Extended Higgs Sector (2HDM, MSSM, NMSSM)

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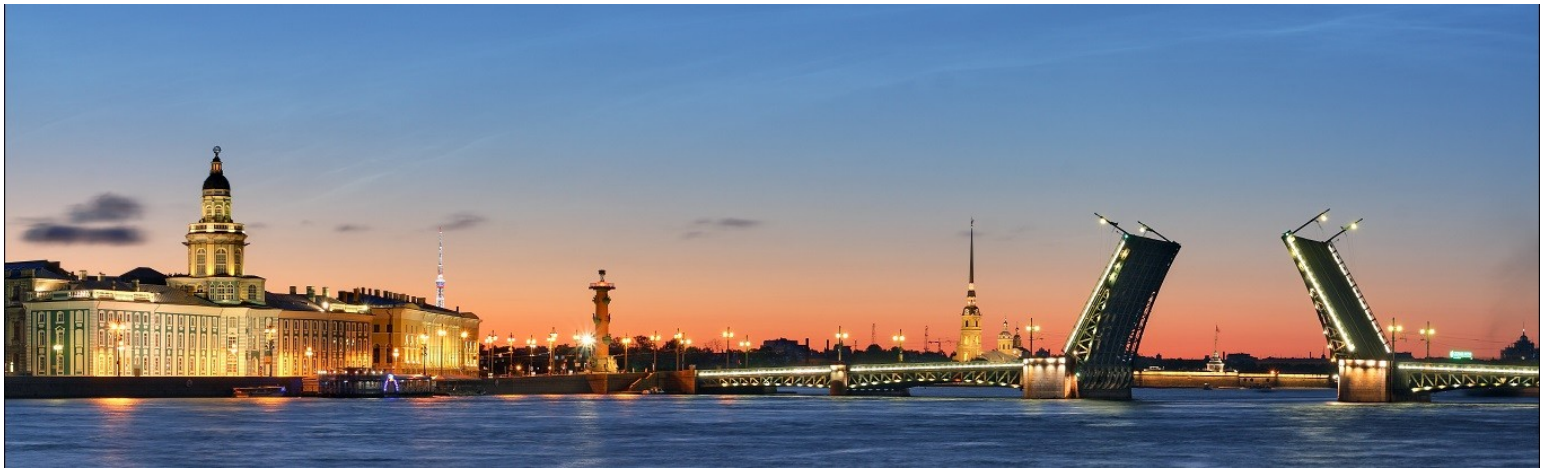
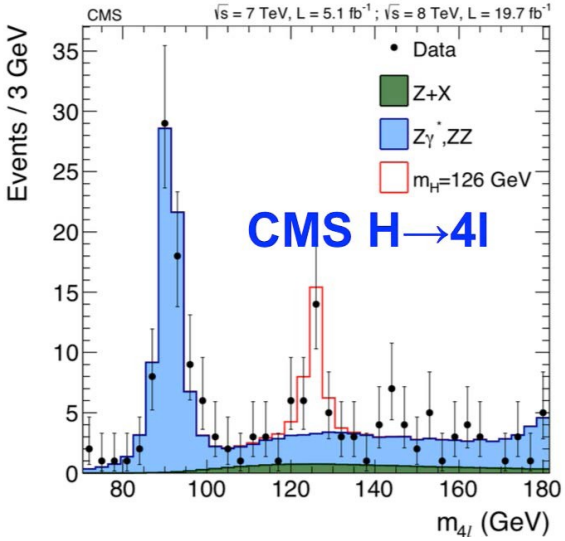
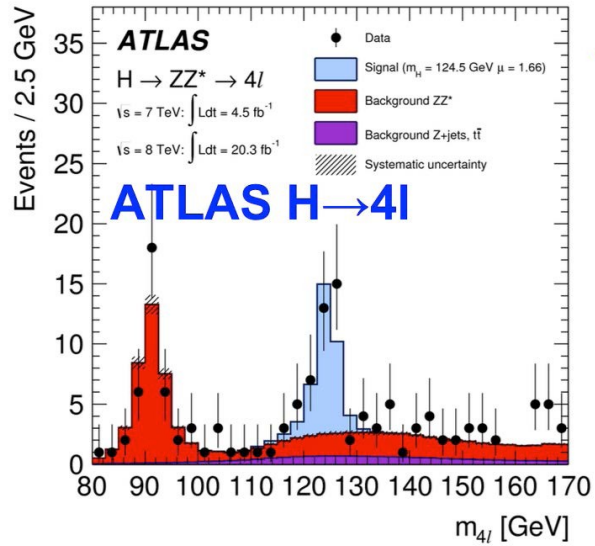
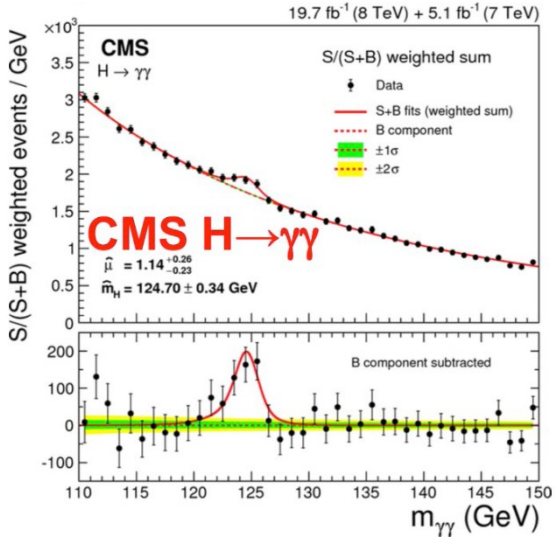


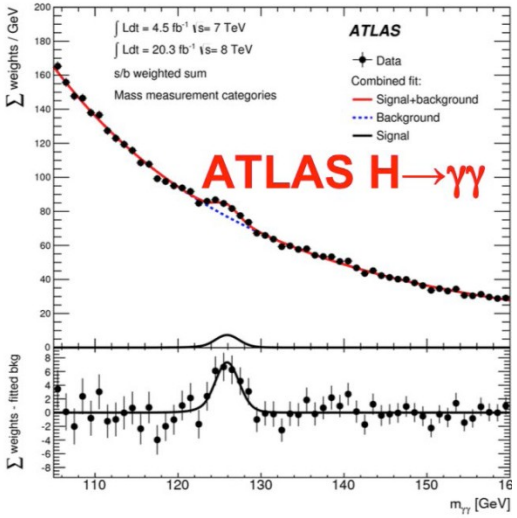
LHCP2015 THE THIRD ANNUAL CONFERENCE ON LARGE HADRON COLLIDER PHYSICS
August 31 - September 5 2015
St. Petersburg, Russia

A SM-like Higgs (scalar 0^+) is discovered



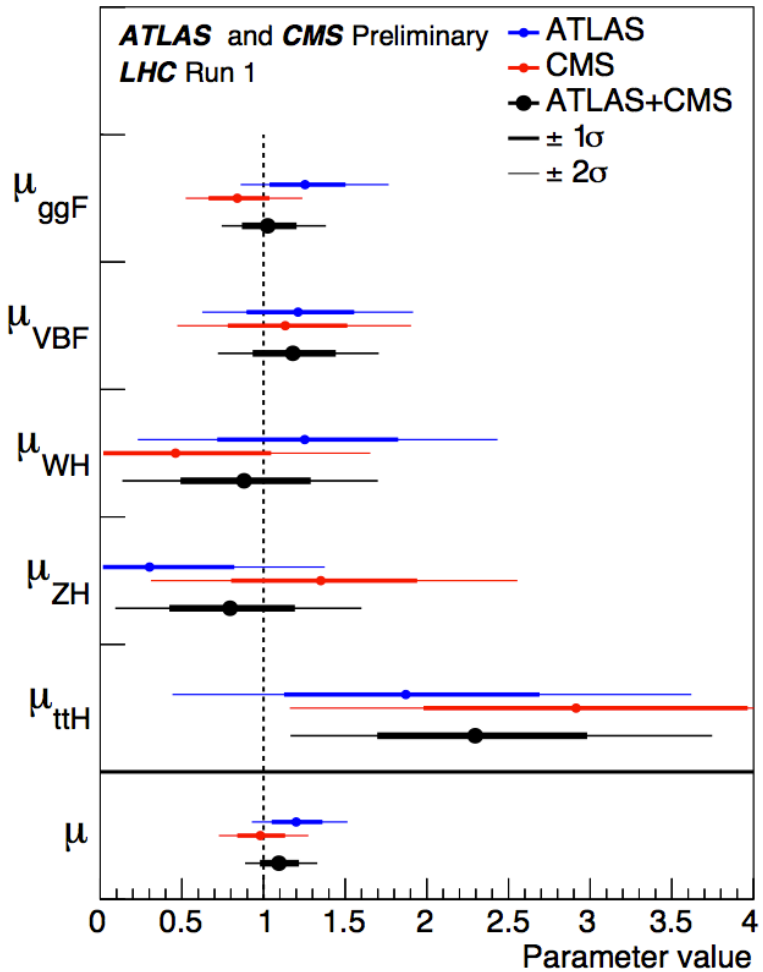


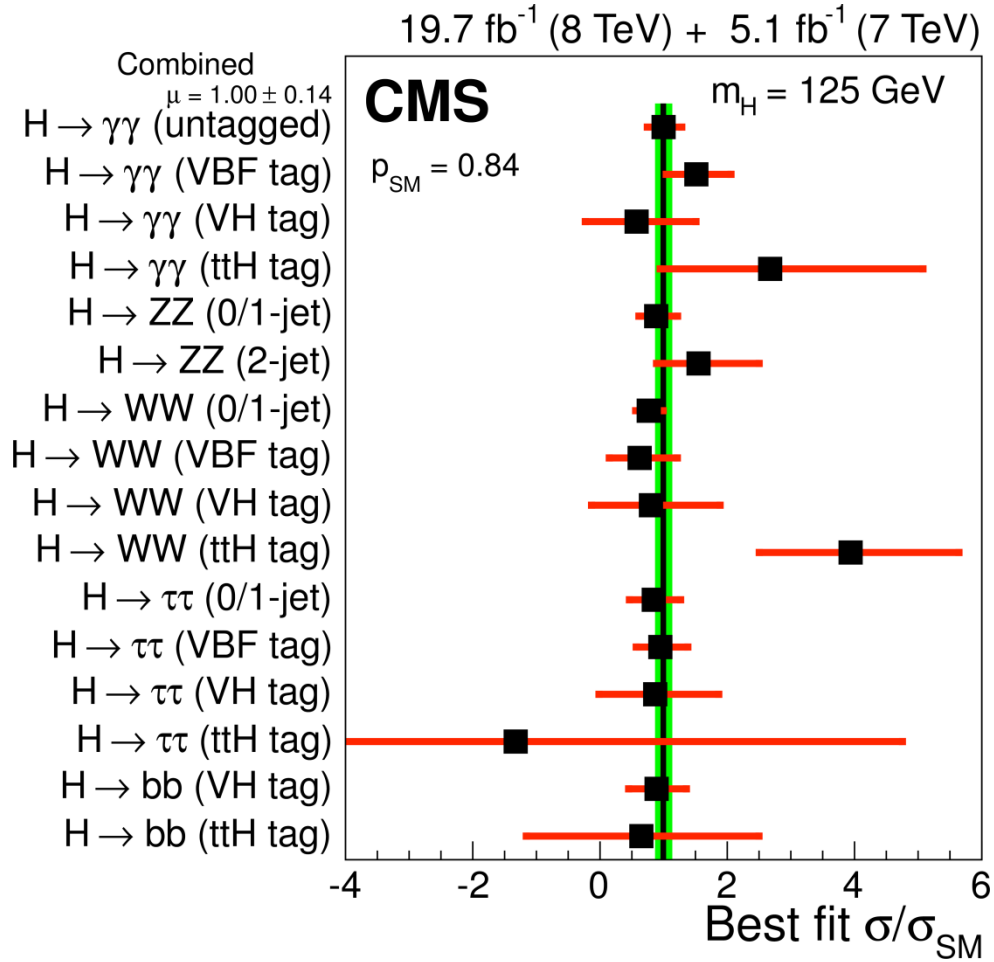




m_H = 125.09±0.21(stat.)±0.11(syst.) GeV

talk by Marco Pieri





Still large errors in individual channels!

Facts needed to be explained

1. Large differences in fermion masses.
   ($M_{top} \approx 173$ GeV, $M_e \approx 0.5$ MeV, $\Delta M_\nu \approx 10^{-3}$ eV)

2. Dark Matter

3. $(g-2)_\mu$ (about 3.5 σ)

4. Neutrino oscillations

5. Particle – antiparticle asymmetry in the Universe,
   CP violation

   baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

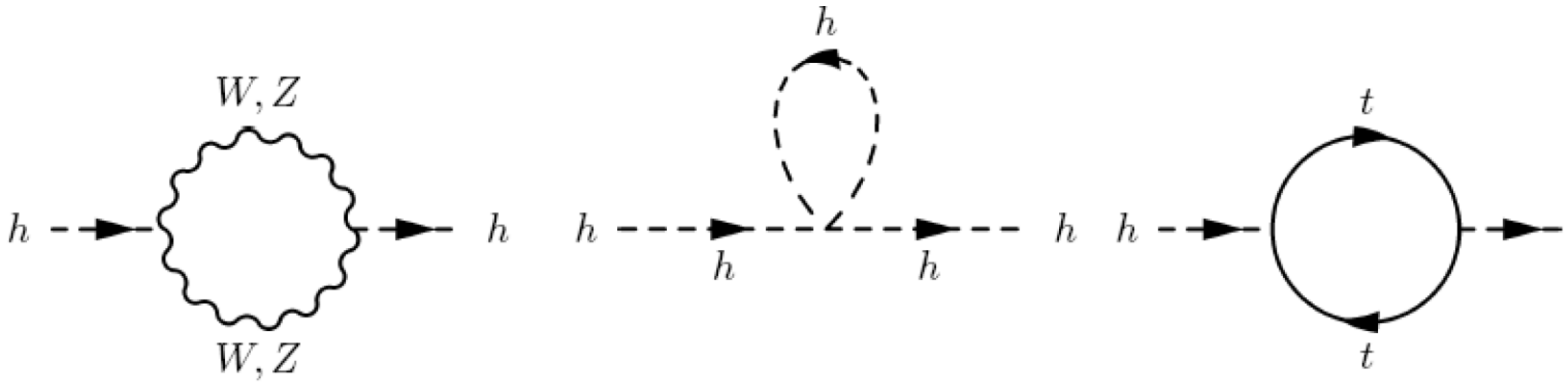
6. Gravity (no connection to EW?). Why gravity is so weak?

Higgs measurements → Room for BSM Higgses (scalars, pseudoscalars…)

However, the simplest Higgs mechanism SM is not stable with respect to quantum corrections (hierarchy problem)

talk by Stefania Gori
talk by Tao Han
talk by David Shih
talk by Pawel Bruckman de Renstrom

Loop corrections to the Higgs mass



$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\,\Lambda)^2$$

$\delta m_H < m_H$ $\Lambda < 1$ TeV

In SM there is no symmetry which protects a strong dependence of Higgs mass on a possible new scale

If naturalness is assumed $\Longrightarrow$
something is needed in addition to SM…

More Higgses practically in all BSM models

1. Fundamental Higgs:

- Supersymmetric models
  (MSSM, NMSSM…)

2. Composite / Partially composite Higgs:

- Models with new strong dynamics
  (Chiral Lagrangians from holography, latest technicolor variants, Little Higgs models, Twin Higgs models…)
- Models with extra space dimensions (radion, dilaton)

2HDM

Why the only one Higgs doublet?
- No fundamental reasons

Simple extension – two Higgs doublets (2HDM)

MSSM prototype, strong CP and axion, CP violation and baryogenesis

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad v^2 \equiv v_1^2 + v_2^2 \qquad \tan\beta \equiv \frac{v_2}{v_1}$$

2 complex scalar doublets => 8 degrees of freedom

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

As in the SM 3 Goldstone bosons are absorbed ("eaten") by $W^\pm$ and Z

5 physics degrees of freedom

h, H – CP even scalars,
A – CP odd scalar,
$H^\pm$ - sharged scalars

Generic Higgs potential is not that simple

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} ,$$

Gunion, Haber, Kane, Dawson '00...

Mostly studied cases with Z_2 symmetry $\Phi_1 \to +\Phi_1 \;\; \Phi_2 \to -\Phi_2$ → $\lambda_6, \lambda_7 = 0$

Physics states – the states with definite masses

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

$$H = (\sqrt{2}\text{Re}\,\Phi_1^0 - v_1)c_\alpha + (\sqrt{2}\text{Re}\,\Phi_2^0 - v_2)s_\alpha ,$$
$$h = -(\sqrt{2}\text{Re}\,\Phi_1^0 - v_1)s_\alpha + (\sqrt{2}\text{Re}\,\Phi_2^0 - v_2)c_\alpha$$

Notations: $\cos\alpha = c_\alpha$, $\sin\alpha = s_\alpha$, $\cos\beta = c_\beta$, $\sin\beta = s_\beta$,
$\cos(\beta-\alpha) = c_{\beta-\alpha}$, $\sin(\beta-\alpha) = s_{\beta-\alpha}$

In the "Higgs basis"

Branco, Lavoura, Silva; Davidson, Haber

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \Phi_1 c_\beta + \Phi_2 s_\beta \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv -\Phi_1 s_\beta + \Phi_2 c_\beta \qquad \langle H_1^0 \rangle = v/\sqrt{2} \qquad \langle H_2^0 \rangle = 0$$

The physical mass eigenstates

$$H = (\sqrt{2}\mathrm{Re}\, H_1^0 - v) c_{\beta-\alpha} - \sqrt{2}\mathrm{Re}\, H_2^0 s_{\beta-\alpha}$$
$$h = (\sqrt{2}\mathrm{Re}\, H_1^0 - v) s_{\beta-\alpha} + \sqrt{2}\mathrm{Re}\, H_2^0 c_{\beta-\alpha}$$

Alignment:

$$c_{\beta-\alpha} \to 0$$

Decoupling limit: $c_{\beta-\alpha} \to 0$ **and** $m_H \gg v$

the state h is behaved as the SM Higgs and the states H, A, $H^\pm$ are very heavy and decouple

However for some parameter space there might be the case

$|c_{\beta-\alpha}| \ll 1$ **but M_H (M_A, $M_{H^\pm}$) is not very heavy**

alignment without decoupling

Gunion, Haber'03; Haber'14; Bernon, Gunion, Haber, Jiang, Kraml'15

Several types of 2HDM depending on Yukawa arrangement

Glashow, Weinberg, Paschos condition '77

Avoid FCNC: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC are absent

Branco, Ferreira, Lavoura, Rebelo, Sher, Silva '11,12

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

MSSM like

Type III

Type IV

Yukawa couplings to the Higgs bosons normalized to SM Higgs

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$s_{(\beta-\alpha)} + c_{(\beta-\alpha)}/t_\beta$

$s_{(\beta-\alpha)} - t_\beta * c_{(\beta-\alpha)}$

Many scenarios, many possibilities, various choices of model parameters

M_h M_H M_A $M_{H\pm}$ $\tan\beta$ $\cos(\beta-\alpha)$
or
Z_4 and Z_5 instead of $M_A, M_{H\pm}$ (from the Higgs potential in the Higgs basis)

Constrains:
EW precision observables; flavor ($Br(B\to s\gamma)$ and B_0-antiB_0 mixing);
unitarity, perturbativity and vacuum stability; DM; Higgs measurements

Many proposals for 2HDM benchmark scenarios by several groups in 2015 (LHC Higgs WG3 Low, Mühlleitner, Pelliccioni, Rompotis)

Haber, Stal

Aggleton, Barducci, Moretti, Nikitenko, Shepherd-Themistocleous

Dorsch, Huber, Mimasu, No

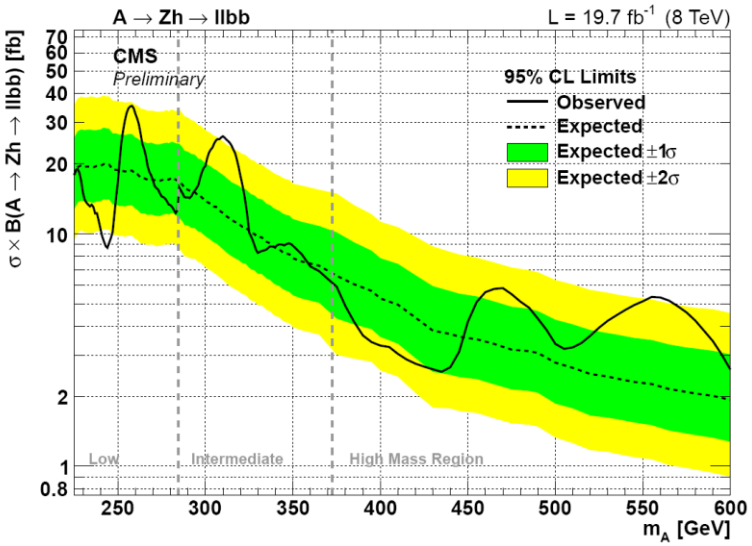
Kling, Shufang Su

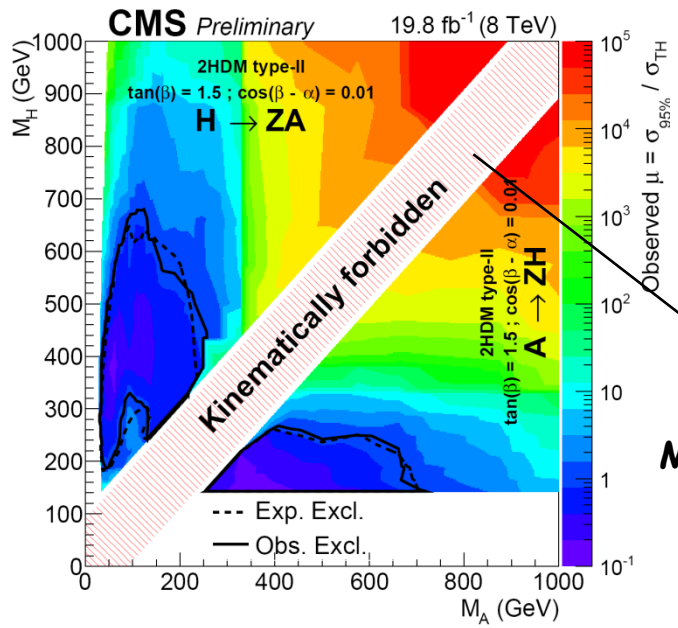
Search strategies

- measuring deviations on couplings of the discovered state h
- new particles, new decays such as

$H \to hh$ and $A \to Zh$ (if kinematically accessible)

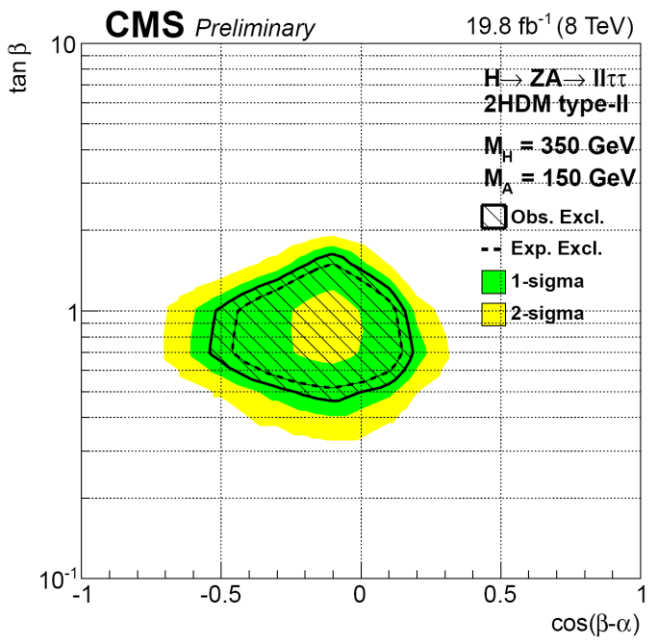
Examples of searches

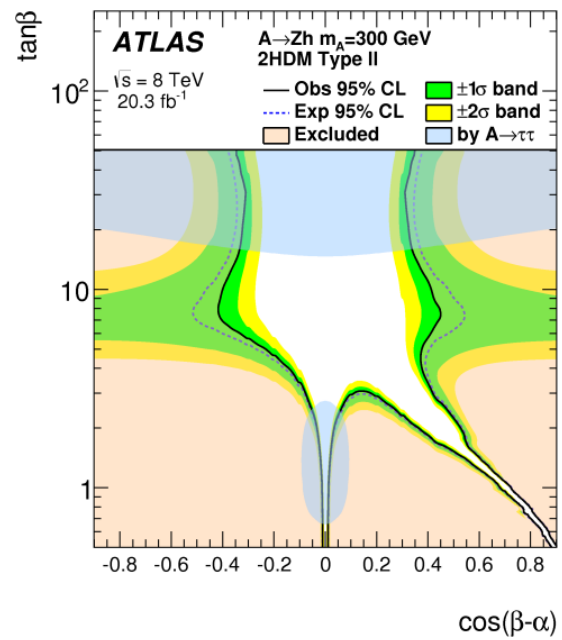




σ_{TH} from NNLO by SusHi

$M_{H/A} < M_{A/H} + M_Z$





MSSM

MSSM potential after supersymmetry breaking

$$V(H_1,H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^T i\tau_2 H_2 + h.c.) +$$
$$\frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left|\left(H_1^T i\tau_2 H_2\right)\right|^2$$

2HDM type II with quartic couplings fixed due to the gauge nature

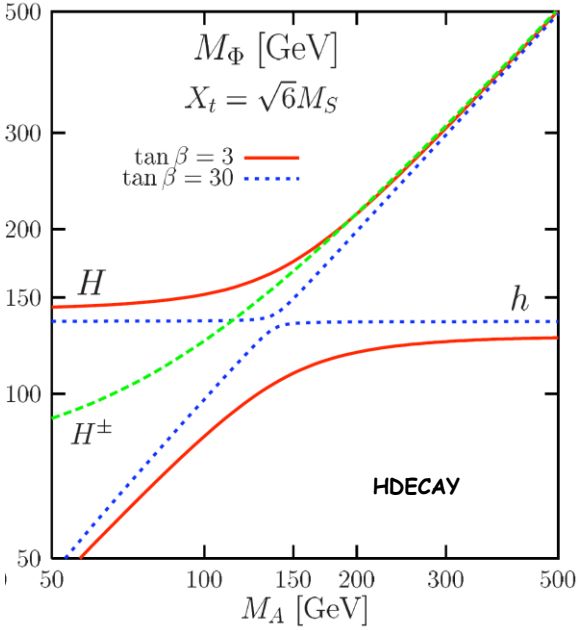
$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}$$

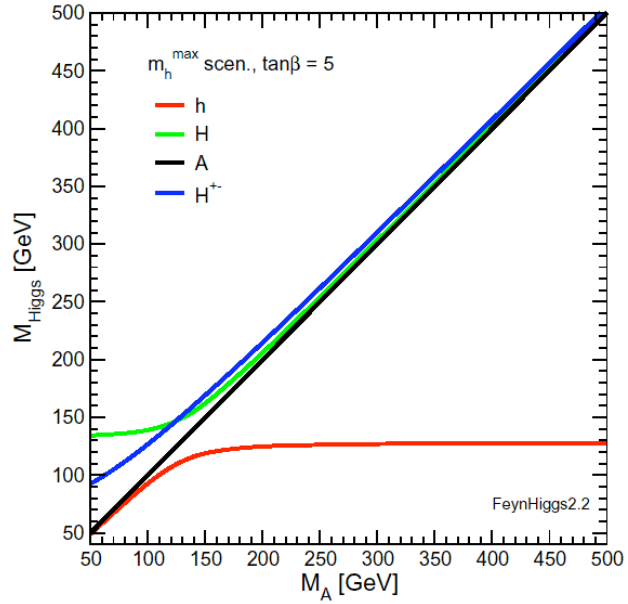
8-3=5 physics states

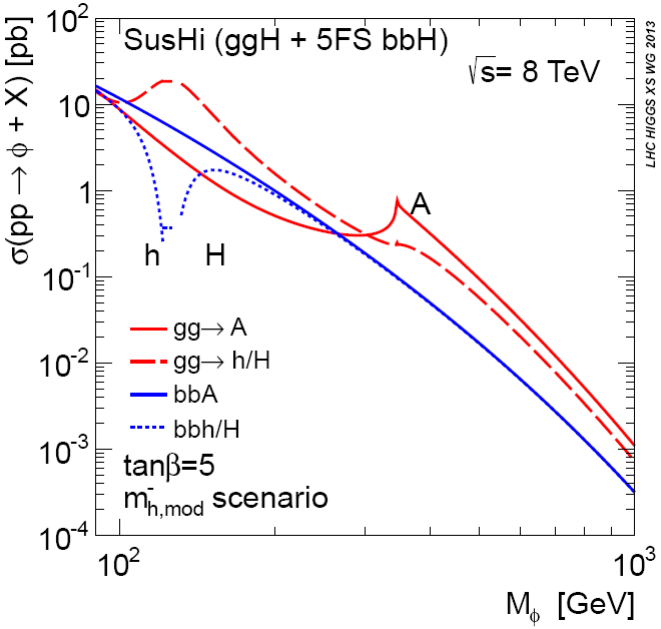
h, H - CP even scalars,
A - CP odd scalar,
H± - charged scalars

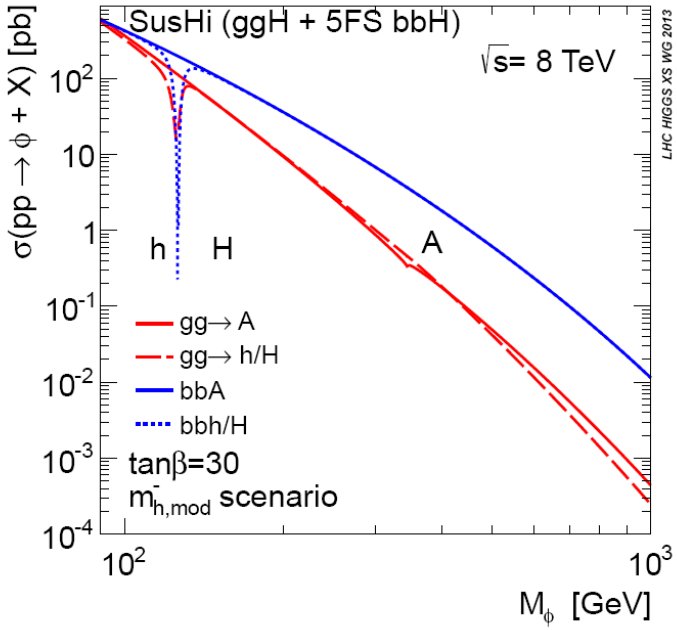
Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}/g_{\Phi H^+W^-}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\propto\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$\propto\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

Couplings are shared between the Higgses: $\sum_i g_{H_iVV}^2 = \left(g_{HVV}^{\rm SM}\right)^2$

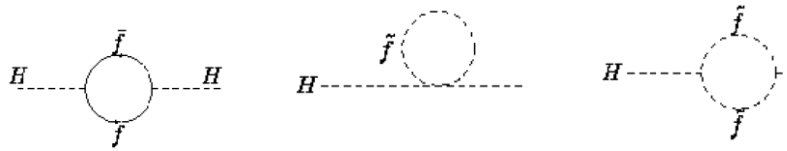

M_Φ [GeV]
$X_t = \sqrt{6} M_S$
$\tan\beta = 3$
$\tan\beta = 30$
H
h
$H^\pm$
HDECAY
M_A [GeV]


m_h^{max} scen., tanβ = 5
h
H
A
H^{+-}
M_{Higgs} [GeV]
FeynHiggs2.2
M_A [GeV]


SusHi (ggH + 5FS bbH)
$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2013
σ(pp → ϕ + X) [pb]
h
H
A
gg→ A
gg→ h/H
bbA
bbh/H
tanβ=5
$m_{h,mod}^-$ scenario
M_ϕ [GeV]


SusHi (ggH + 5FS bbH)
$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2013
σ(pp → ϕ + X) [pb]
h
H
A
gg→ A
gg→ h/H
bbA
bbh/H
tanβ=30
$m_{h,mod}^-$ scenario
M_ϕ [GeV]

M_H is protected due to cancellation of Λ^2 dependence!



talk by Stefania
talk by Tao
talk by David
talk by Pawel

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

($X_t = \sqrt{6}\, M_{SUSY}$ Maximal mixing scenario)

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot\beta$$

Only two parameters at tree level

$$\tan\beta \equiv \frac{v_2}{v_1}$$, M_A

But large loop correction

$$M_h^2 \leq M_Z^2 + \Delta m_h^2$$

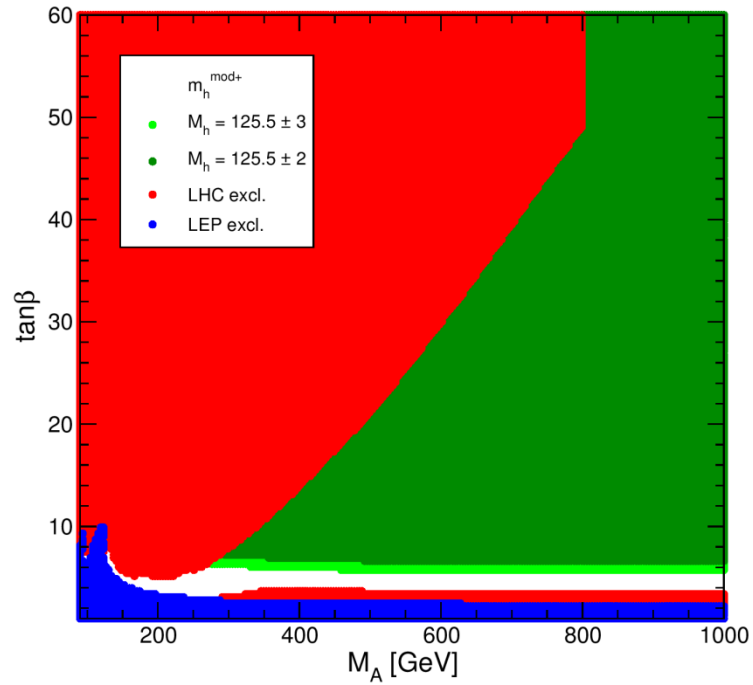
125 GeV^2 91 GeV^2 86 GeV^2

Available parameter range after all constrains ?

Carena, Heinemeyer, Stal, Wagner, Weiglein'13

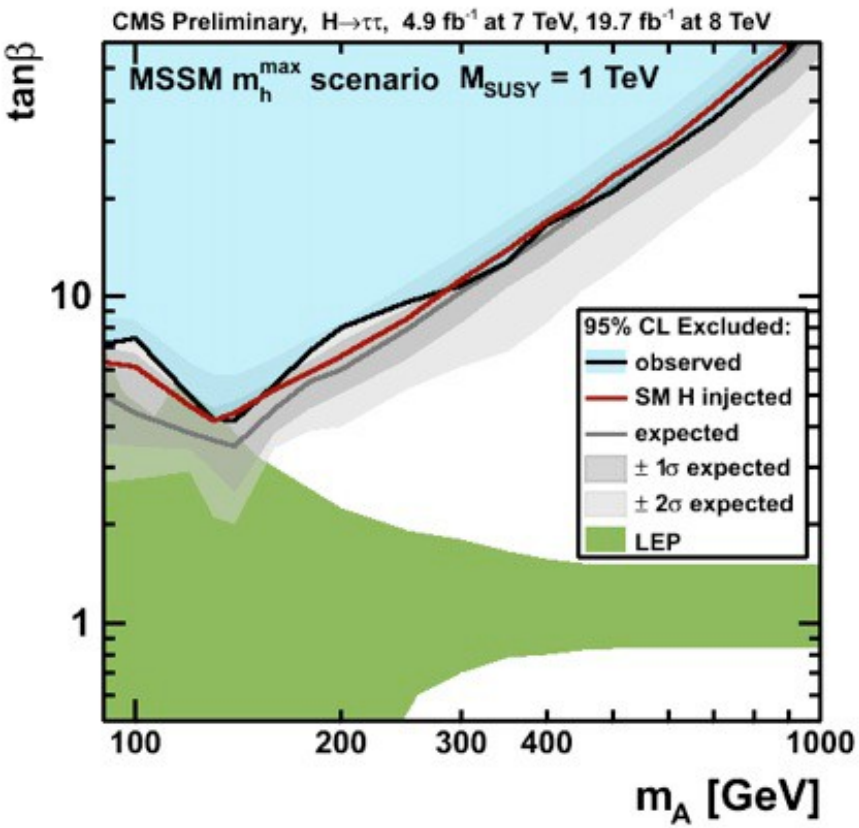
Parameter	$m_h^{\max}$	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$	*light stop*	*light stau*	*τ-phobic*	*low-M_H*
m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
M_A	varied	varied	varied	varied	varied	varied	110
$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
M_{SUSY}	1000	1000	1000	500	1000	1500	1500
$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
$X_t^{\text{OS}}/M_{\text{SUSY}}$	2.0	1.5	−1.9	2.0	1.6	2.45	2.45
$X_t^{\overline{\text{MS}}}/M_{\text{SUSY}}$	$\sqrt{6}$	1.6	−2.2	2.2	1.7	2.9	2.9
A_t	Given by $A_t = X_t + \mu\cot\beta$						
A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	0	$= A_t$
μ	200	200	200	350	500 (450)	2000	varied
M_1	Fixed by GUT relation to M_2						
M_2	200	200	200	350	200 (400)	200	200
$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0

Carena, Heinemeyer, Stal, Wagner, Weiglein '14

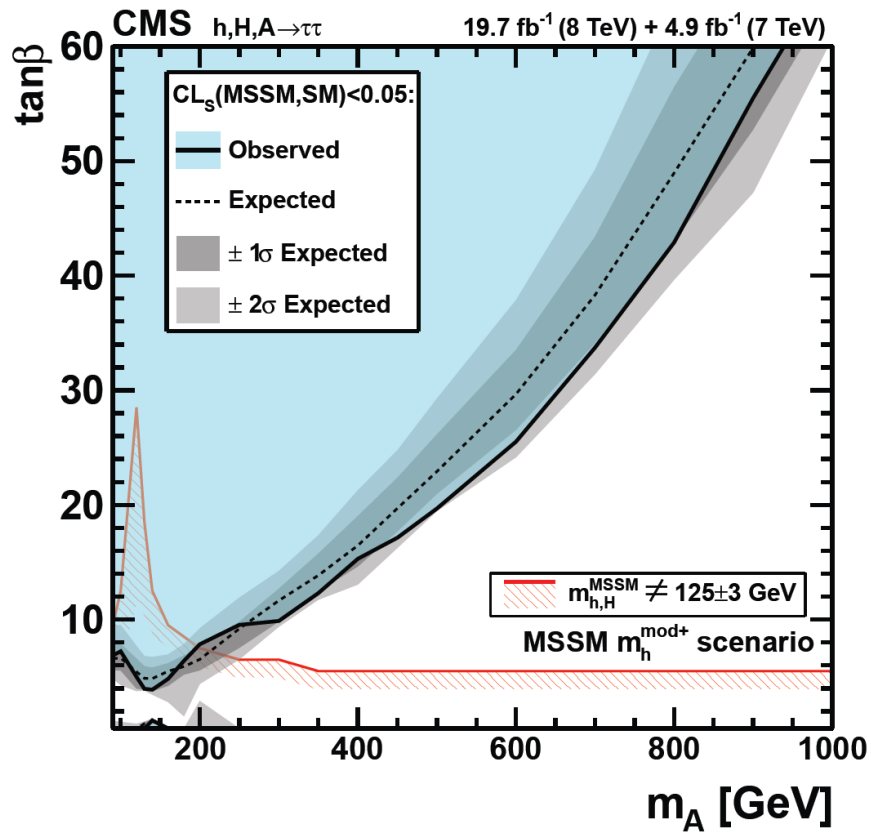


Intensively used in experimental analyses

CMS searches as an example



1408.3316



hMSSM

M_h is fixed to be 125 GeV

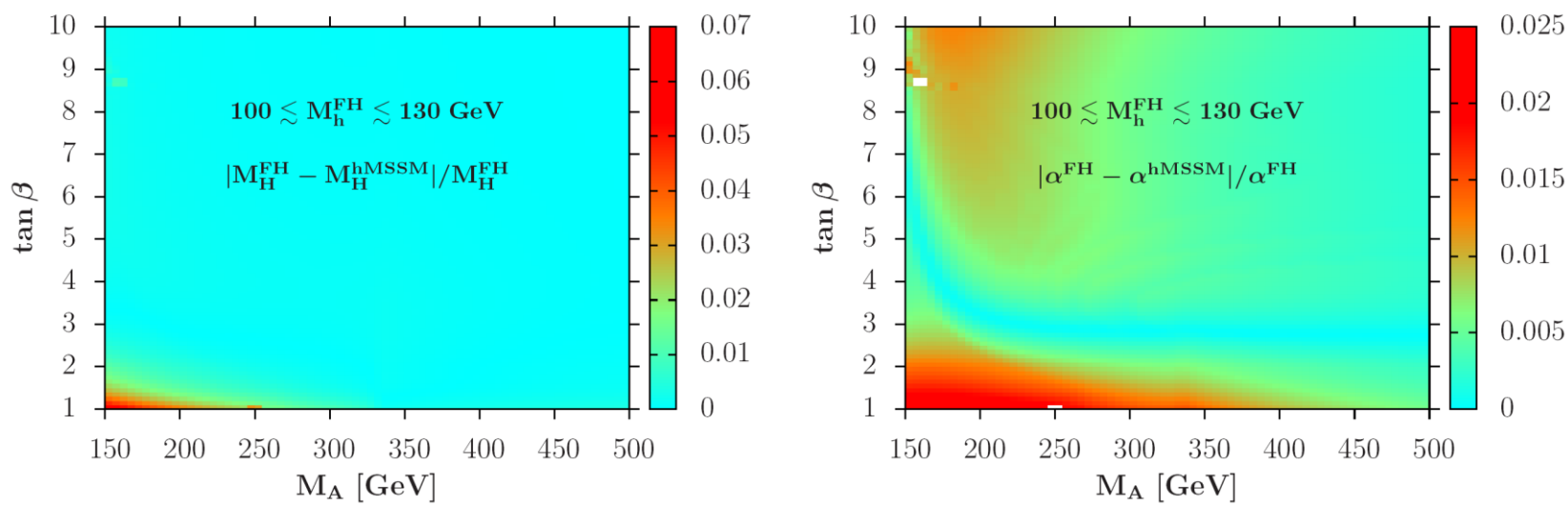
With few simplified assumptions one gets (including leading loops)

$$M_H^2 = \frac{(M_A^2 + M_Z^2 - M_h^2)(M_Z^2 \cos^2\beta + M_A^2 \sin^2\beta) - M_A^2 M_Z^2 \cos^2 2\beta}{M_Z^2 \cos^2\beta + M_A^2 \sin^2\beta - M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2 + M_A^2)\cos\beta\sin\beta}{M_Z^2 \cos^2\beta + M_A^2 \sin^2\beta - M_h^2}\right)$$

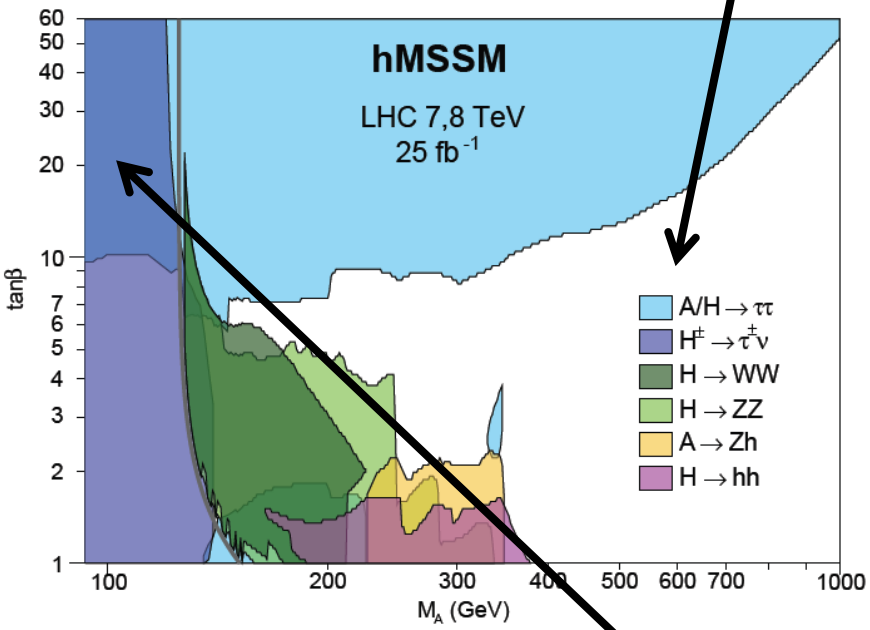
Djouadi, Maiani, Moreau, Polosa, Quevillon, Riquer (1502.05653)

Validation with FeynHiggs



Parameter space to be covered in future

1502.05653



hMSSM approximation is not valid

NMSSM

Fayet '75;
Dine, Fischler, Srednicki '81;
Nilles, Srednicki, Wyler '83;
Ellis, Gunion, Haber,
Roszkowski, Zwirner '85
Vysotsky, ter-Martirosian '86
…
King, Mühlleitner, Nevzorov'12
Beskidt, de Boer, Kazakov '13
King, Mühlleitner, Nevzorov, Walz '14
…
…

MSSM + a singlet chiral superfield

Physical Higgses:

SM 4 – 3 = 1 h

MSSM (2HDM) 2*4 – 3 = 5 CP-even H1, H2; CP-odd A; charged $H^{\pm}$

NMSSM (2HDM + complex scalar) 2*4 + 2 – 3 = 7 CP-even H1, H2, H3; CP-odd A1, A2; charged $H^{\pm}$ (for CP conserving case)

- μ-problem is solved dynamically $\mu(H_u^{\mathrm{T}}\epsilon H_d) \longrightarrow \lambda S\left(H_u^{\mathrm{T}}\epsilon H_d\right) + \frac{1}{3}\kappa S^3$

- less fine tunning compared to MSSM $m_Z^2\cos^2(2\beta) \longrightarrow m_Z^2\left(\cos^2(2\beta) + \frac{2|\lambda|^2\sin^2(2\beta)}{g_1^2+g_2^2}\right)$

NMSSM Higgs Lagrangian

$$
\begin{aligned}
V &= V_F + V_D + V_{soft} + \Delta V \,, \\
V_F &= \lambda^2 |S|^2 (|H_1|^2 + |H_2|^2) + \lambda^2 |(H_1 \epsilon H_2)|^2 + \lambda\kappa \left[S^{*2} (H_1 \epsilon H_2) + h.c. \right] + \kappa^2 |S|^4 \,, \\
V_D &= \frac{g^2}{8} \left(H_1^+ \sigma_a H_1 + H_2^+ \sigma_a H_2 \right)^2 + \frac{g'^2}{8} \left(|H_1|^2 - |H_2|^2 \right)^2 \,, \\
V_{soft} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_S^2 |S|^2 + \left[\lambda A_\lambda S (H_1 \epsilon H_2) + \frac{\kappa}{3} A_\kappa S^3 + h.c. \right] \,,
\end{aligned}
$$

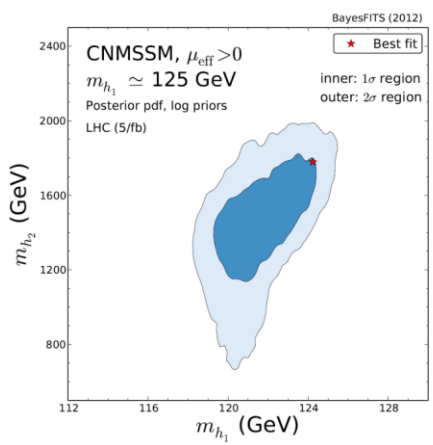
$H_1 = H_d$, $H_2 = H_u$

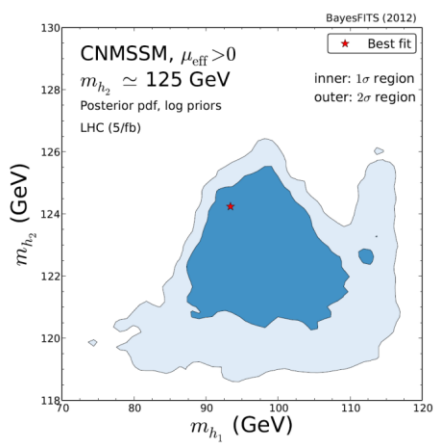
Parameters at three level

λ, κ, A_λ, A_κ, $\tan\beta = v_2/v_1$, $\mu_{eff} = \lambda \langle S \rangle$

Many open possibilities

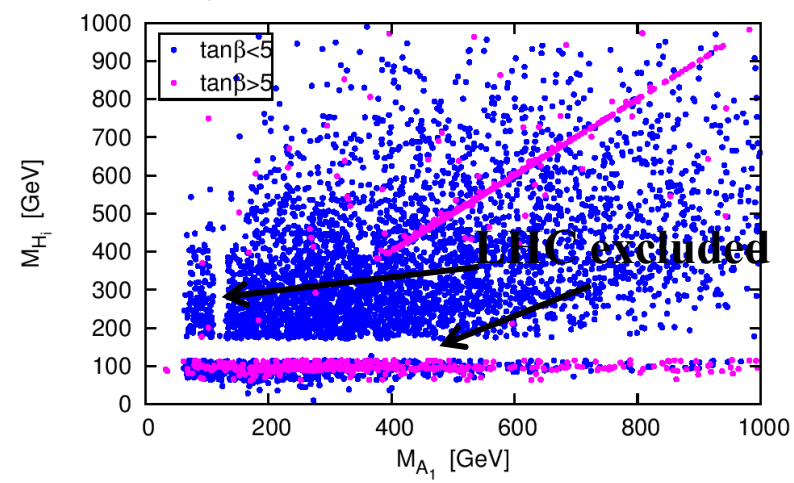
Kowalska et al '12





King, , Mühlleitner, , Nevzorov, Walz '14

H_i (i=1,2) is the non-SM-like CP-even Higgs boson



FlexibleSUSY
http://flexiblesusy.hepforge.org/

NMSSMCALC
http://www.itp.kit.edu/~maggie/NMSSMCALC/

NMSSMTools
http://www.www.th.u-psud..fr/NMHDECAY/nmssmtools.html

SoftSUSY
http://softsusy.hepforge.org/

SPheno
http://spheno.hepforge.org/

……

Validation, Comparison,
Understanding the differences
1507.05093
Staub, Athron, Ellwanger, Gröber, Mühlleitner, Slavich, Voigt

For example,

Set of parameters used in the NMSSMCALC code performing higher order and and CP violating studies

$$\underbrace{t_{h_d},\, t_{h_u},\, t_{h_s},\, t_{a_d},\, t_{a_s},\, M_W^2,\, M_Z^2,\, e,\, M_{H^\pm}^2}_{\text{on-shell}},\ \underbrace{\tan\beta,\, v_s,\, |\kappa|,\, |\lambda|,\, \mathrm{Re}A_\kappa,\, \varphi_y,\, \varphi_z'}_{\overline{\mathrm{DR}}}$$

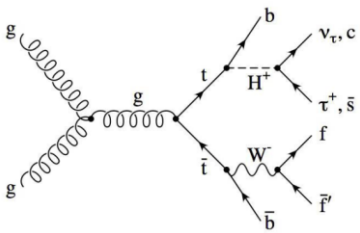
Tadpoles $t_x = \langle \partial V/\partial x \rangle = 0$ ($x = h_d, h_u, h_s, a_d, a_s$)

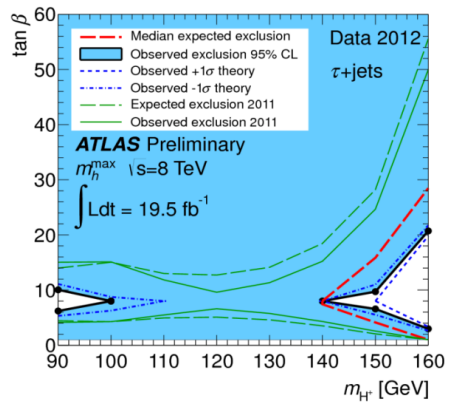
Bench mark NMSSM scenarios under intensive discussions

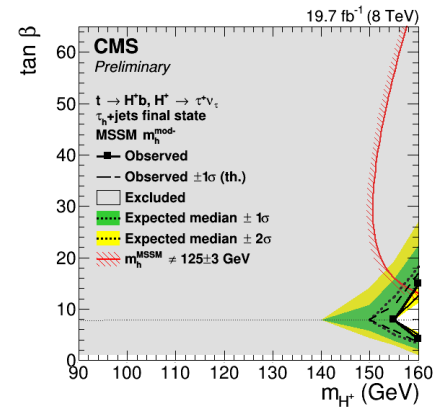
BSM Higgs WG3 (Low, Mühlleitner, Pelliccioni, Rompotis)

Charged Higgses are predicted in many BSM (2HDM, MSSM, NMSSM…)

Light H± in top decays

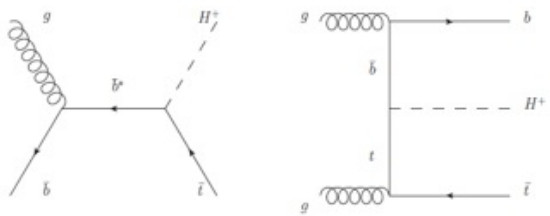


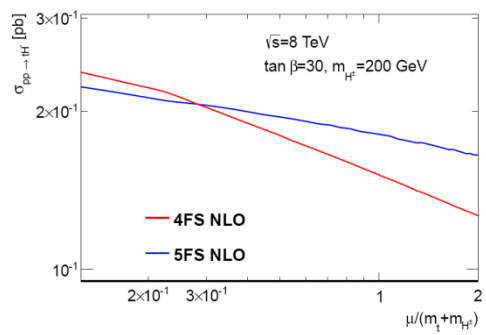


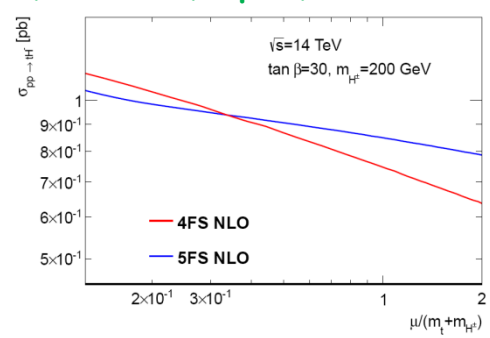


Flechl, Klees, Kraemer, Spira, Ubiali '14

Heavy H± in associated production

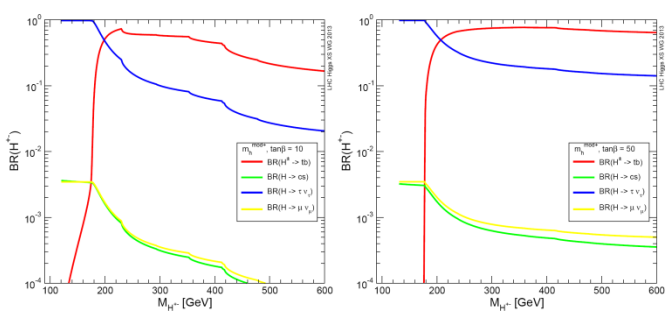


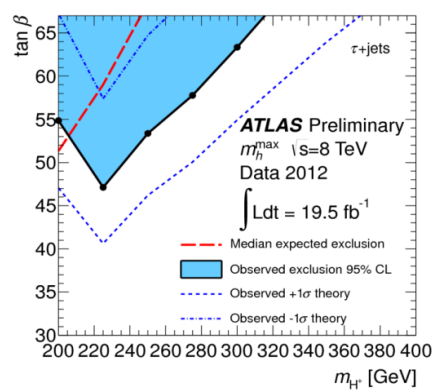




Decay modes

Heinemeyer et al. [LHC HCSWG] '13





Tao Han

EW production

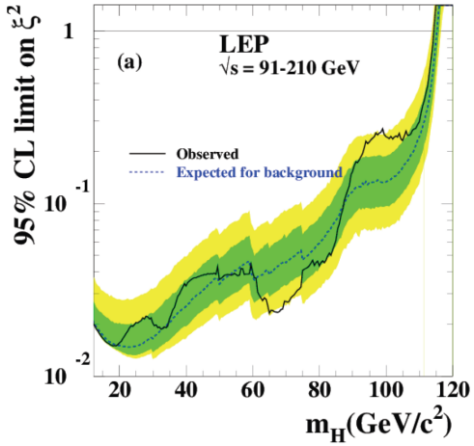
$W^+W^- \to H^+H^-$

$\gamma/Z\,\gamma/Z \to H^+H^-$

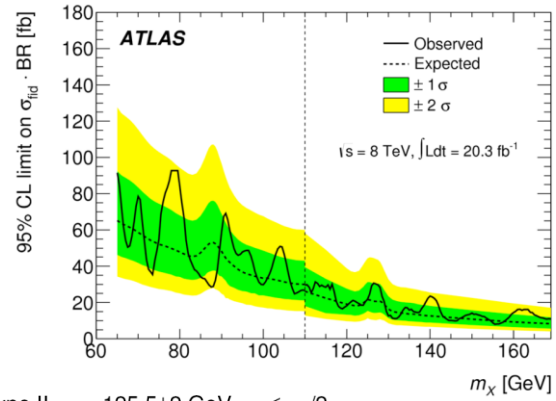
Heavier Higgs is 125 GeV Higgs and other state(s) is (are) lighter

Not excluded yet if hVV coupling is suppressed

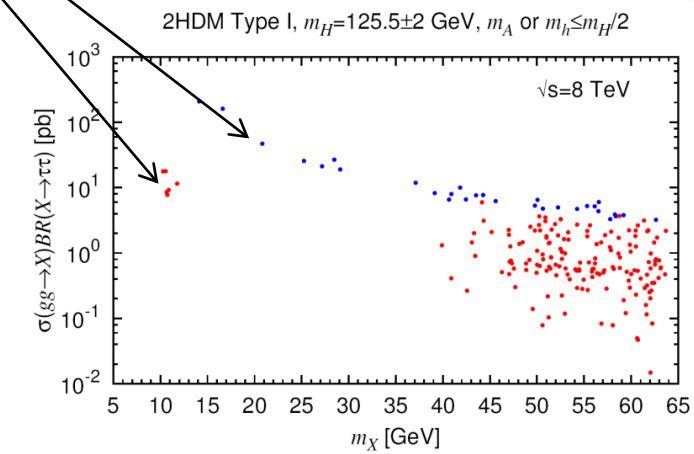
$\xi = g_{hVV}^{SM}/g_{hVV}^{BSM}$

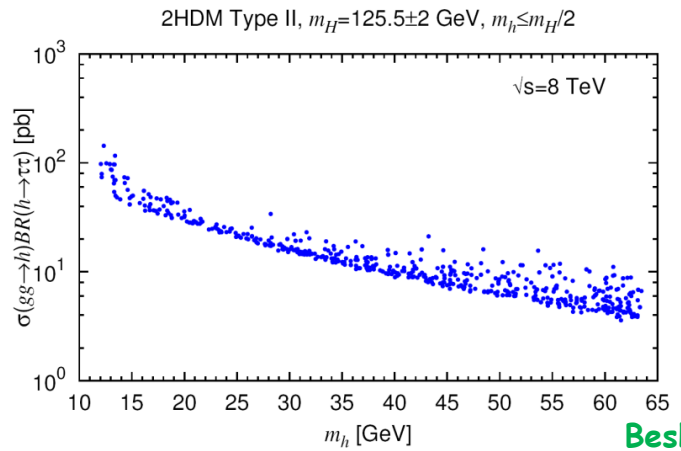


ATLAS search in γγ-mode



h A

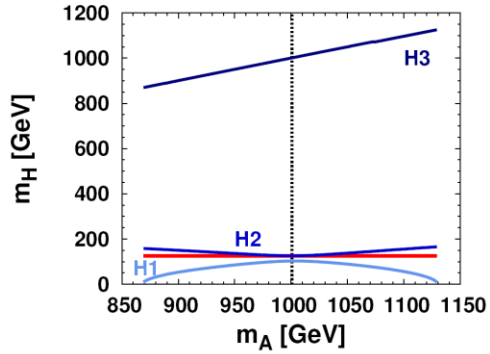


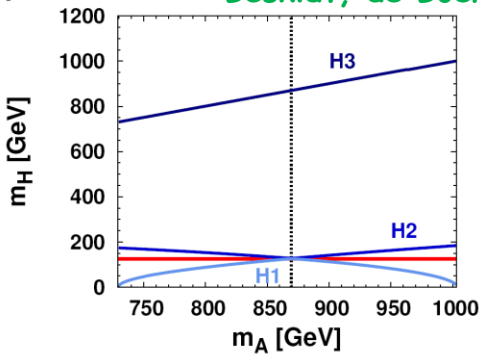


Bernon, Gunion, Jiang, Kraml '14,15

Beskidt, de Boer, Kazakov '13

Also possible at various NMSSM scenarios





Concluding remarks

1. New Higgs-like state is found being in an agreement with the SM Higgs. However a precision of various signal strength measurements is still not good leaving many possibilities (parameter points) for extended Higgs models, in particular, for 2HDM, MSSM, NMMSM, which satisfy all the constrains from EW precision observables, flavor ($Br(B\to s\gamma)$ and B_0-antiB_0 mixing), unitarity, perturbativity and vacuum stability, and DM.

2. In some variants - one of the states is 125 GeV CP even scalar boson and another Higgs(es) could be heavier or lighter, or nearly degenerate.

3. Reinterpretation of the same experimental searches in various extended Higgs models

4. Very delicate task to cover all areas in model parameter spaces. Motivated way to proceed – benchmark scenarios. Tools are important

Very difficult or even impossible to exclude completely discussed extensions…

Of course, it helps if something new (e.g., not yet excluded light Higgs state) will be found

Many thanks to the organizers!

Apologizes for not mentioning many important studies

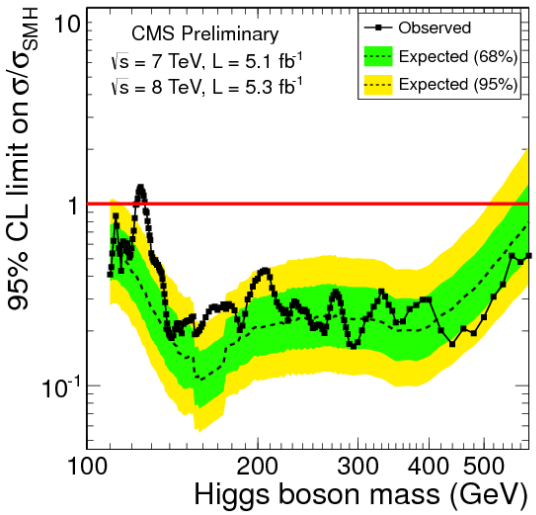
After a (the) Higgs boson discovery in 2012

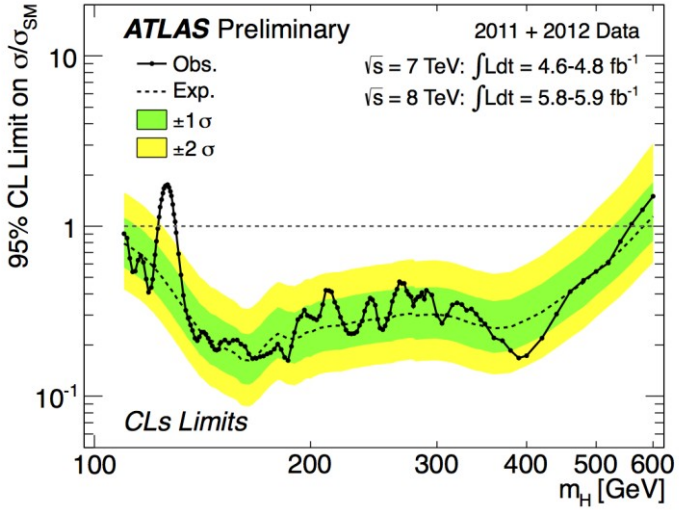
MSSM papers > 280 NMSSM papers > 100 2HDM papers > 50

in 2015

MSSM papers > 70 NMSSM papers > 40 2HDM papers > 15

Back up slides

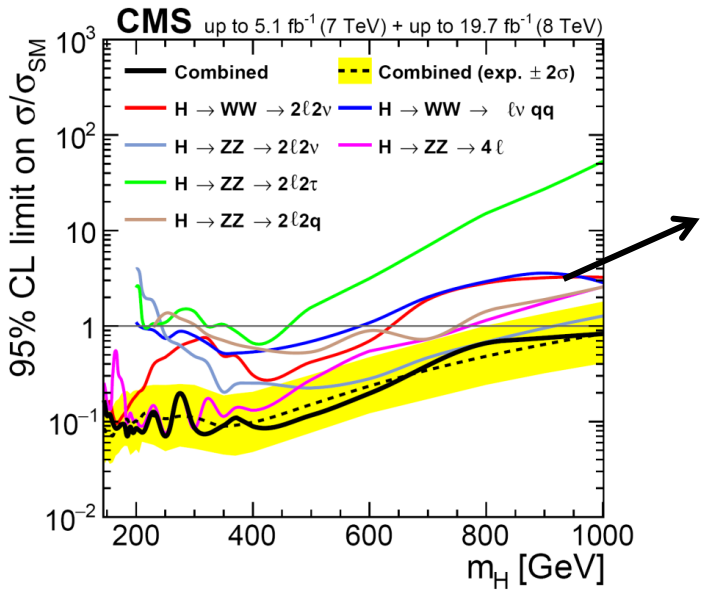




Both CMS and ATLAS have excluded SM Higgs in the mass interval up to 600 GeV

Exclusion region was extended up to about 1 TeV

CMS 1504.00936



ATLAS 1507.05930