Singlet Higgs and Double Higgs Production

Víctor Martín Lozano
Universidad Autónoma de Madrid
Instituto de Física Teórica

VII CPAN Days
01/12/2015

In collaboration with Jesús Moreno and Chan Beom Park,
based on **JHEP 1508 (2015) 004** (arXiv: 1501.03799)

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European Research Council

SPLE Advanced Grant

Introduction

- The addition of a scalar singlet is the MINIMAL extension of the Higgs sector.
- Helps to stabilize the Higgs potential at high energy.
- Induces 1st order Electroweak Phase Transition
- Provides mass to right handed neutrinos.
- Connects to DM sector:
  - Dark Matter candidate $\rightarrow \mathbb{Z}$ symmetry.
  - Acts as a portal.

The Model

Potential,

$$V(\Phi,S) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{\alpha}{3}S^2 + \frac{\lambda_S}{4}S^4 + \frac{\omega}{2}(\Phi^\dagger\Phi)S + \frac{\lambda_{\Phi S}}{2}(\Phi^2\Phi)S^2$$

After EWSB,

$$\Phi = \begin{pmatrix} 0 \\ v+\phi \end{pmatrix} \qquad S = s + v_s$$

Mass Eigenstates,

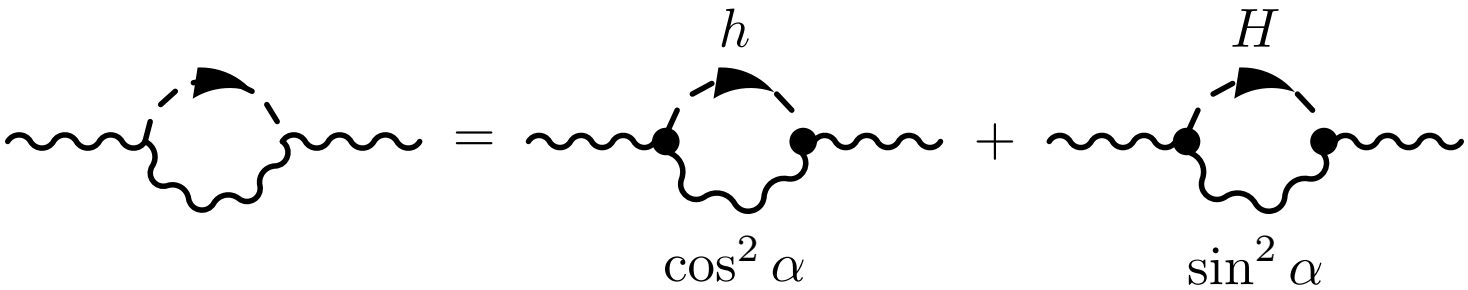
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix}$$

We assume that h is the scalar boson discovered at LHC ($m_h \sim 125$ GeV) and $m_H > m_h$

Constraints

Electroweak Precision Data

The Higgs boson is involved in 1-loop corrections to the electroweak observables.



These corrections are sensitive to both the Higgs mass and the Higgs couplings

We consider the variables S, T and U, as well as a set of observables.

$$(m_W, \Gamma_W, \Gamma_Z, \sigma^0_{had}, R^0_\ell, A^{0,\ell}_{FB}, A_\ell, \sin^2\theta^\ell_{eff}, A_c, A_b, A^{0,c}_{FB}, A^{0,b}_{FB}, R^0_c, R^0_b)$$

Constraints

LHC Higgs Data

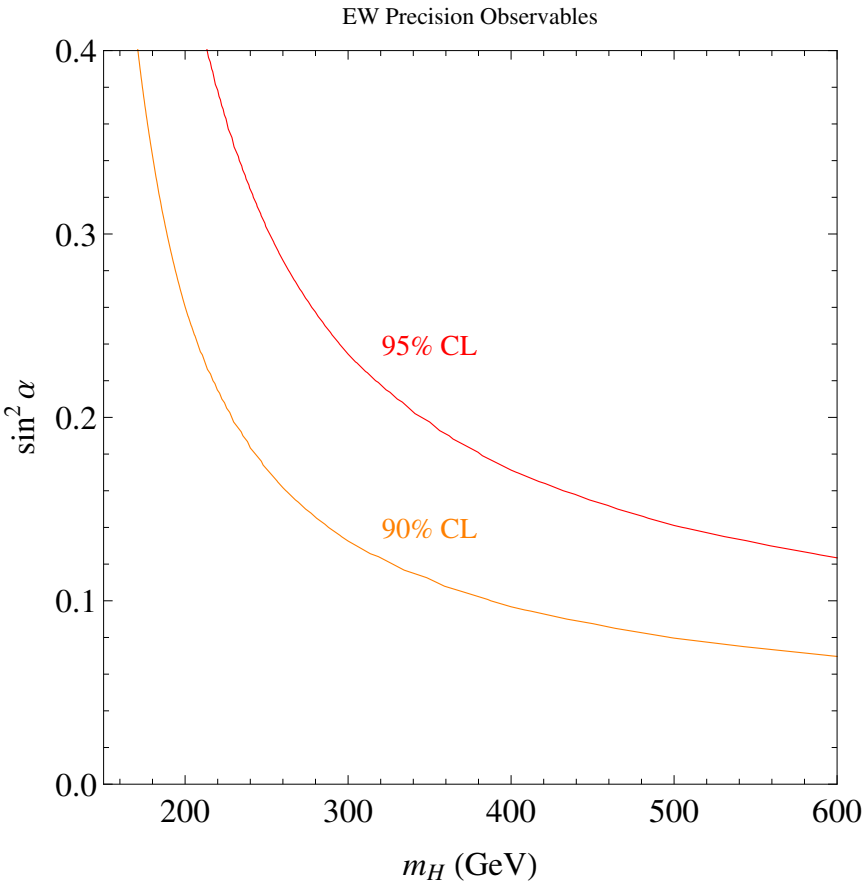
The mixing angle can be constrained from the SM-like Higgs boson signal strength

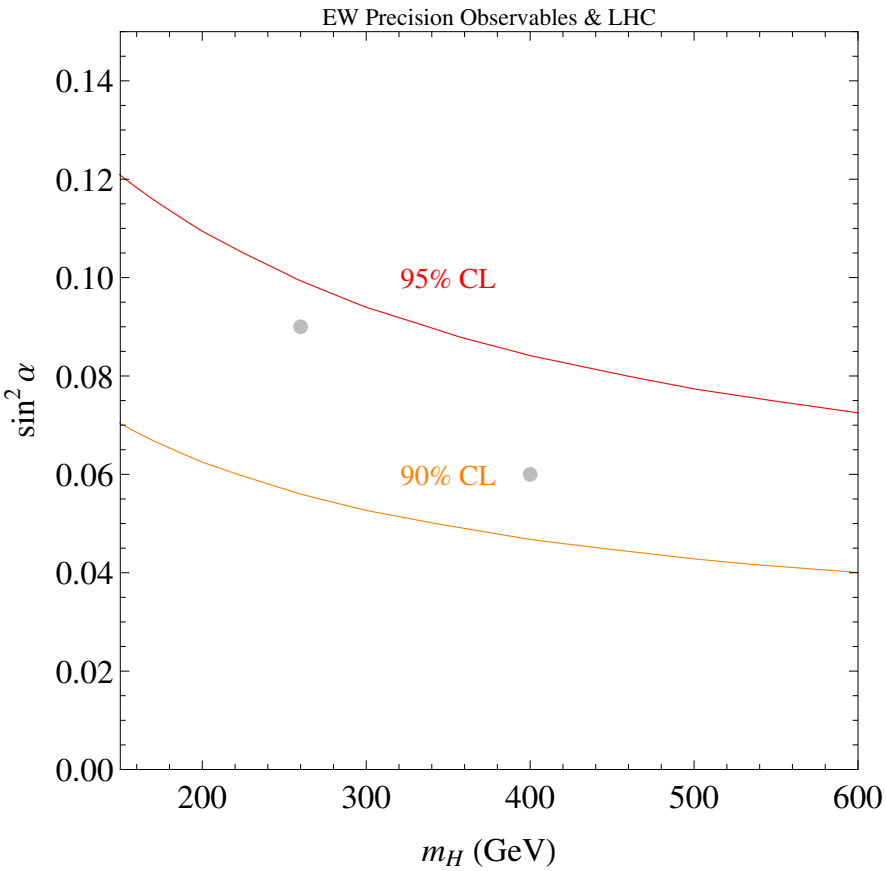
$$\frac{\mu}{\mu_{exp}} = \frac{\sigma \times BR}{\sigma \times BR_{exp}} = \cos^2 \alpha$$

$$\mu_{\text{ATLAS+CMS}} = 1.09 \pm 0.10$$

$$\sin^2 \alpha < 0.080(0.133) \text{ at } 90\% \ (95\%) \text{ CL}$$

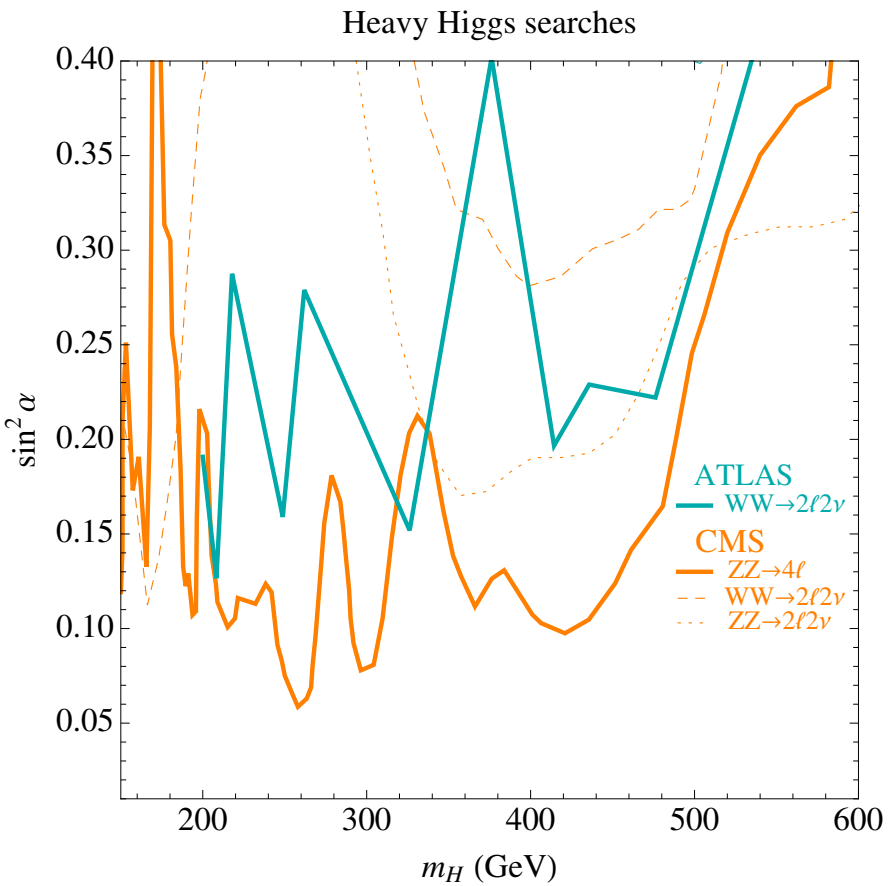
Constraints

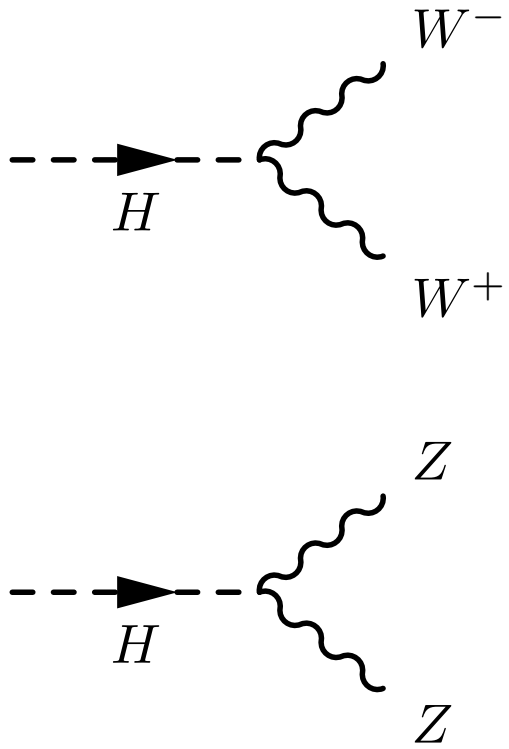




Constraints

LHC Heavy Higgs Data



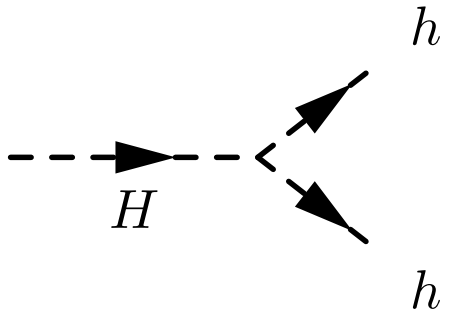


$$\mathrm{BR}(H \to hh) = 0$$

Double Higgs Production

Double Higgs production

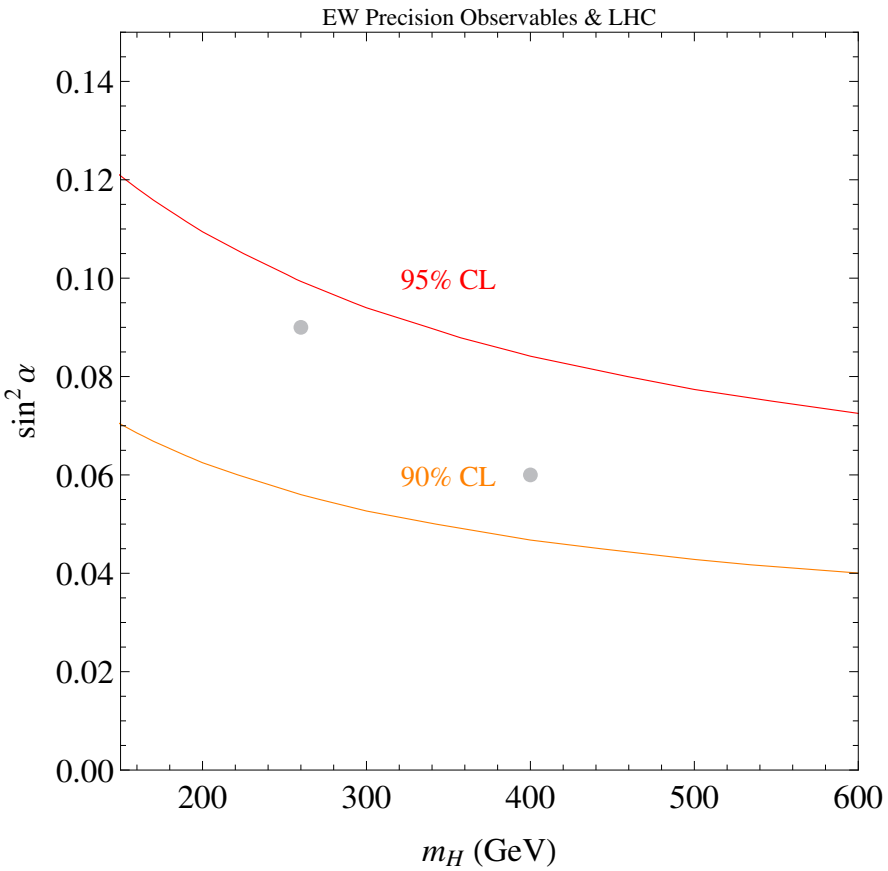
- Dominant decay: $H \to hh \to b\bar{b}b\bar{b}$
  - Four jets
  - Poor reconstruction efficiency $\sim \epsilon_b^4$
- Subleading decay: $H \to hh \to b\bar{b}WW^*$
  - Fully hadronic: Reconstruction + jets
  - Leptonic: Missing Energy from neutrinos $\to$ difficulties reconstructing the Higgs mass



$H \to hh \to b\bar{b}WW^* \to b\bar{b}\ell^+\nu\ell^-\bar{\nu}$ is less vulnerable concerning jet reconstruction but more challenging.

Double Higgs Production

Benchmark Points



- $m_H = 400$ GeV, $\sin^2\alpha = 0.06$, $\sigma = 1.09$ pb
- $m_H = 260$ GeV, $\sin^2\alpha = 0.09$, $\sigma = 1.71$ pb

Double Higgs Production

Background

Process	Cross section
$H \to hh$ $(m_H = 400\,\text{GeV})$	0.66
$H \to hh$ $(m_H = 260\,\text{GeV})$	1.18
$t\bar{t}$	844.43
GGF h	50.35
VBF h	4.17
hW/Z	2.39
$ht\bar{t}$	0.61
hh	0.033
DY	91130.0
Di-boson	121.0

$t\bar{t} \to$ TOP ++

GGF, VBF h $\to$ Pythia 8

Drell-Yan $\to$ Pythia 8

hh $\to$ HPair-Pythia 6

Rest $\to$ Pythia 8

Double Higgs Production

Cuts

$$m_H = 400 \text{ GeV}$$

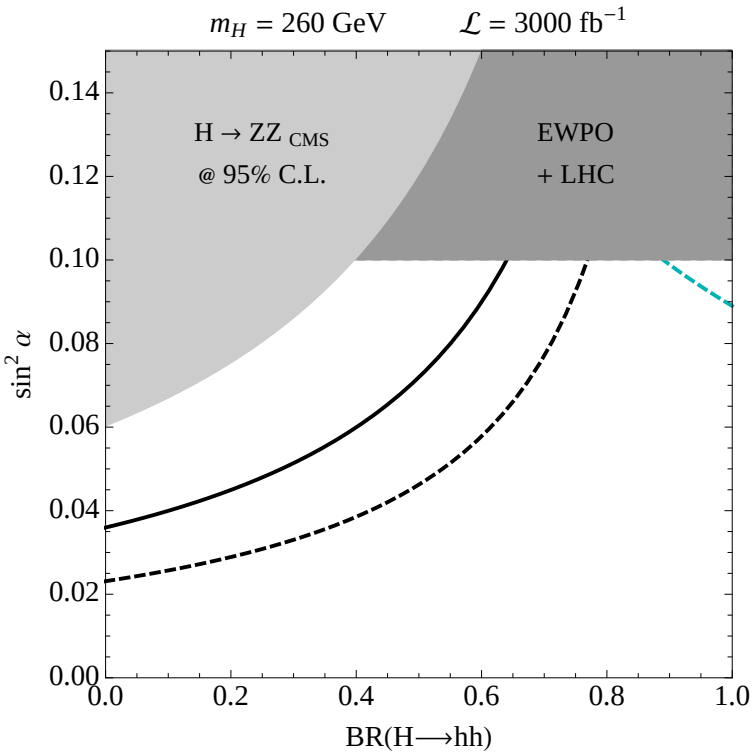
Selection cuts	$H \to hh$	$t\bar{t}$	GGF h	$ht\bar{t}$	hh	DY	VV	$\hat{\sigma}_{3000}$
Basic selection	0.54	3560.36	0.15	0.072	0.024	272.41	0.90	0.48
$\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, $p_{\rm T}^{\ell\ell}$	0.40	562.02	0.11	0.015	0.019	33.56	0.047	0.90
$m_{\ell\ell}$, $M_{\rm T2}^{\ell\ell}$	0.36	314.95	0.097	0.009	0.017	11.20	0.0	1.1
$m_h^{\rm maos}$, $M_{\rm T}^{\ell\ell}$	0.33	237.96	0.097	0.007	0.015	11.20	–	1.2
ΔR_{bb}, $p_{\rm T}^{bb}$	0.23	73.03	0.008	0.002	0.012	3.73	–	1.4
m_{bb}	0.14	16.24	0.0	$\simeq 0.0$	0.007	0.0	–	1.9
$\Delta\phi_{bb,\ell\ell}$, $m_{bb\ell\ell}$	0.13	11.99	–	–	0.005	–	–	2.1
$M_{\rm T2}^{bb\ell\ell}$	0.059	1.31	–	–	0.004	–	–	2.8
Signal region	0.048	0.70	–	–	$\simeq 0.0$	–	–	3.1

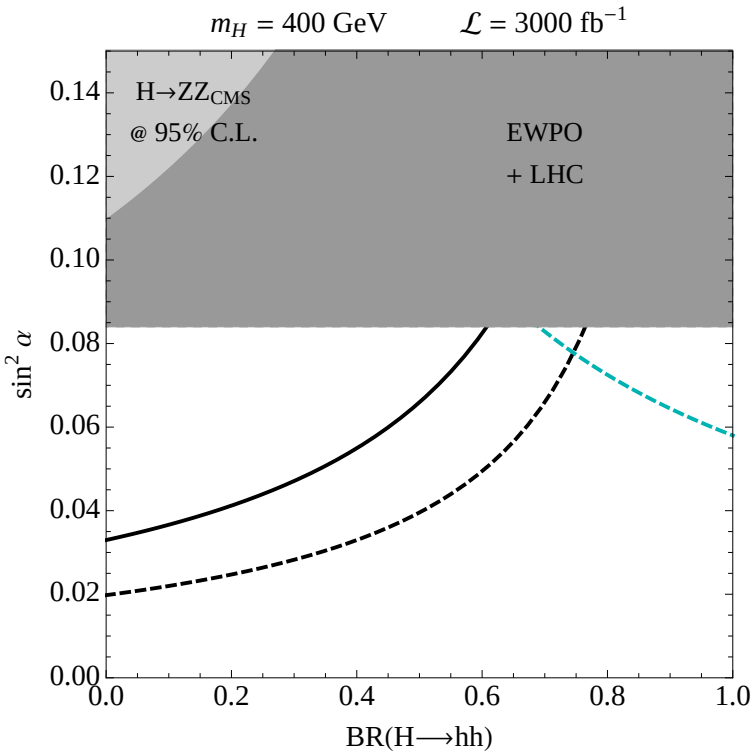
$$m_H = 260 \text{ GeV}$$

Selection cuts	$H \to hh$	$t\bar{t}$	GGF h	$ht\bar{t}$	hh	DY	VV	$\hat{\sigma}_{3000}$
Basic selection	0.48	3560.36	0.15	0.072	0.024	272.41	0.90	0.43
$\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, $p_{\rm T}^{\ell\ell}$	0.28	818.01	0.15	0.020	0.022	48.51	0.095	0.70
$m_{\ell\ell}$, $M_{\rm T2}^{\ell\ell}$	0.21	206.23	0.11	0.006	0.007	0.0	0.0	0.80
$m_h^{\rm maos}$, $M_{\rm T}^{\ell\ell}$	0.19	140.69	0.08	0.004	0.005	–	–	0.88
ΔR_{bb}, m_{bb}	0.104	6.65	0.008	$\simeq 0.0$	$\simeq 0.0$	–	–	2.21
$m_{bb\ell\ell}$	0.009	3.03	0.008	–	–	–	–	2.82
$M_{\rm T2}^{bb\ell\ell}$	0.083	2.29	0.0	–	–	–	–	2.99
Signal region	0.083	2.19	–	–	–	–	–	3.06

Double Higgs Production

Results





Conclusions

- LHC data are compatible with the minimal extension of the Higgs sector.
- $H \to hh$ decay offers a new opportunity at the LHC.
- The $H \to hh \to b\bar{b}\ell^+\nu\ell^-\bar{\nu}$ channel is promising but also challenging.
- A significance ~ 3 is achieved for a LHC configuration of $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000$ fb^{-1}. It should be combined with different channels.
- Nice complementarity between this search, $H \to hh$ and the $H \to ZZ$.