Higgs Singlet extension in the light of the LHC discovery

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based on

G.M. Pruna, TR (arXiv:1303.1150)

TU Dresden

HHXWG meeting, 30.4.13

1. The model
   - Tree level: rescaling wrt Standard Model
2. Parameter space including bounds
   - Scan suggestion (at tree level)
3. Tools
   - Including higher order corrections: principle
   - Currently avalaible tools (incomplete list)
4. Summary and Outlook

The model (LO)

Higgs Singlett extension (aka The Higgs portal)

The model

- Singlet extension:
  simplest extension of the SM Higgs sector
- add an **additional scalar**, singlet under SM gauge groups
  (further reduction of terms: impose additional symmetries)

$\Rightarrow$ potential (H doublet, χ singlet)

$$\mathbf{V} = -\mathbf{m^2 H^\dagger H} - \mu^2 \mid \chi \mid^2 + \lambda_1 (\mathbf{H^\dagger H})^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 \mathbf{H^\dagger H} \mid \chi \mid^2,$$

- collider phenomenology studied by many authors: Schabinger, Wells; Patt, Wilzcek; Barger ea; Bhattacharyya ea; Bock ea; Fox ea; Englert ea; Batell ea; Bertolini/ McCullough; ...
- our approach: **minimal:** no hidden sector interactions
- equally: **Singlet acquires VeV**: no dark matter candidate

Singlet extension: free parameters in the potential

$$\text{VeVs: } H \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, \; \chi \equiv \frac{h'+x}{\sqrt{2}}.$$

- potential: 5 free parameters: 3 couplings, 2 VeVs

$$\lambda_1, \; \lambda_2, \; \lambda_3, \; v, \; x$$

- rewrite as

$$\mathbf{m_h}, \; \mathbf{m_H}, \; \sin\alpha, \; \mathbf{v}, \; \tan\beta$$

- **fixed**, **free**

$\sin\alpha$: mixing angle, $\tan\beta = \frac{v}{x}$

- physical states ($m_h < m_H$):

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

Tree-level rescaling (1)

Question 1:
Modfication for SM-like final states at tree level ?

- light/ heavy Higgs non-singlet component $\sim \cos\alpha / \sin\alpha$

$\Rightarrow$ for heavy Higgs: every SM-like coupling is **rescaled by** $\sin\alpha$

$\Rightarrow$ this alone would lead to **"global"** $\sin^4\alpha$ $\left(\sin^2\alpha\right)$ for full production and decay (production or decay)

Tree-level rescaling (2)

- in addition: **new physics channel:**

$$H \to h\,h$$

- effect:

$$\Gamma_{\text{tot}}(H) = \sin^2\alpha\,\Gamma_{\text{SM}}(H) + \Gamma_{H\to h\,h},$$

needs to be included for SM like decays

$$\kappa \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{\text{BSM}}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}} = \frac{\sin^4\alpha\,\Gamma_{\text{tot,SM}}}{\Gamma_{\text{tot}}}$$

- breakdown:

$$\sigma_{\text{prod}} = \sin^2\alpha \times \sigma_{\text{prod,SM}},\ \text{BR}_{H\to\ldots} = \sin^2\alpha\,\frac{\Gamma_{\text{tot, SM}}}{\Gamma_{\text{tot}}} \times \text{BR}^{\text{SM}}_{H\to\ldots}$$

$\Rightarrow$ sufficient for tree level rescaling $\Leftarrow$

Other tree-level effects...

- in principle:

$$\mathbf{H \to W\,W} \tag{1}$$

  could be mimicked by

$$\mathbf{H \to h\,h \to W\,W}\,\gamma\,\gamma \tag{2}$$

  ($\gamma\gamma$ escape), if $H \to h\,h$ is large enough
- **maximal allowed scenario**:

$$\mathrm{BR}_{\mathbf{hh}} \sim \mathbf{0.25},\ \mathrm{BR}_{\mathbf{WW}} \sim \mathbf{0.45}$$

- $(2)/(1) \sim 10^{-4}$, **highly suppressed**

Bounds

(arXiv: 1303.1150)

Theoretical and experimental constraints on the model

our study: $m_h = 125\,\mathrm{GeV}$, $600\,\mathrm{GeV} \leq m_H \leq 1\,\mathrm{TeV}$

we considered

1. limits from **perturbative unitarity**
2. limits from EW precision observables through S, T, U (with a small caveat...)
3. **perturbativity** of the couplings (up to certain scales)
4. **vacuum stability and minimum condition** (up to certain scales)
5. measurement of **light Higgs signal strength**

(debatable: minimization up to arbitrary scales, $\Rightarrow$ perturbative unitarity to arbitrary high scales...)

(these are common procedures though in the SM case)

Results (for details, cf arXiv: 1303.1150)

- **strongest constraints:**

$$m_H \lesssim 700\,\mathrm{GeV} \quad : \quad \textbf{light Higgs coupling strength}$$
$$m_H \gtrsim 700\,\mathrm{GeV} \quad : \quad \textbf{perturbativity of couplings}$$

$\Rightarrow$ $\kappa \leq 0.04$ for all masses considered here

$\Rightarrow$ in addition: smallish values for $\Gamma_{H \to h\,h}\,(\leq 5\,\mathrm{GeV})$

$$\Gamma_{\mathbf{tot}} \lesssim 0.02\, m_H$$

$\Rightarrow$ Highly (??) suppressed, narrow(er) heavy scalars $\Leftarrow$

$\Rightarrow$ new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range $\Leftarrow$

(note: $\Gamma_{\mathrm{tot}} \lesssim 0.08\, m_H$ from signal strength limit only)

Treatment of light Higgs coupling strength μ

- assume **no** (weaker: negligible) hidden sector interactions for the light Higgs
- in this case **(LO treatment, NO fit !!!)**

$$\cos\alpha^2 \equiv \mu$$

with μ: coupling strength

(this assumes parton-level-like definition of μ)

- **we took** *(Phys.Lett., B716:1–29, 2012;Phys.Lett., B716:30–61, 201)*

$$\mu_{\text{ATLAS}} = 1.4 \pm 0.3,\ \mu_{\text{CMS}} = 0.87 \pm 0.23$$
$$\overline{\mu} = 1.14 \pm 0.19,\ \cos\alpha^2 \geq 0.95$$
$$\Rightarrow \sin\alpha \leq \mathbf{0.23}$$

(more updated numbers even more generous:
$\cos^2\alpha \geq 0.93 \Rightarrow \sin\alpha \leq 0.27$)

Comments on other constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \to 2$ scattering amplitudes for $s \to \infty$
- makes sure that the largest eigenvalue for the "0"-mode partial wave of the diagnolized system ≤ 0.5
- "crude" check that unitarity is not violated

  (in the end: all "beaten" by perturbativity of running couplings)
  (more sopisticated methods to unitarize theories: Argand circle, ...
  $\Rightarrow$ WS in DD 09/13)

Perturbativity of couplings

- make sure that no coupling $\geq 16\,\pi$ ("typical" loop prefactor^{-1})
- at ew scale: perturbative unitarity stronger

Comments on other constraints (2) - EW precision data

S, T, U

- parametrize deviations from SM in electroweak sector
- here: neglected contributions from $H \longrightarrow h\,h$ (OK ??)
- anyways: all "beaten" by μ restriction on $\sin\alpha \Rightarrow$ not relevant

  (should be redone using full theory though...; cf eg Dawson/ Yan, 2009)

Comments on other constraints (3) - running couplings and vacuum

Vacuum stability and perturbativity of couplings at arbitrary scales

- clear: vacuum should be stable for large scales
- unclear: do we need ew-like breaking everywhere ? perturbativity ?

$\Rightarrow$ check at relative low scale (cf next slide)

$\Rightarrow$ bottom line: small mixings excluded from stability for larger scales (for $m_H \leq 1\,\mathrm{TeV}$!! for the model-builders...)

- arbitrary large m_H can cure this !! cf Lebedev; Elias-Miro ea. Out of collider range though (...like SUSY, this model can never be excluded...)
- perturbativity of couplings severely restricts parameter space, even for low scales

RGE running in more detail

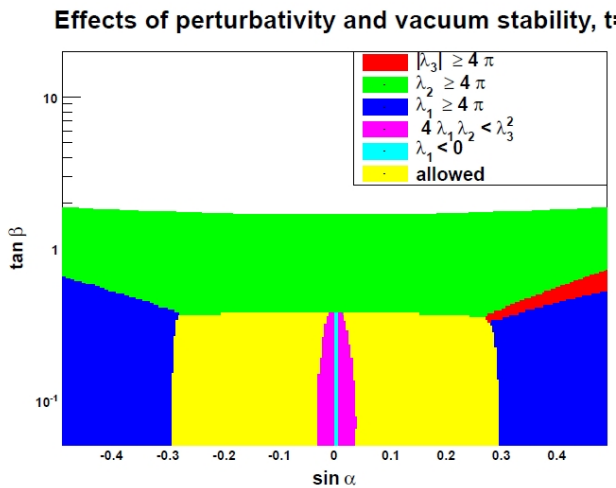
Question: at which scale did we require perturbativity ?
Answer: "just above" the SM breakdown

(other answers equally valid...)

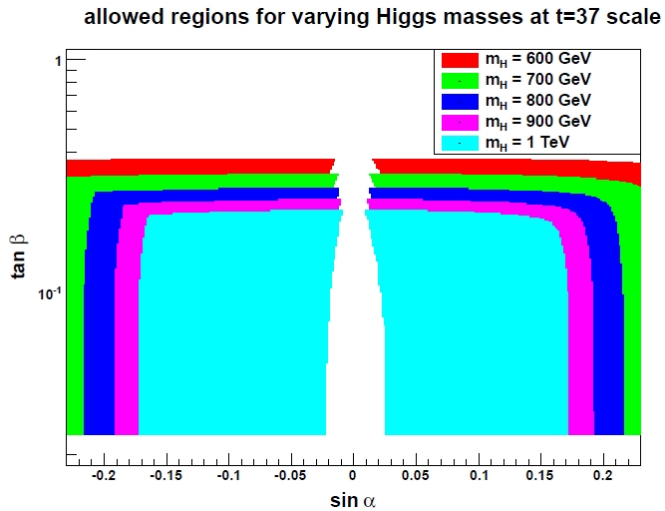
- RGEs for this model well-known (cf eg Schabinger, Wells)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM,break}} \sim 1.6 \times 10^{16}\,\text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 2.6 \times 10^{16}\,\text{GeV}$

  (higher scales $\Longleftrightarrow$ stronger constraints)

Limits on $\sin\alpha$, $\tan\beta$, $\mu_{\text{run}} \sim 2.6 \times 10^{16}\,\text{GeV}$



Limits in $\sin\alpha$, $\tan\beta$ plane, $m_H = 600\,\text{GeV}$ including all bounds

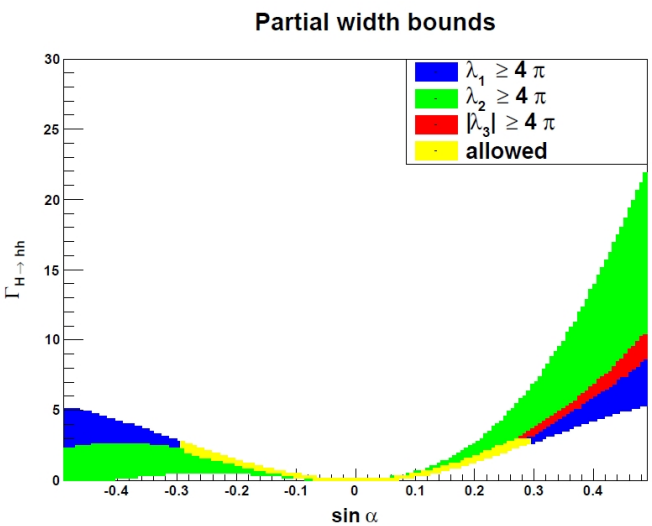


Limits in $\sin\alpha$, $\tan\beta$ plane, varying m_H including all bounds

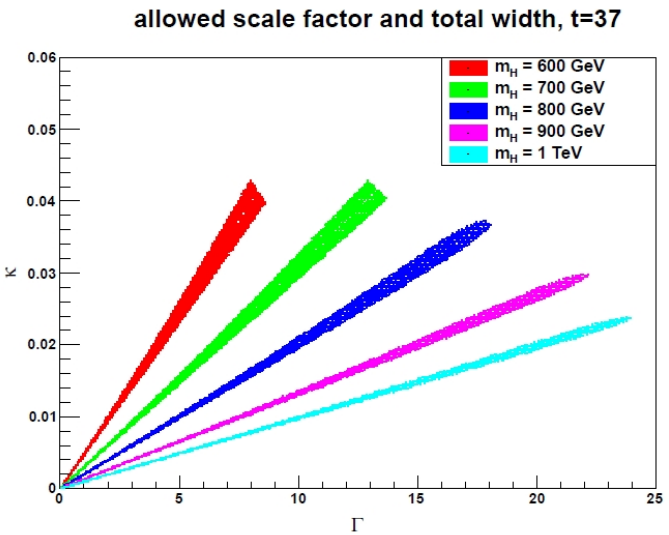
for $\sin\alpha \leq 0.23$: only λ_2 **running important**

Limits on κ, Γ_{tot}, $\mu_{\text{run}} \sim 2.6 \times 10^{16}\,\text{GeV}$

translation to collider observables κ, Γ_{tot}



Limits on $\Gamma_{H \to h\,h}$ from perturbativity



limits on κ, Γ plane from all constraints

- constraint from μ on $\sin\alpha$: $\Gamma_{H \to h\,h}$ already small ($\lesssim 0.08\,m_H$)
- running of couplings: even stronger constraints

Could we have seen them ?? YES !!

(at least they could have been produced...)

all numbers below: $\sqrt{S_{\mathbf{hadr}}} = 7\mathrm{TeV}, \int \mathcal{L} = 25\,\mathrm{fb}^{-1}$

$m_H\,[\mathrm{GeV}]$	κ_{max}	$\#gg\ \sim$	$\#\mathrm{VBF}\ \sim$
600	0.04	330	60
700	0.04	130	40
800	0.04	60	20
900	0.03	20	12
1000	0.025	8	7

maximal number of events from production $\times$ decay to SM-like final states

(cross sections from "Handbook of LHC Higgs Cross sections I", Dittmaier ea)

for specific final state, multiply with SM-like BR (LO approx)

$\Longrightarrow$ **Model awaits discovery !! (optimist)** $\Longleftarrow$

(or at least limits...) (pessimist)

Tree-level like scan suggestion (from a theorist ⇒ mb redundant)

- parametrize everything in κ, Γ_{tot}
- start with "best case scenario"

$$\kappa \sim 0.04, \Gamma_{\mathbf{tot}}\,(m_H = 600\,\text{GeV}) \sim 6\,\text{GeV}$$

- rescale σ_{SM} by κ as given previously
  (this assumes factorized production and decay)
- walk around Γ, κ plane with above-inspired upper limits
  (even if you dont hit our allowed parameter space this way, its still at least some general guidance...)
- retranslation to bounds on fundamental parameters straightforward

⇒ **together with m_H: parameters of the (visible part of the) theory determined/ constrained** ⇐

$N^x L^y O$

Higher order corrections in the Singlet extension (1) - QCD

(All below are just generic arguments, not based on any calculation)

Question: What are the changes in higher order corrections wrt the current (SM-like) description ??

- remember: every SM-like coupling is **rescaled by** $\sin\alpha$

$\Rightarrow$ every $(\alpha_s, y_i, ...)$ with heavy Higgs $\Rightarrow$ $(\alpha_s, y_i, ...) \times \sin^2\alpha$

$\Rightarrow$ **naive approach:**
higher order (differential/ non-differential) **K-factors remain the same**, only tree level production/ decay needs rescaling

$\Rightarrow$ would lead to same scaling with κ**, ...** as tree level, with (differential) higher order K-factors as in SM

Higher order corrections in the Singlet extension (2) - EW

- previous slide: ignored $H \longrightarrow h\,h$ contributions

$\Rightarrow$ valid for strong corrections

- left out: corrections with h running in the loop (vertex, propagator,...)
- BR can be $\sim 25\,\%$

$\Rightarrow$ current status (at least for me): **effects/ changes from including these not clear, in principle full calculation** (including renormalization) **needed to check**

$\Rightarrow$ **available ??**

Higher order corrections in the Singlet extension (2b) - EW

Some comments re full NLO treatment...

- SM-sector: contributions from new heavy Higgs to finite part of gauge Boson propagators

$\Rightarrow$ influences renormalization of m_W, m_Z

- Higgs sector itself can be renormalized in on-shell scheme
  (thanks to C. Pietsch for comments)
- other (possibly important) effects: **one-loop contribution to**

$$H \to t\bar{t}$$

$\Rightarrow$ could lead to modifications in $t\bar{t}$ production

(remember: production suppressed by $\sin^2\alpha$,
$\sigma \lesssim 0.(0)1\,\mathrm{pb}$ for (7) 14 TeV)

Higher order corrections in the Singlet extension (2c) - EW

A rough estimate...

[(nearly) all below: $\sin\alpha$ small, $m_h^2 \ll m_H^2$]

- coupling $Ht\bar{t} \sim \frac{y_t(m_H)}{\sqrt{2}} \sin\alpha$
- coupling $Hh\,h \sim \frac{m_H^2}{v} \sin\alpha$

$$\frac{\Gamma_{tt}}{\Gamma_{hh}} \sim \frac{y_t^2(m_H)\,N_c}{\left(\frac{m_H^2}{2\,v^2}\right)} \left(\frac{\beta_t}{\beta_h}\right)^3 \lesssim 0.6 \quad \left(\beta_i = \sqrt{1-4\,m_i^2/m_H^2}\right)$$

$\Rightarrow$ contribution via loop (in small mixing limit $\sin\alpha \ll 1$)

$$\sim \left(\frac{y_t(m_h)}{\sqrt{2}}\right)^2 \frac{m_H^2}{v} \sin\alpha$$

could in principle be sizeable, $\mathcal{O}(10\,\%)$

$\Rightarrow$ more accurate calculation needed...

Higher order corrections in the Singlet extension (2d) - EW

- along similar lines: loop contributions to

$$\mathbf{H \to W W}$$

  from $H\,h\,h$ coupling (for **production in VBF** and **decay**)

$\Rightarrow$ probably not as important as decay to tops, but still large(ish)

- also: $H \to g\,g$,...
- probably/ maybe all subdominant wrt "standard" (QCD) NLO effects...

Higher order corrections in the Singlet extension (3) - width and on-shellness

- is the width small enough to neglect "broadness" complications ?
- naive argument: **error**

$$\sim \frac{\Gamma_H}{m_H} \lesssim 2\,\%$$

$\Rightarrow$ **might be OK for a rough estimate**

- alternative: redo cross section calculations eg in complex pole scheme (needed ??) with reduced Γ (how much effort ?? Γ is varied; mb start with a maximal value...)

  (not necessary imho)
- another point: "sideband" complications vanish

Tools which can do it ?? (incomplete list)

("it"=LO,NLO,...)

- LO: **any tool talking to FeynRules** (in principle)/ **LanHep** (in practice)
- implemented and run: **CompHep** (M. Pruna), **Sherpa** ($\pm$) (would need some modification, T. Figy), privately modified codes (??)
- NLO: (mb) a modified version of **aMC@NLO** (R. Frederix) ?? (production only; might be important for VBF)
- higher orders: would need to be implemented in respective tools (I am not aware of any at the moment)

Suggestion

My conclusion:

This is about BSM discovery,

lets worry about precision later...

$\Rightarrow$ in this spirit: **simple rescaling of tree-level by κ**, together with **SM-like QCD K-factor**, should work as a first guess...

$\Rightarrow$ could be done with **factorized production $\times$ decay**

$\Rightarrow$ should be **doable with standard tools**
(as long as they dont assume broad widths)

If you insist on NLO from BSM...

- $\sigma \times \mathrm{BR}_{\mathrm{SM}}$ might deviate from simple rescaled κ due to loops including $h\,h$

$\Rightarrow$ need calculations here

- for a generic coupling g_{SM} and $H \longrightarrow X_{\mathrm{SM}}\, X^*_{\mathrm{SM}}$

$$\Delta_{\mathrm{NLO,\ rel}} \sim \frac{g^2_{\mathrm{SM}}(m_h)}{g_{\mathrm{SM}}(m_H)} \frac{m^2_H}{v} \times (\text{your favourite scale})^x$$
$$\times\, (\text{your favourite loop approximation})$$

(x depends on dimensions of couplings)

One more word about $H \longrightarrow h\,h$

- all above: **focuses on SM-like decays**
- **viable alternative:** search for

$$H \longrightarrow h\,h \longrightarrow \ldots$$

- **widely discussed in the literature**
  (for recent work, cf Gouzevitch/ Oliveira/ Rojo/ Rosenfeld/ Salam/ Sanz, and references therein)
- **HOWEVER** in our scan, WW **always dominant**

$\Rightarrow$ **would go for this first**
(but mb more than 1 group is interested...)

more details $\Rightarrow$ backup

Summary and Outlook

Summary and Outlook

- Singlet extension: **simplest extension of the SM Higgs sector, easily identified with one of the benchmark scenarios of the HHXWG**
- constraints on parameter space: **signal strength of light Higgs, perturbativity of the couplings**
- **quite narrow widths wrt SM-like Higgses** in this mass range
  $\Rightarrow$ **better theoretical handle**
- quite low (??) production cross sections due to small mixings
- LO predictions: **simple**
- NLO QCD: can use **normal K-factor**
- NLO EW: need in principle a full calculation due to $H \longrightarrow h\,h$

Summary and Outlook

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG
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- quite low (??) production cross sections due to small mixings
- LO predictions: **simple**
- NLO QCD: can use **normal K-factor**
- NLO EW: not for first guess !!

Final comments

Thanks for letting me present our work

Please dont hesitate to contact me (even later...)

[my current affiliation is TU Dresden

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!! Thanks for listening !!

Appendix

$H \to h\,h$

- in addition: **new physics channel:**

$$H \to h\,h$$

- effect:

$$\Gamma_{\text{tot}}(H) = \sin^2\alpha\,\Gamma_{\text{SM}}(H) + \Gamma_{H\to h\,h},$$

$$\kappa' \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{H\to h\,h}}{1}\sigma_{\text{SM}} = \frac{\sin^2\alpha\,\Gamma_{H\to h\,h}}{\Gamma_{\text{tot}}}$$

$$\kappa + \kappa' = \sin^2\alpha$$

Could we have seen them ?? yes-maybe...

all numbers below: $\sqrt{S_{\mathbf{hadr}}} = 7\,\mathrm{TeV}$, $\int \mathcal{L} = 25\,\mathrm{fb}^{-1}$,

$m_H\,[\mathrm{GeV}]$	κ'_{max}	$\#gg\ \sim$	$\#\mathrm{VBF}\ \sim$
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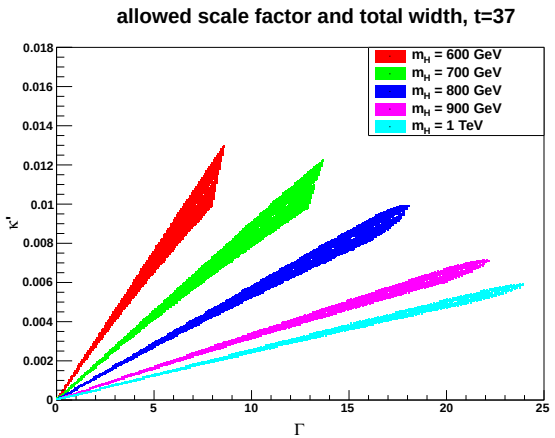


maximal number of events from $H \to h\,h$

(cross sections from "Handbook of LHC Higgs Cross sections I", Dittmaier ea)

for specific final state, multiply with SM-like BR for m_h

"naively": many b-jets with $m_{bb} \sim 125\,\mathrm{GeV}$, or $bb\,\gamma\,\gamma$, or...

Coupling and mass relations

$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (3)$$

$$m_H^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (4)$$

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \quad (5)$$

$$\cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \quad (6)$$

Numbers used in loop approximation

small $\sin\alpha$, m_h limit

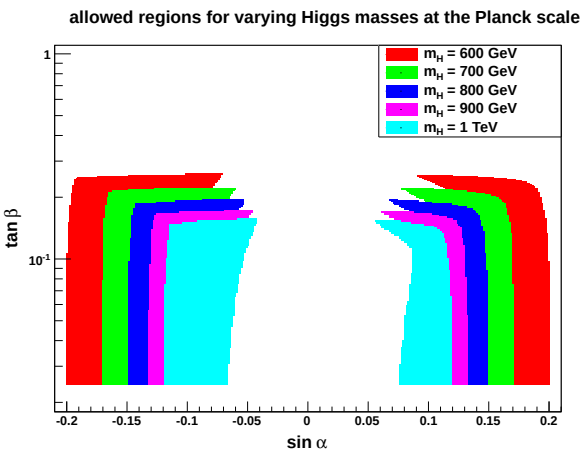
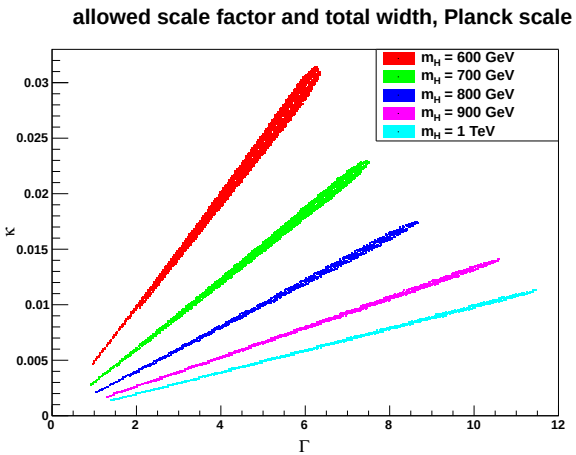
$$\lambda_1 \sim \frac{m_h^2}{2\,v^2}, \lambda_2 \sim \frac{m_H^2}{2\,x^2}, \lambda_3 \sim \frac{m_H^2}{v\,x}\,\sin\alpha$$

$$\mu \sim -\sin\alpha\,\frac{m_H^2}{2\,v}$$

running couplings and βs

$$y_t(125\,\mathrm{GeV}) = 0.95,\ y_t(600\,\mathrm{GeV}) = 0.88,$$
$$\beta_t = 0.82,\ \beta_h = 0.91$$

Perturbativity of couplings λ_2, λ_3 :

$$\tan\beta \leq \frac{4\sqrt{2\,\pi}\,v}{m_H},\ \tan\beta \leq \frac{16\,\pi\,v^2}{\sin\alpha\,m_H^2}$$

Limits at Planck scale