Singlet Benchmarks for LHC Run II

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WG3: Extended scalars benchmarking

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benchmarks mostly based on arXiv:1501.02234

The model

Simplest extension of the Standard Model (SM) by a real Higgs singlet S with non-zero VEV x.

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda\Phi^\dagger\Phi S^2$$

with $\Phi = \begin{pmatrix} 0 & \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}^T$ and $S = \frac{h'+x}{\sqrt{2}}$.

(Z_2 symmetry imposed to forbid linear and cubic terms of S in potential.)

Mass eigenstates given by rotation of gauge eigenstates

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}$$

Model can be fully parametrized in terms of 5 parameters,

$$m_h,\ m_H,\ \alpha,\ v,\ \tan\beta \equiv v/x,$$

out of which two parameters $(m_{H_{\mathrm{SM}}},\ v)$ are known.

Higgs production and decay rates

Higgs production cross sections are suppressed by mixing angle α:

$$\sigma_h(m) \simeq \cos^2\alpha \cdot \sigma_{H_{\mathrm{SM}}}(m) \qquad \text{(light Higgs)}$$

$$\sigma_H(m) \simeq \sin^2\alpha \cdot \sigma_{H_{\mathrm{SM}}}(m) \qquad \text{(heavy Higgs)}$$

(neglecting interference effects)

Decay rates of h, H as in SM, unless Higgs-to-Higgs decay $H \to hh$ is kinematically accessible:

$$\Gamma_{H\to hh} = \frac{|\mu'|^2}{8\pi m_H}\sqrt{1-\frac{4m_h^2}{m_H^2}}$$

$\Rightarrow$ Heavy Higgs decay rates to SM particles may be suppressed, but opportunity to search for $H \to hh$.

Theoretical and experimental constraints

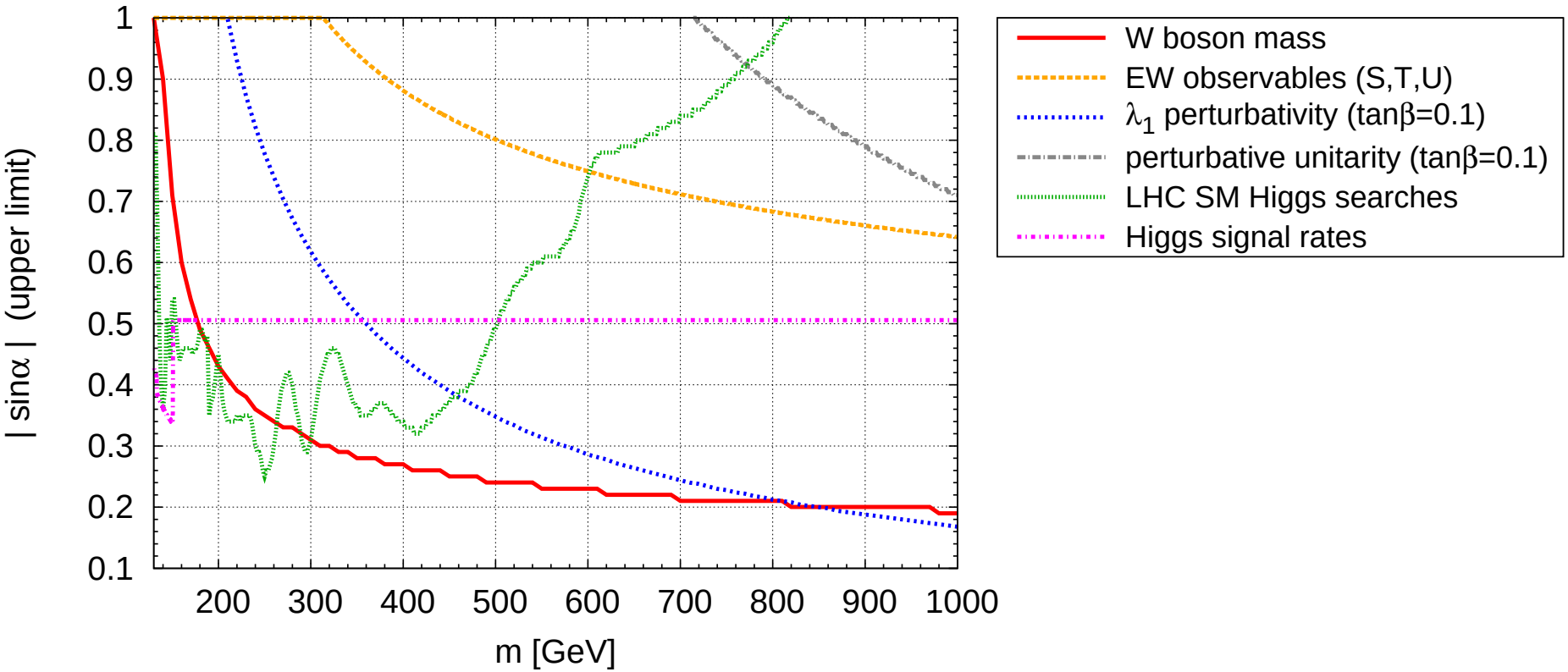
Theoretical constraints:

- Vacuum stability / potential minimization up to scale $\mu_{\text{run}} \sim 4 \times 10^{10}$ GeV,
  (only applied if light Higgs $h \simeq H_{\text{SM}}$)
- perturbative unitarity,
- perturbativity of couplings, $|\lambda_i| \leq 4\pi$, up to scale μ_{run}.

Experimental constraints:

- Electroweak oblique parameters S, T, U,
- NLO calculation of W boson mass, [D. López-Val, T. Robens, arXiv:1406.1043]
- 95% C.L. limits from Higgs searches at LEP and LHC (`HiggsBounds`),
- Consistency with Higgs signal strength (`HiggsSignals`).

Constraints on $|\sin\alpha|$ — Comparison



- Strongest upper limit on $|\sin\alpha|$ obtained from (roughly):

  $m_H \in [130, 300]$ GeV: LHC SM Higgs searches,
  $m_H \in [300, 800]$ GeV: W boson mass,
  $m_H \geq 800$ GeV: perturbativity of couplings.

Search for *(i)* SM-like final states and *(ii)* di-Higgs final states.

Define signal strength scale factors:

$$\kappa \equiv \frac{\sigma}{\sigma_{\text{SM}}} \times \text{BR}(H \to \text{SM}) = \sin^4\alpha \, \frac{\Gamma_{\text{SM,tot}}}{\Gamma_{\text{tot}}}$$

$$\kappa' \equiv \frac{\sigma}{\sigma_{\text{SM}}} \times \text{BR}(H \to hh) = \sin^2\alpha \, \frac{\Gamma_{H\to hh}}{\Gamma_{\text{tot}}}$$

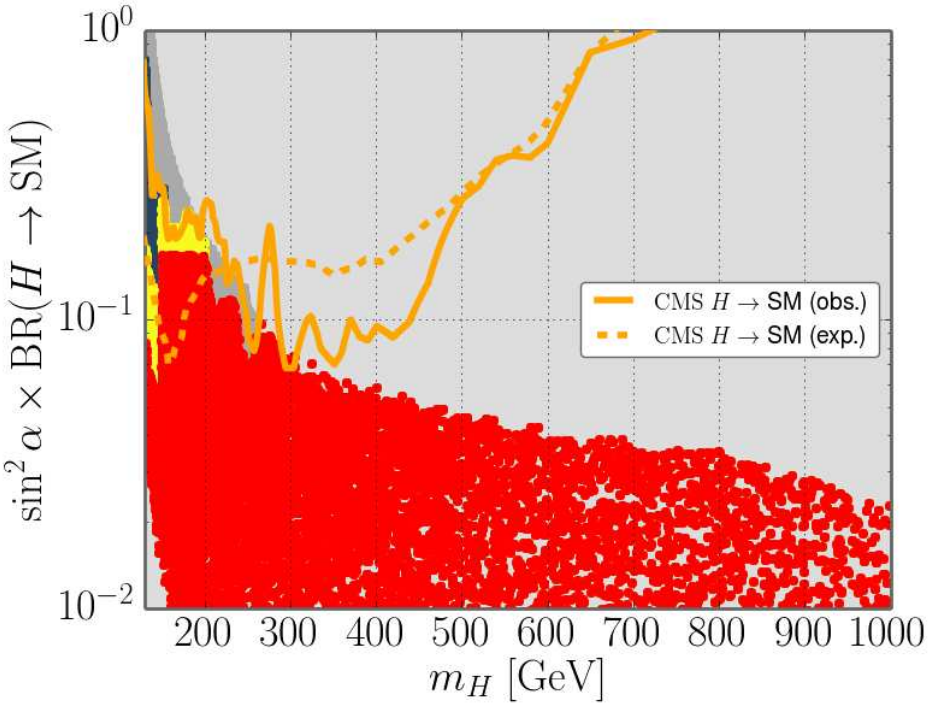
Strategy for defining benchmark scenarios:

Take maximally allowed mixing angle $|\sin\alpha|$, together with either (i) minimal or (ii) maximal $\text{BR}(H \to hh)$.

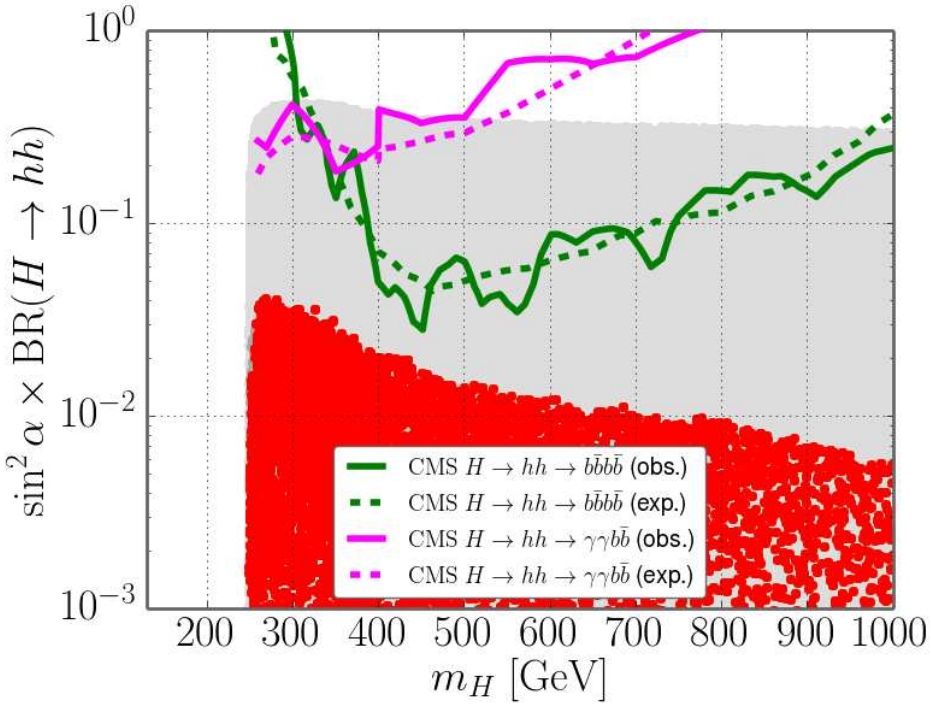
$\Rightarrow$ *Expected signal rate in relevant search channel is maximized.*

Current LHC limits (status: January 2015)

(i) SM particle final states



(ii) Di-Higgs final states

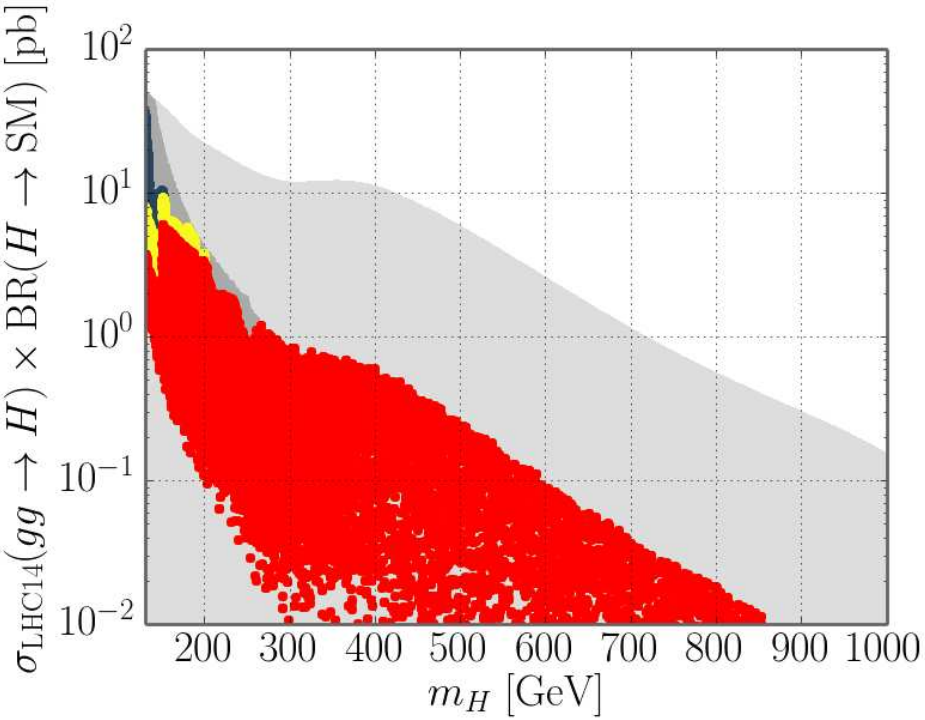


Color code:

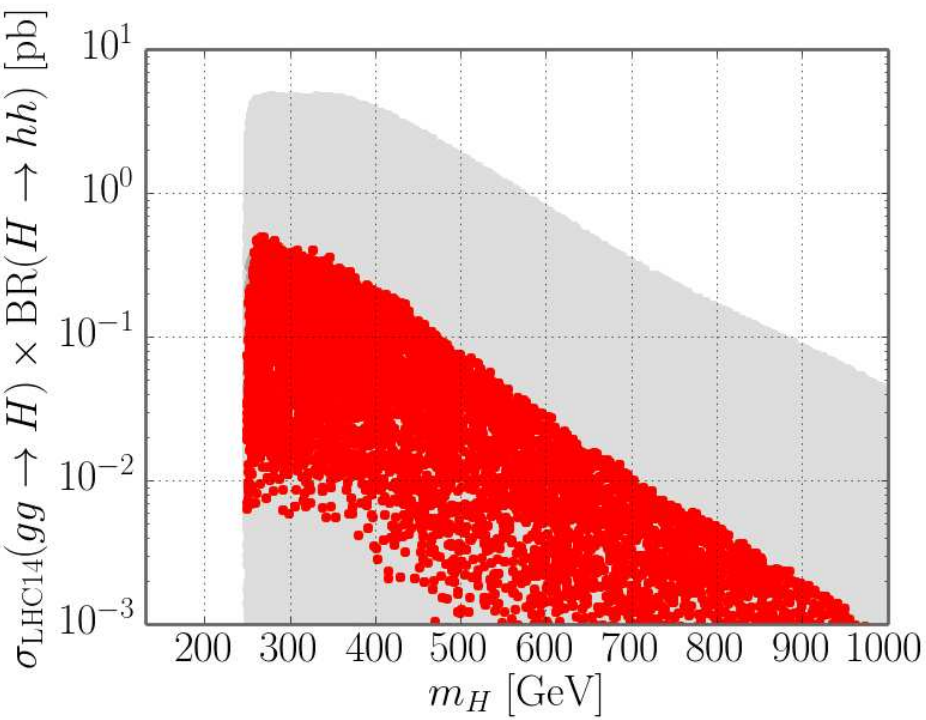
- dark gray fulfill theoretical constraints + S, T, U + W boson mass,
- blue points survive `HiggsBounds` constraints,
- red (yellow) are 1σ (2σ) favored points from `HiggsSignals`.

Translation into LHC $\sqrt{s} = 14$ TeV rates

(i) SM particle final states



(ii) Di-Higgs final states



Note: Naively scaled the SM cross sections predicted by the LHCHXSWG.

Some concrete numbers. . .

The write-up provides detailed tables, e.g.

Mass regime *below* $H \to hh$ threshold:

m_H [GeV]	$\lvert \sin\alpha \rvert_{\max}$	$\tan\beta_{\max}$
130	0.42	1.79
135	0.38	1.73
140	0.36	1.67
...	...	...
245	0.36	0.97

Mass regime *above* $H \to hh$ threshold:

m_H [GeV]	$\lvert \sin\alpha \rvert_{\max}$	$\mathrm{BR}(H \to hh)_{\min}$	$\mathrm{BR}(H \to hh)_{\max}$
250	0.35	0.12	0.26
255	0.35	0.17	0.26
260	0.34	0.18	0.33
...	...	...	...
1000	0.17	0.19	0.21

B. Benchmarks for light Higgs searches ($m_H \simeq 125$ GeV, $|\sin\alpha|_{\rm SM} = 1$)

Search for *(i)* direct production of light Higgs or *(ii)* Higgs at 125 GeV decaying into light Higgs bosons.

(i) Maximally allowed cross section:

m_h [GeV]	$\sigma^{14\ \mathrm{TeV}}_{gg\to h}$ [pb]
120	8.40
110	8.12
100	14.96
90	16.26
80	5.41
70	6.73
60	1.38
50	0.96
40	1.50

(ii) Maximally allowed $\mathrm{BR}(H \to hh)$:

m_h [GeV]	$\sin\alpha$	$\mathrm{BR}(H \to hh)_{\rm max}$
60	0.9996	0.225
50	0.9998	0.251
40	0.9996	0.255
30	0.9999	0.253
20	0.9999	0.251
10	0.9996	0.248

Note: For $\tan\beta = -\arctan\alpha$, the Higg-to-Higgs decay always vanishes, $\mathrm{BR}(H \to hh) = 0$.

Summary

Benchmark proposal for LHC searches for additional singlet-like Higgs states, for the cases

- Heavy additional Higgs boson ($m_H \geq 130$ GeV)

  (i) LHC searches with SM particle final states,

  (ii) LHC searches with di-Higgs final states.

- Light additional Higgs boson ($m_h \leq 120$ GeV)

  (i) LHC searches for direct production of light Higgs,

  (ii) LHC searches for SM-like Higgs decaying into light Higgs bosons.

On the to-do list:

Need precise rate predictions that take interference effects into account.