.

bb$\gamma\gamma$ appears to have the best sensitivity, *bb*$\tau\tau$ should help too, *bbWW* and *bbbb* have higher rates, but also large backgrounds.

$$\boxed{\text{Expect to achieve } \frac{\Delta\lambda}{\lambda} \sim 30\%}$$

(two experiments at HL-LHC)



Baglio et al, arXiv: 1212.5581

Summary

All property measurements of the newly discovered Higgs boson are consistent with expectations from the Standard Model.

However, deviations from TeV-scale new physics are expected to be small from most models, smaller than the precisions of current measurements.

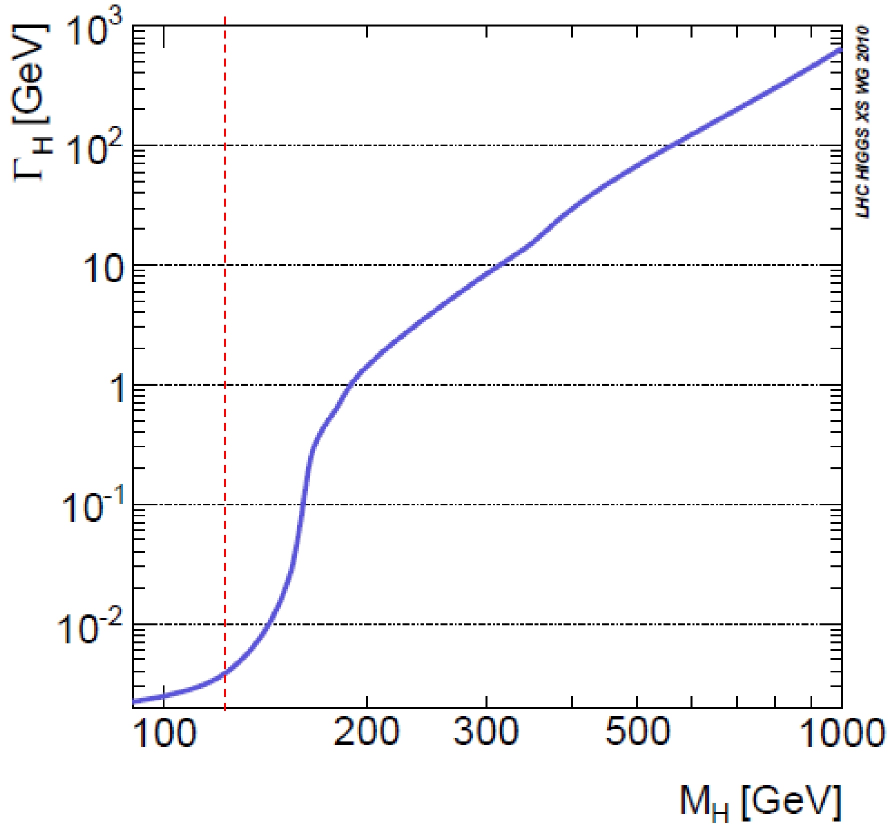
Direct searches for non-Standard Model decays or additional Higgs bosons have so far yielded no evidence, severely constrain the parameter space of the models studied.

Upcoming LHC Run 2 will be crucial. While continuing the study of well defined signatures, could be new physics hide in unusual places?

Additional Slides

Higgs Boson Width

SM @ 125 GeV: $\Gamma_h \approx 4.07$ MeV $\ll$ smaller than the experimental resolutions of direct measurements



For measurements: 

hard to measure experimentally though indirect measurements can significantly improve the precision

For searches: 

Even a small contribution to the width from potential new physics can lead to a sizable decay BR

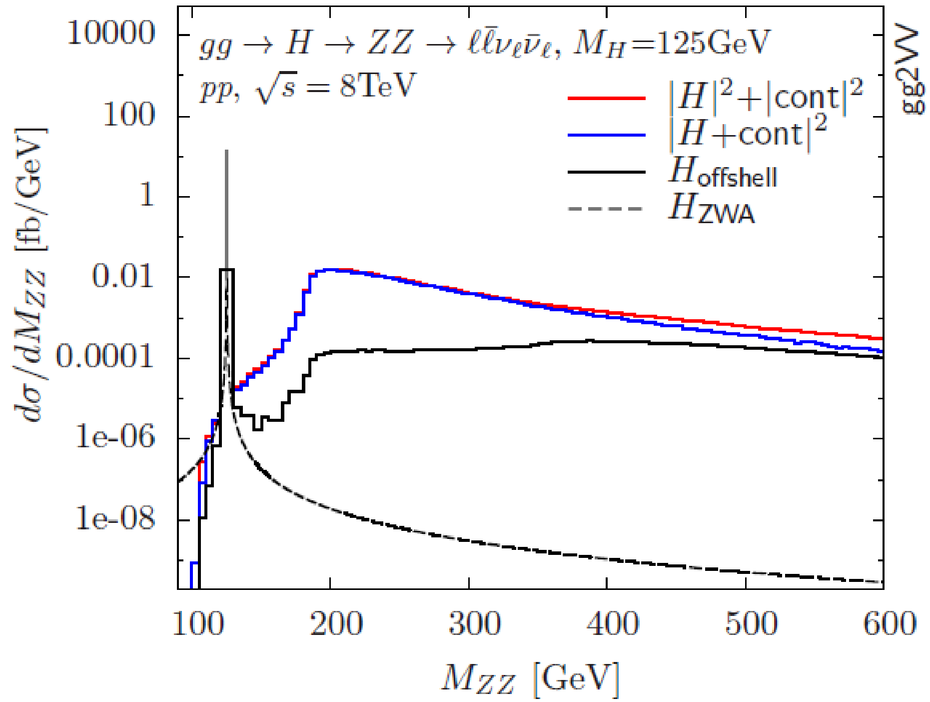
Indirect Width Measurement

Process $i \to H \to f$: $\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$

Kauer & Passarino, arXiv:1206.4803
Campbell & Ellis, arXiv:1311.3589

On-peak: $\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{m_H^2 \boxed{\Gamma_H^2}}$

Off-peak: $\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{\left(m^2 - m_H^2\right)^2}$



on-shell measures $\left(g_i g_f / \Gamma_H\right)^2$,

off-shell measures $\left(g_i g_f\right)^2$

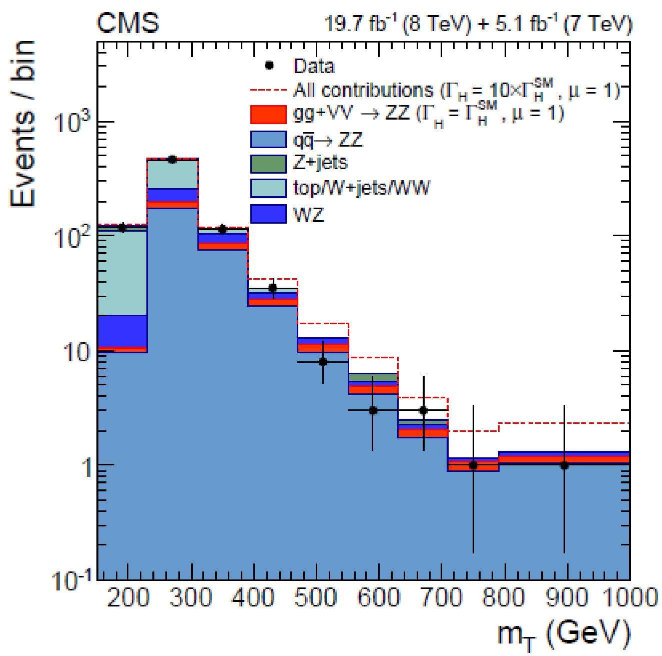
Extract Γ_H by comparing the two measurements (thanks to the large off-shell contributions)

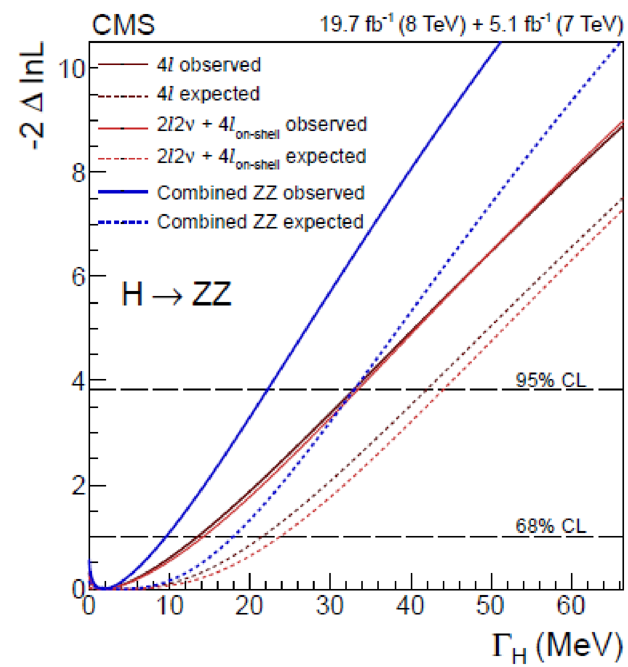
	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Indirect Width Measurement

The key is to isolate off-shell Higgs signal from the continuum background, such as $q\bar{q}/gg \to WW, ZZ$ for the case of $H \to WW, ZZ$

arXiv:1405.3455 (CMS)





CMS has studied $H \to ZZ^* \to 4\ell, \ell\ell\nu\nu$ with the combined observed (expected) limit: $\Gamma_H < 22(33)$ MeV or $5.4(8.0)\times\Gamma_H^{SM}$ @ 95% CL

Or as a measurement $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

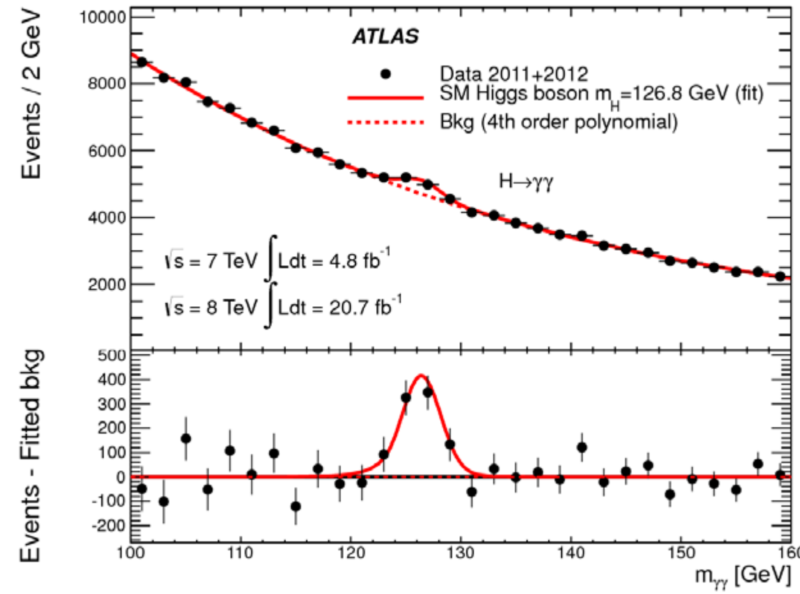
However, there is the issue whether theory uncertainty is under control.

Direct Width Measurement

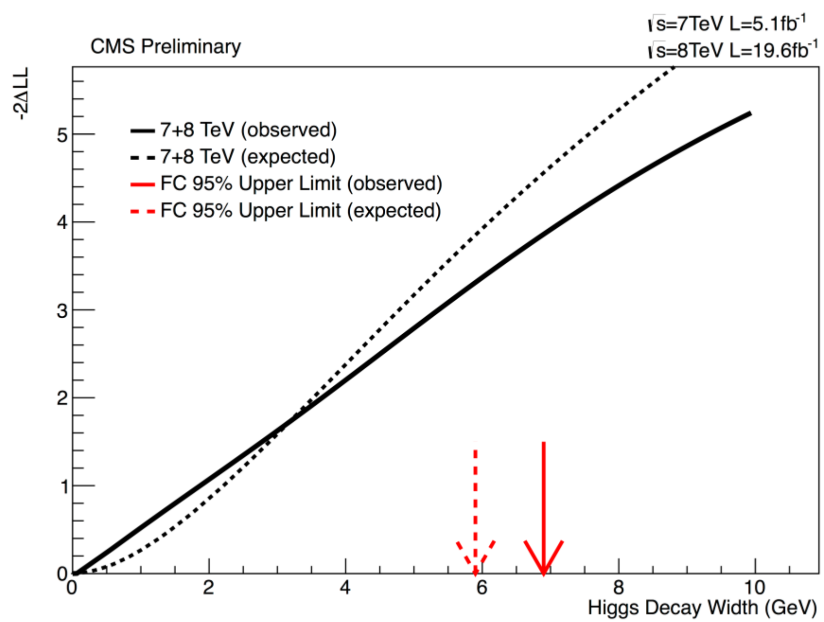
The Higgs width can be in principle extracted from the $m_{\gamma\gamma}$ or $m_{4\ell}$ distributions with the signal lineshape

$$\text{Breit-Wigner}(m, \Gamma_H) \otimes \text{Gaussian}(\sigma)$$

Limited by detector mass resolution and large background



CMS-PAS-HIG-13-016



Observed (expected) limit

$$\Gamma_H < 6.9(5.9) \text{ GeV @ 95\% CL}$$

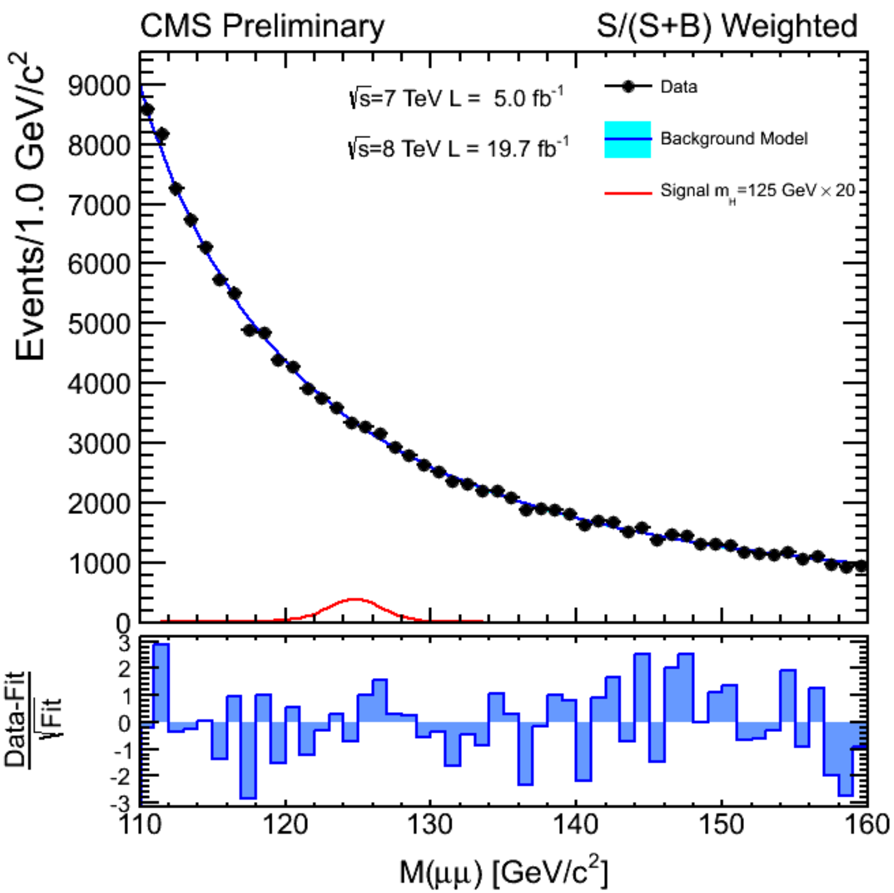
$$\sim 1500 \times \Gamma_H^{SM}$$

Rate Decay: $H \to \mu\mu$

$$BR(H \to \mu\mu) \simeq \left(\frac{m_\mu}{m_\tau}\right)^2 \times BR(H \to \tau\tau) \approx 0.022\%$$

CMS-PAS-HIG-13-007
ATLAS-CONF-2013-010

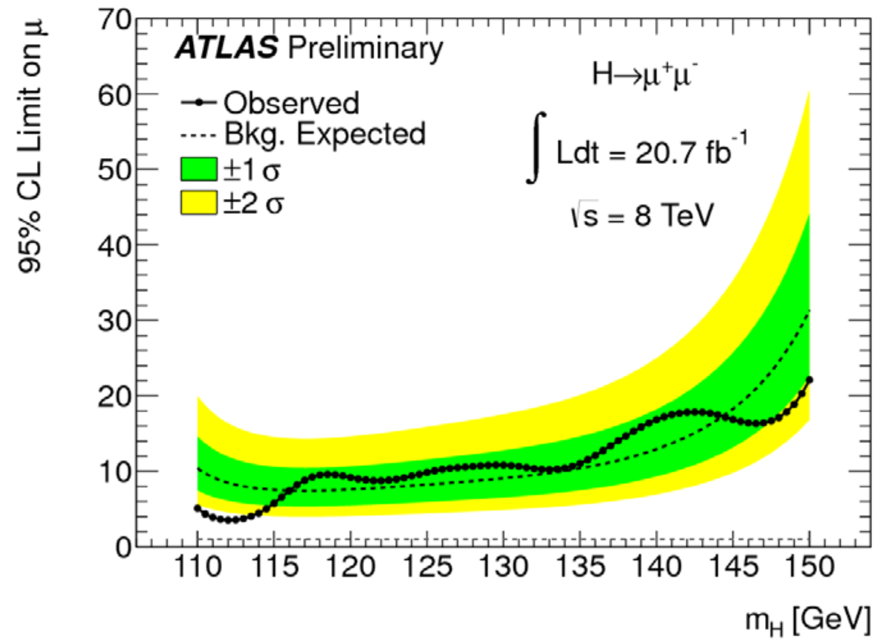
Clean signature, but suffer from large Drell-Yan background



Observed (expected) upper limits

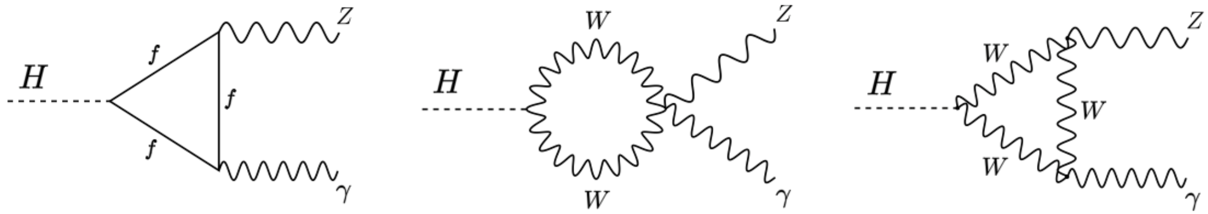
ATLAS: 9.8 (8.2) and CMS: 7.4 (5.1)

on $(\sigma \times BR)/(\sigma \times BR)_{SM}$ at 95% CL



Rare Decay: $H \to Z\gamma$

$$BR(H \to Z\gamma) \approx 0.15\% \text{ @ } 125\text{ GeV}$$



At $m_H = 125$ GeV:

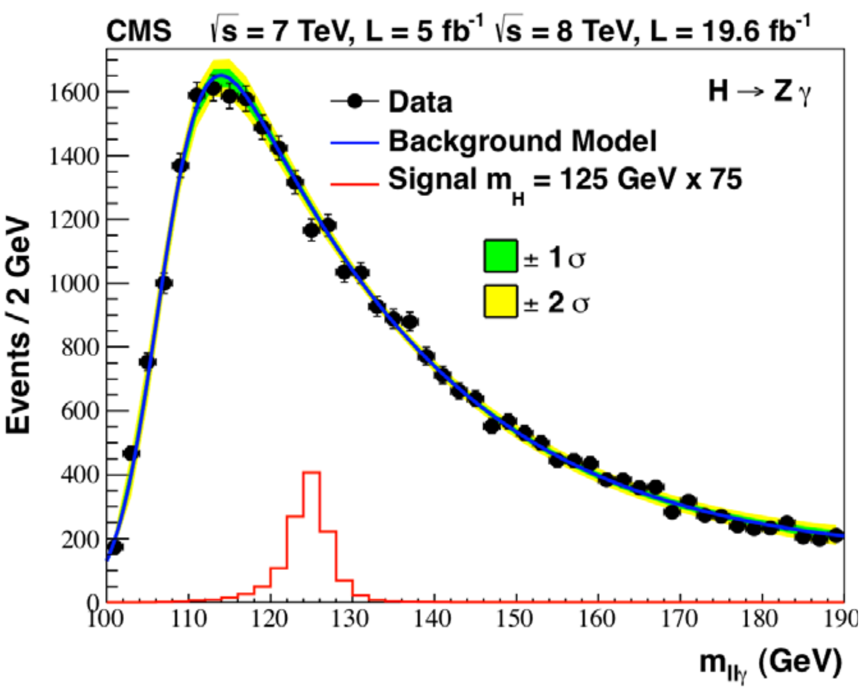
$\sigma_H \times Br(H \to Z\gamma \to \ell\ell\gamma) \sim 2.3$ fb

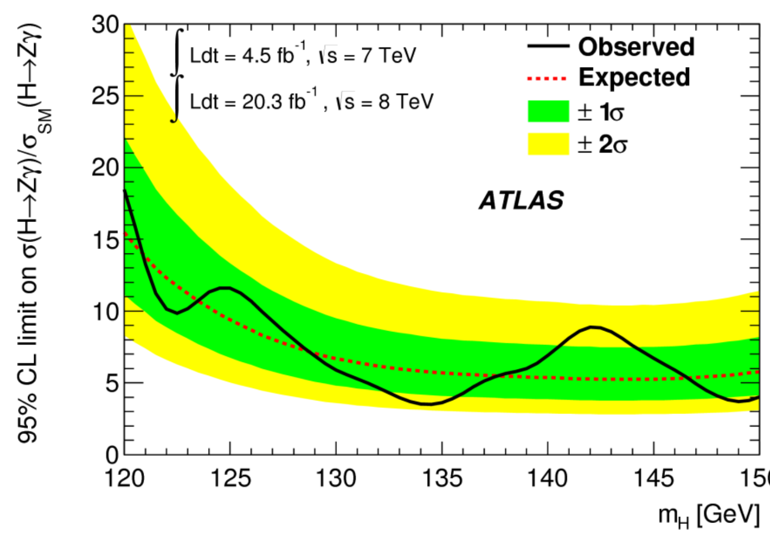
~ 55 events in 2011+2012 dataset

Search for a narrow resonance over continuum (mostly $Z\gamma$) backgrounds

Current sensitivity is about $10\times$ the standard model expectation

arXiv: 1307.5515 (CMS)





arXiv: 1402.3051 (ATLAS)

Other Rare Decays

$H \to J/\psi\,\gamma$ decay has been proposed as a way to access *Hcc* coupling, but the rate is very low: $N\left(H \to J/\psi\gamma \to \mu\mu\gamma\right) \approx N\left(H \to Z\gamma \to \mu\mu\gamma\right)/340$

$$\mathrm{BR}_{\mathrm{SM}}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6},$$
$$\mathrm{BR}_{\mathrm{SM}}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}.$$

Bodwin, Petriello, Stoynev and Velasco, arXiv:1306.5770

Relative easy to search, but rate is too late even for high luminosity LHC or even for any proposed lepton collider

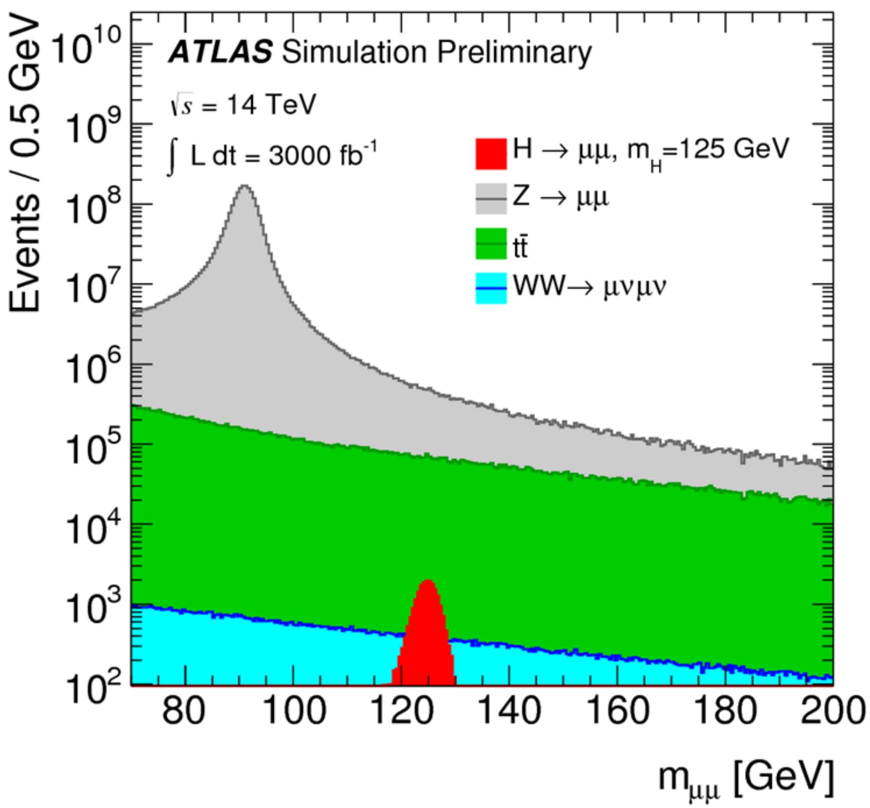
There are other potential rare decays, but backgrounds are likely too large to be feasible

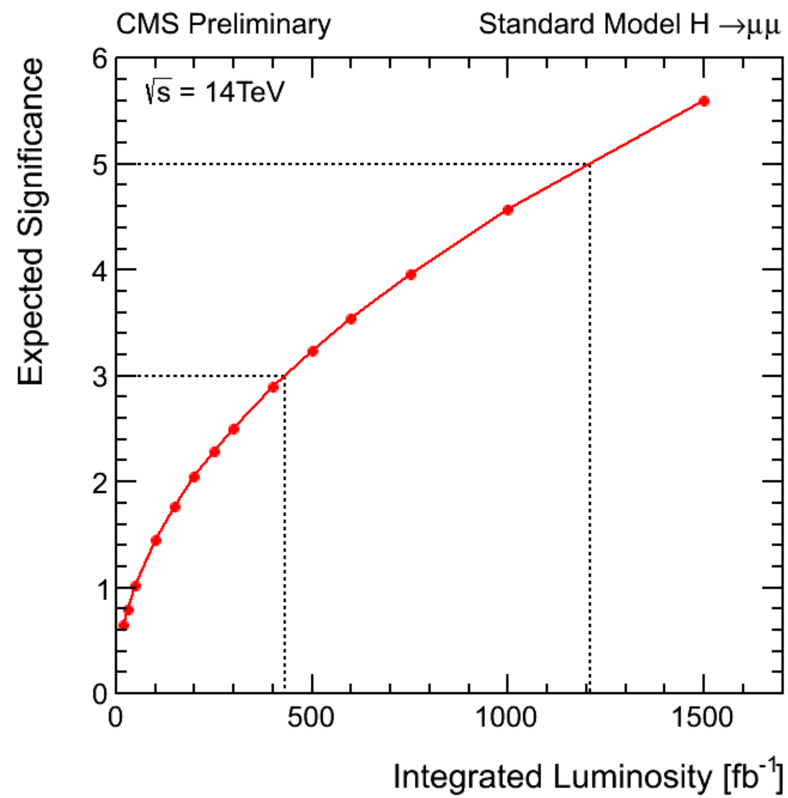
VP mode	$\mathcal{B}^{\mathrm{SM}}$	VP^* mode	$\mathcal{B}^{\mathrm{SM}}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	$Z^0 J/\psi$	2.2×10^{-6}

Isidori, Manohar and Trott, arXiv:1305.0663

Rare Decay Prospects

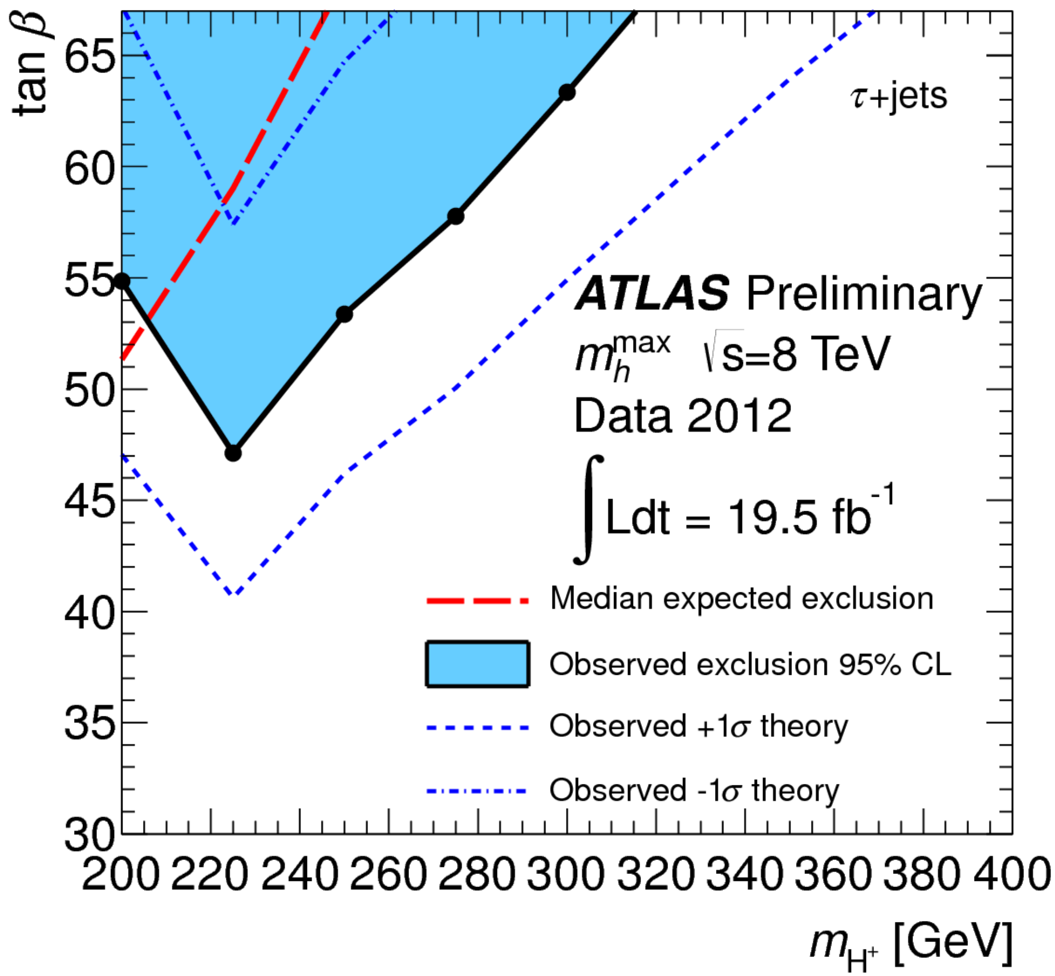
$H \to \mu\mu$: Projections from both ATLAS and CMS indicate a 5σ observation with $\sim 1000\ \mathrm{fb}^{-1}$ at 14 TeV.





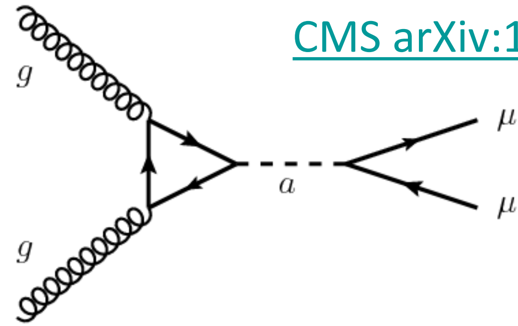
$H \to Z\gamma$: $\sim 4\sigma$ per experiment significance is expected with $3000\ \mathrm{fb}^{-1}$

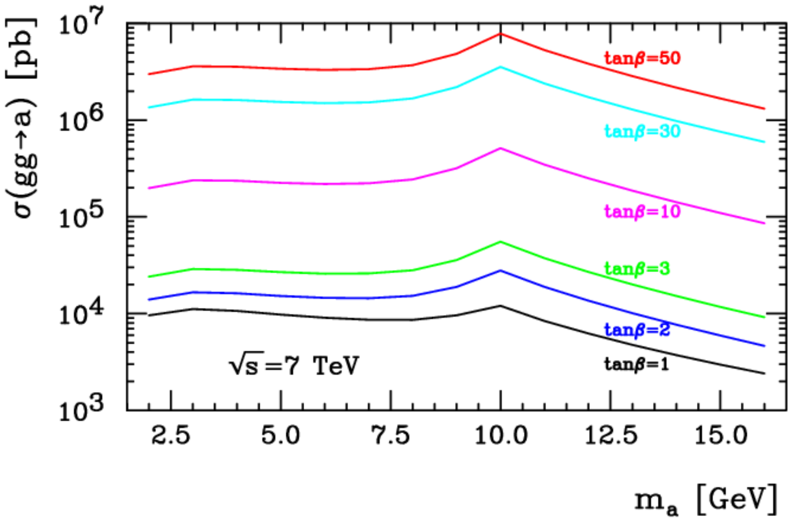
Charged Higgs Boson



Search for $a \to \mu\mu$

CMS arXiv:1206.6326

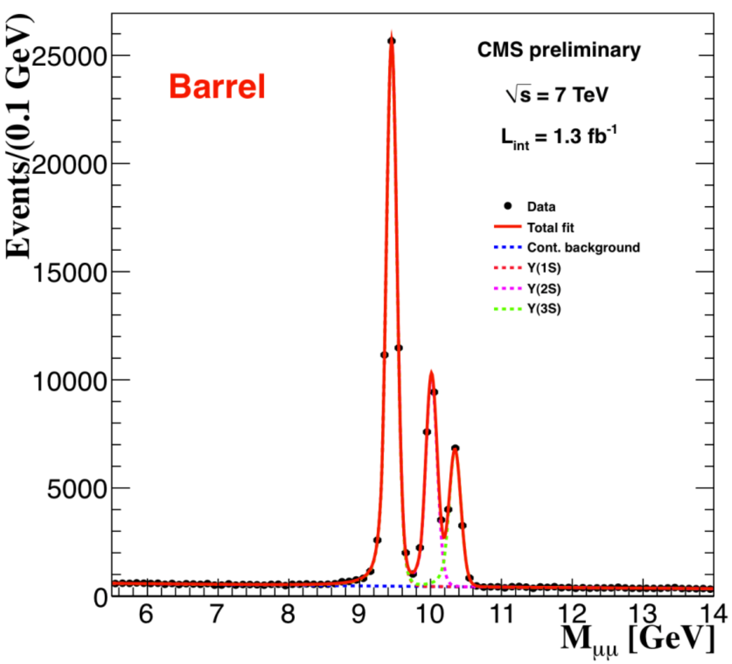


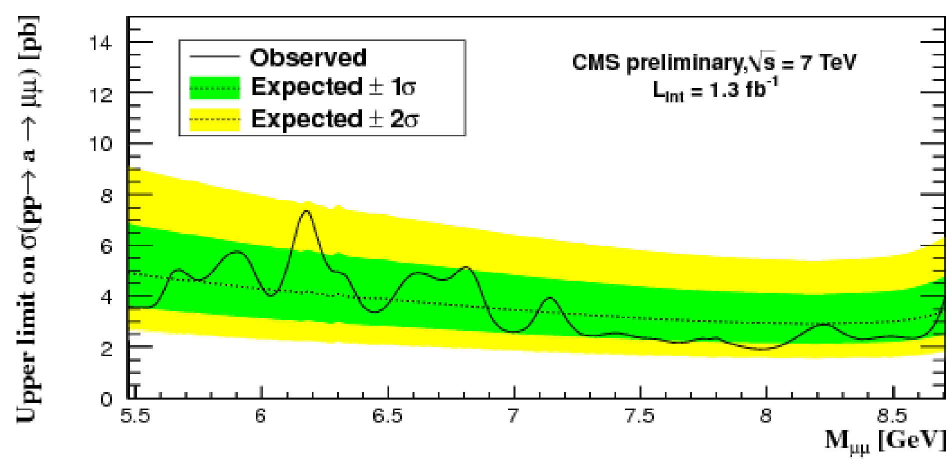


a can be singularly produced in *gg* fusion with a relative large cross section, can be searched in $a \to \mu\mu$ decay.

Searching for narrow $\mu\mu$ resonance away from the known quarkonium resonances.

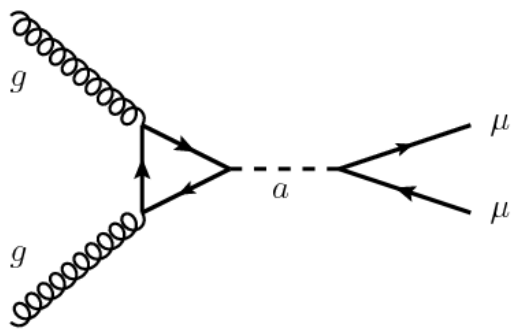
Only 7 TeV results from CMS are public available so far





Search for $a \to \mu\mu$

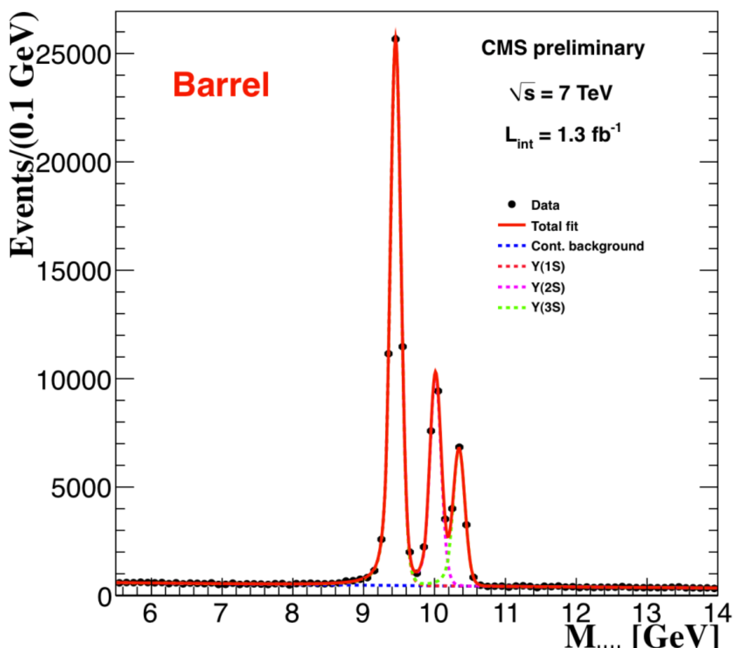
CMS arXiv:1206.6326
(7 TeV results)

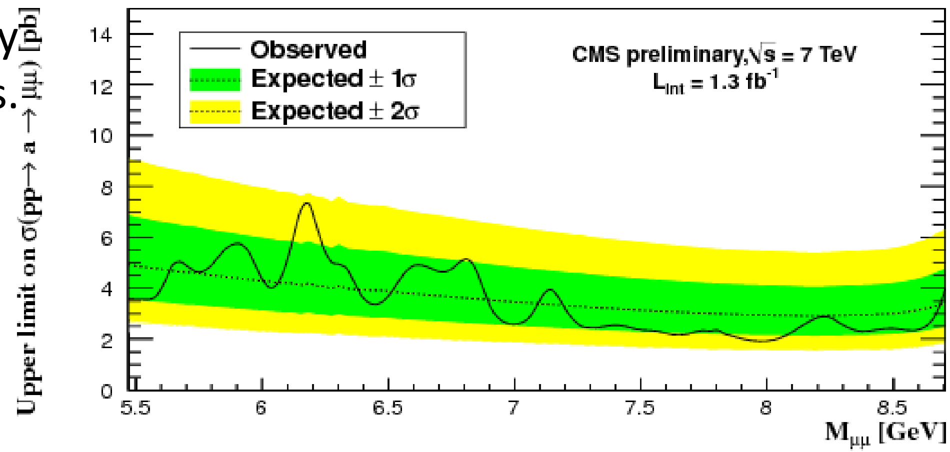


Trigger: two muons with $p_T > 3.5$ GeV
Offline: two muons with $p_T > 5.5$ GeV

MSSM pseudoscalar A is used to model the signal using PYTHIA

Searching for narrow $\mu\mu$ resonance away from the known quarkonium resonances.





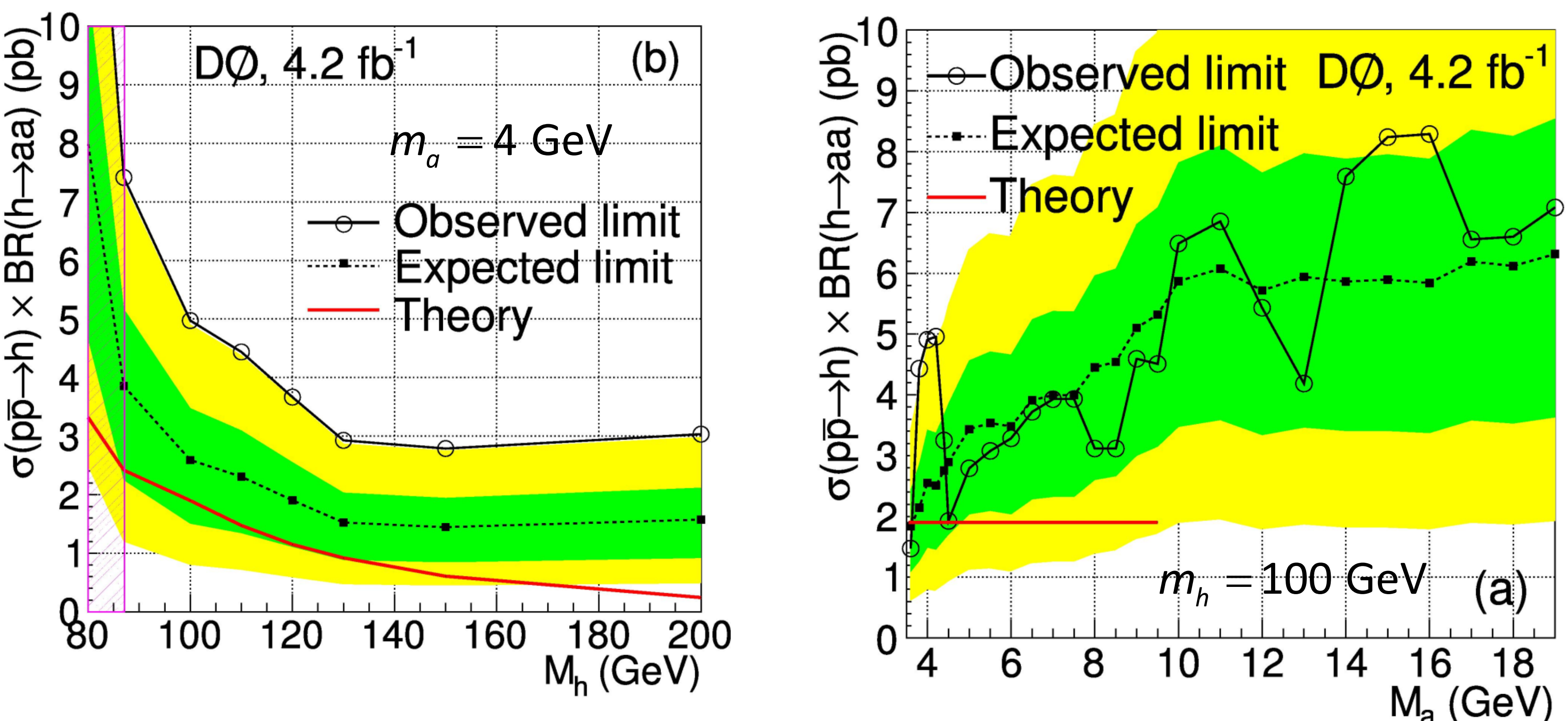
Warning:

For small values of m_a $(<\sim 2p_T)$, only highly boosted signal events are selected. Can we really trust PYTHIA to model the p_T of the Higgs boson?

Search for $h \to aa \to 4\mu,\ 2\mu 2\tau$

Public result from CMS on $h \to aa \to 4\mu$, clean signature but relative low rate $\Rightarrow$ presentation by Alexei Safonov

$h \to aa \to \mu\mu\tau\tau$ should significantly improve the search sensitivity as D0 has done. LHC should be able to explore interesting parameter space.



arXiv:0905.3381 (D0)

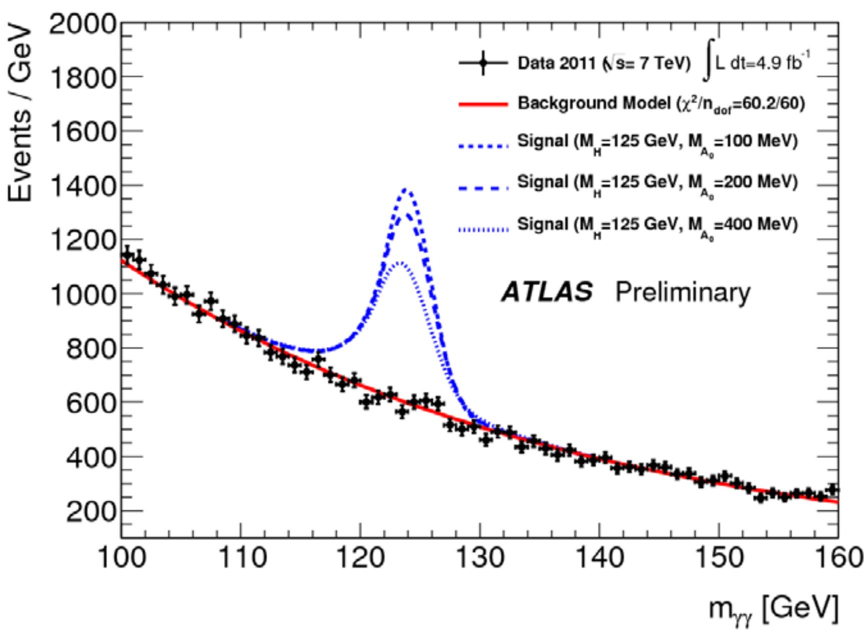
Search for $h \to aa \to 4\gamma$

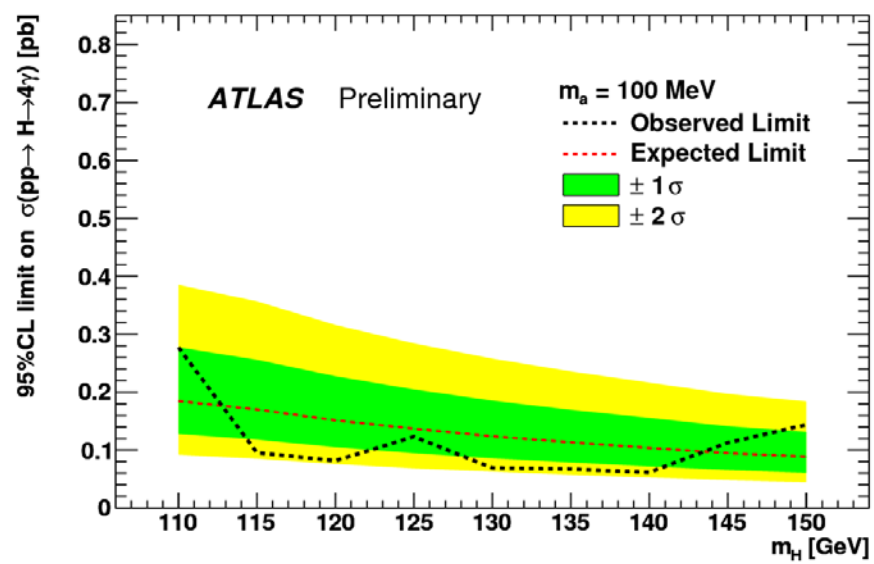
ATLAS-CONF-2012-079

An old analysis, partly motivated by the excess in $h \to \gamma\gamma$.

The pseudoscalar a from $h \to aa$ decay will be highly boosted if a is very light ($m_a <\sim 1$ GeV). The two photons from $a \to \gamma\gamma$ decay will be collimated, contributing effectively to the $h \to \gamma\gamma$ signal.

Search for two "photon-like" objects with $E_T > 40{,}25$ GeV. Upper cross section limits are set for $100 < m_a < 400$ MeV.





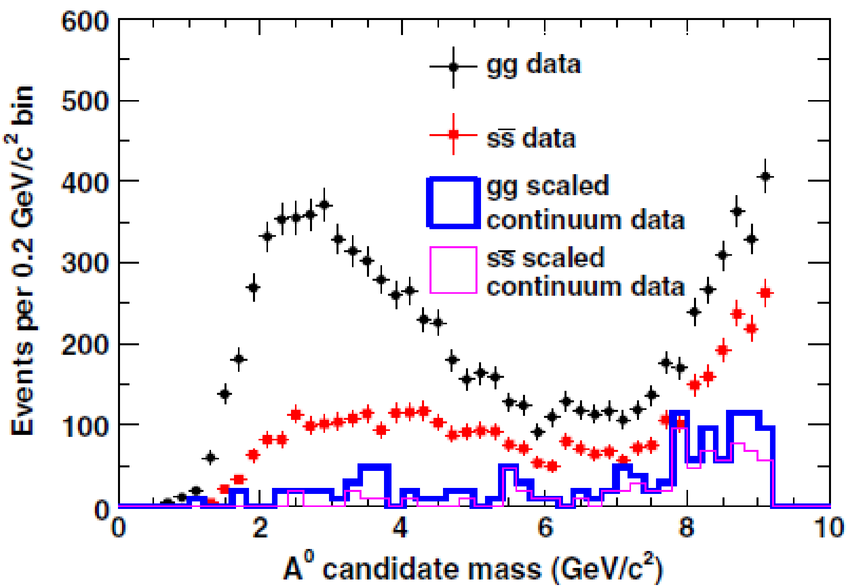
Searches at BABAR

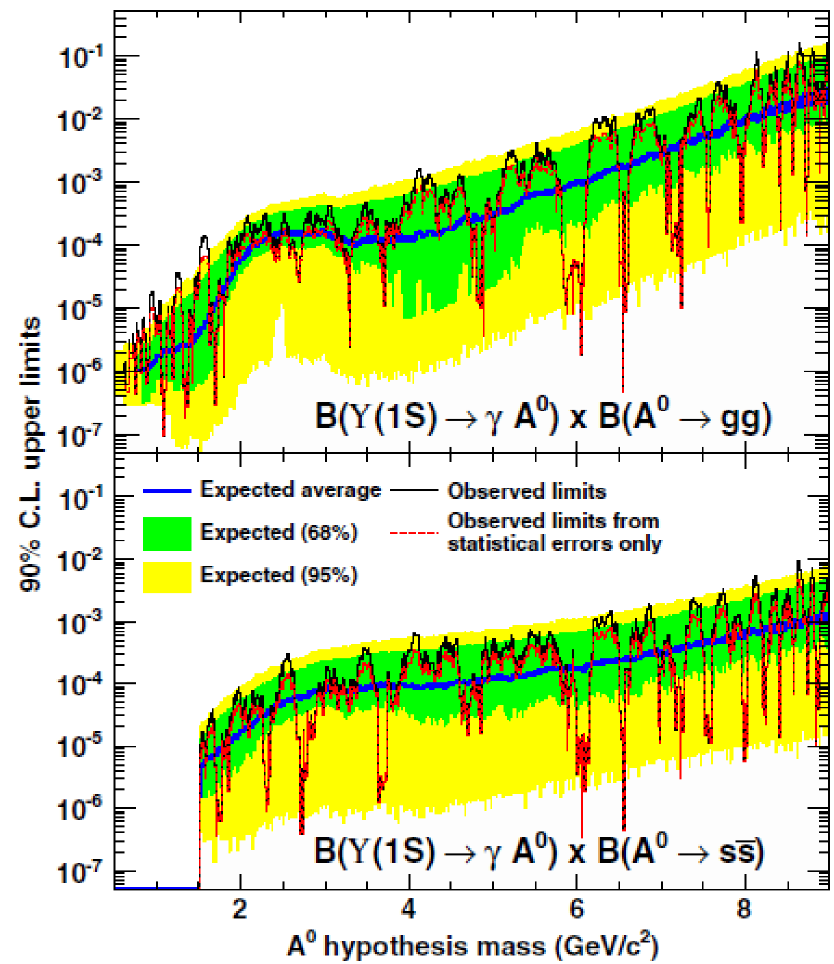
Hadronic decays such as $a \to c\bar{c},\ gg$ (dominant below $2m_\tau$) are not feasible at hadron colliders, but can be searched in $\Upsilon(nS) \to a\gamma$ decays at B-factories.

The radiative $\Upsilon \to a\gamma$ decay is predicted to have a BR up to 10^{-5}.

Full reconstruction of *a* decays in exclusive final states.

No sign of *a* !





BABAR: Phys. Rev. D 88, 031701 (2013)

MSSM Tree-Level Relations

Minimal Supersymmetric Standard Model (MSSM) is a Type II 2HDM with supersymmetrized Higgs potential. At tree-level, the MSSM Higgs sector is completely determined by two parameters, often chosen to be:

- $\tan\beta$: ratio of two V.E.V
- m_A : mass of the pseudoscalar Higgs boson

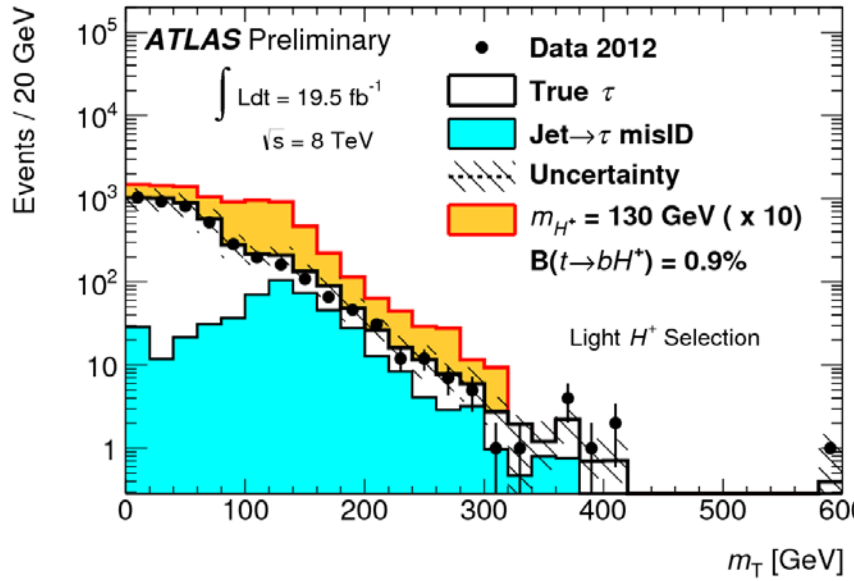
With tree-level mass relations:

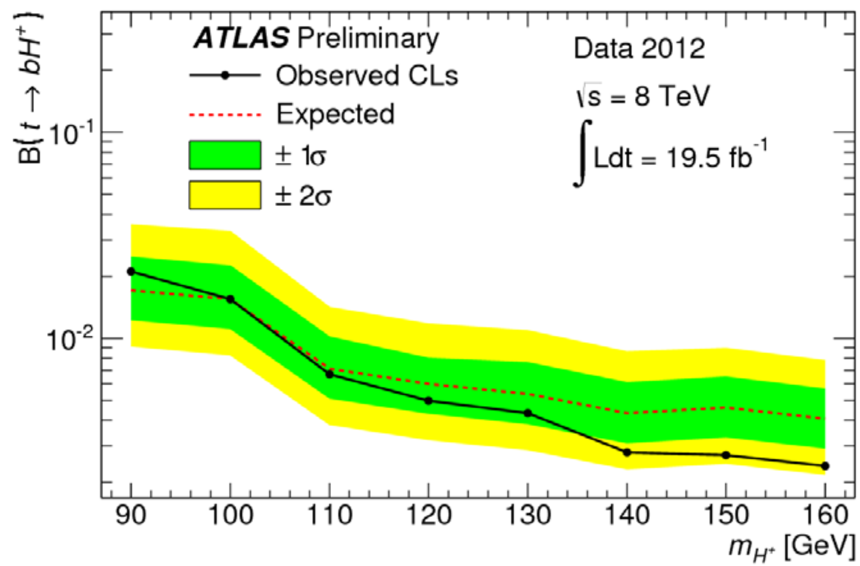
$$\boxed{\begin{aligned} & m_{H^\pm}^2 = m_A^2 + m_W^2 \\ & m_{h,H}^2 = \frac{1}{2}\left(m_Z^2 + m_A^2 \mp \sqrt{\left(m_Z^2+m_A^2\right)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta} \right) \\ & \cos^2(\beta-\alpha) = \frac{m_h^2\left(m_Z^2 - m_h^2\right)}{m_A^2\left(m_H^2 - m_h^2\right)} \quad \text{with} \quad \begin{cases} 0 \le \beta \le \pi/2 \\ -\pi/2 \le \alpha \le 0 \end{cases} \end{aligned}}$$

and the tree-level mass bound:

$$m_h = \frac{2m_Z^2 m_A^2 \cos^2 2\beta}{m_Z^2 + m_A^2 + \sqrt{\left(m_Z^2+m_A^2\right)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}} \le m_Z^2 \cos^2 2\beta$$

Charged Higgs Boson





Heavy Neutral Higgs Boson