The Higgs Singlet Extension at LHC Run 2

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.
based on
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G.M. Pruna, TR (PRD 88 (2013) 115012)
D. Lopez-Val, TR (PRD 90 (2014) 114018)
TR, T. Stefaniak (EPJC (2015) 75:105, arXiv:1601.07880)

F. Bojarski, G. Chalons, D. Lopez-Val, TR (JHEP 1602 (2016) 147)

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Higgs Singlet 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)

⇒ potential (H doublet, χ real singlet)

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

- 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**

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**

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

- physical states ($m_h < m_H$):

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

Phenomenology (in the following: focus on $m_h \sim 125\,\mathrm{GeV}$)

- SM-like couplings of **light/ heavy** Higgs:
  rescaled by $\sin\alpha$, $\cos\alpha$
- in addition: **new physics channel:** $H \rightarrow h\,h$

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

- **SM like decays** parametrized by

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

- **new physics channel** parametrized by

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

Theoretical and experimental constraints on the model

our studies: $m_{h,H} = 125.09\,\mathrm{GeV},\ 0\,\mathrm{GeV} \leq m_{H,h} \leq 1\,\mathrm{TeV}$

1. limits from **perturbative unitarity**
2. limits from EW precision observables through $S,\ T,\ U$
3. special: **limits from W-boson mass** as precision observable
4. **perturbativity** of the couplings (up to certain scales*)
5. **vacuum stability and minimum condition** (up to certain scales*)
6. **collider limits** using HiggsBounds
7. measurement of **light Higgs signal rates** using HiggsSignals and ATLAS-CONF-2015-044 [signal strength combination]

(debatable: minimization up to arbitrary scales, $\Rightarrow$ perturbative unitarity to arbitrary high scales [these are common procedures though in the SM case])

(*): only for $m_h = 125.09\,\mathrm{GeV}$

Results

- **strongest constraints:**

$$m_H \gtrsim 800\,\text{GeV} \;:\; \textbf{perturbativity of couplings}$$
$$m_H \in [270;800]\text{GeV} \;:\; m_W \textbf{ @ NLO}$$
$$m_H \in [175;270]\text{GeV} \;:\; \textbf{experimental searches}$$
$$m_H \in [120;175]\text{GeV} \;:\; \textbf{signal strength}$$
$$m_h \lesssim 120\,\text{GeV} \;:\; \textbf{SM-like Higgs coupling rates } (+\text{ LEP})$$

$\Rightarrow \kappa \leq 0.25$ for all masses considered here

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

⇒ Highly (??) suppressed, narrow(er) heavy scalars ⇐

⇒ new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range ⇐

[width studies (∼ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson, Lewis; ...]

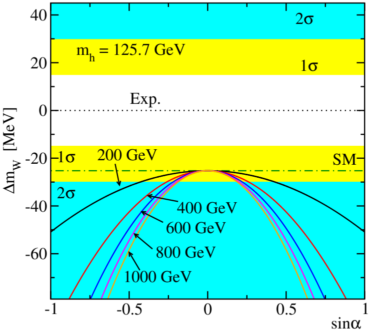
NLO corrections to m_W (D. Lopez-Val, TR, PRD 90 (2014) 114018)

- electroweak fits: fit $\mathcal{O}\,(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim 10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture of onshell/ $\overline{MS}$

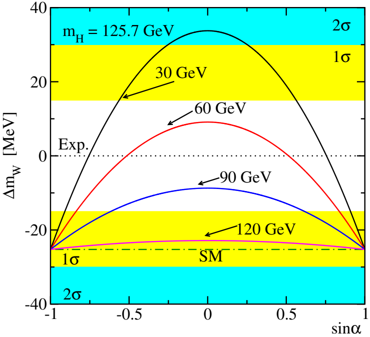
  (in this case: $\delta\,\lambda$ only enter at 2-loop $\Longrightarrow$ not relevant here)
- first step on the road to full renormalization

NLO corrections to m_W (D. Lopez-Val, TR, PRD 90 (2014) 114018)

Contribution to m_W for different Higgs masses



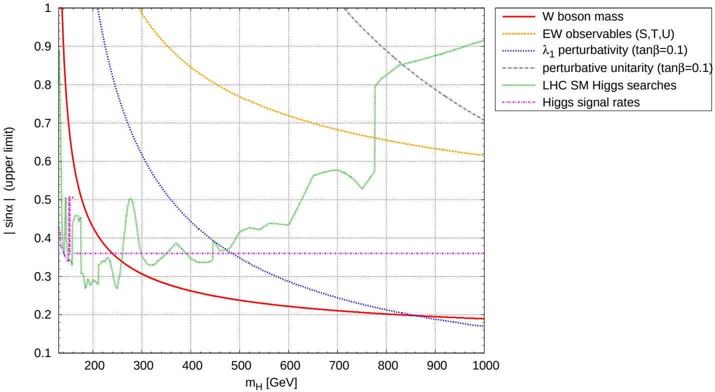
$m_h = 125.7$ GeV



$m_H = 125.7$ GeV

$\Longrightarrow$ **low m_h bring m_W^{NLO} close to m_W^{exp}** $\Longleftarrow$

Combined limits on $|\sin\alpha|$ (TR, T. Stefaniak, arXiv:1601.07880)



several bounds on $|\sin\alpha|$

m_W, perturbativity, LHC direct searches, Higgs Signal strength

Results from generic scans and predictions for LHC 14

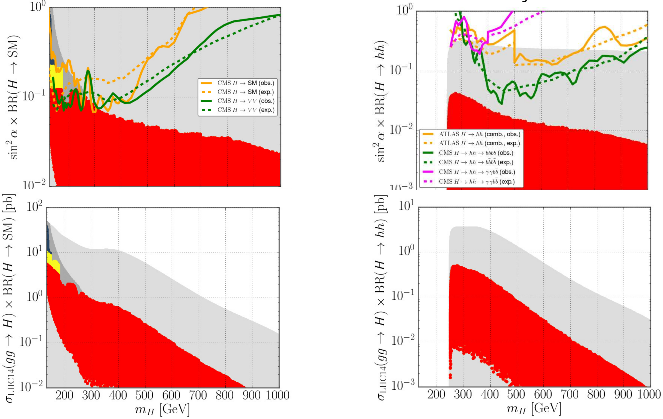
(TR, T. Stefaniak, arXiv:1601.07880)

1 σ, 2 σ, allowed

SM like decays | BSM decay to hh

limits

pred.



Full renormalization (1)

(F. Bojarski, G. Chalons, D. Lopez-Val, TR, JHEP 1602 (2016) 147)

- next topic: **full electroweak renormalization**
- many parts of ew sector: **follow SM prescriptions**
- **new:** renormalize

$$T_{h,H};\ v;\ x;\ m^2_{h,H};\ Z_{h,H,hH,Hh};\ m^2_{hH}$$

⇒ in total: **11 parameters in scalar sector**

⇒ need to be determined by **suitable renormalization conditions**

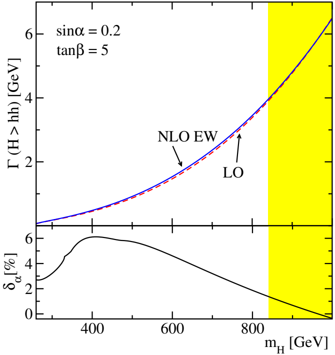
Full renormalization (2)

$\Longrightarrow$ Our choices $\Longleftarrow$

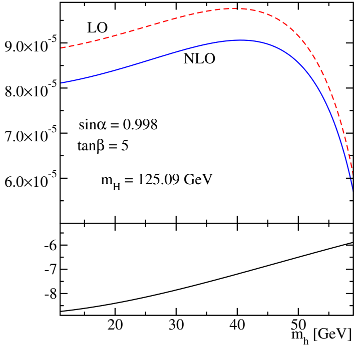
- Tadpoles: $\delta T = -T$ $[\hat{T}=0]$
- v: as in SM, on-shell (ie through ew gauge sector)
- $\delta x = 0$ (not fixed by any measurement) **!!! choice !!!**
  [no UV-divergence ! ; Sperling ea, 2013]
- $\delta m_{h,H}$, $\delta Z_{H,h}$: on-shell
- difficult part **off-diagonal terms** m^2_{hH}, δZ_{hH} **!!**
- we choose: **'improved on-shell scheme' !!**
- for the experts: leads to gauge-invariant counterterms without resorting to physical measurements; tested via SloopS (Boudjema, Semenov, Temes 2005; Baro, Boudjema, Semenov 2007/ 2008;Baro, Boudjema 2009)
- based on 'Pinch Technique' (Cornwall 1982; Cornwall, Pappavassoliou 1989; Espinosa, Yamada, 2002; Binosi, Papavassiliou 2009;...)

Renormalization: numerical results

... just some numerical results for allowed regions...



$m_h = 125\,\mathrm{GeV}$



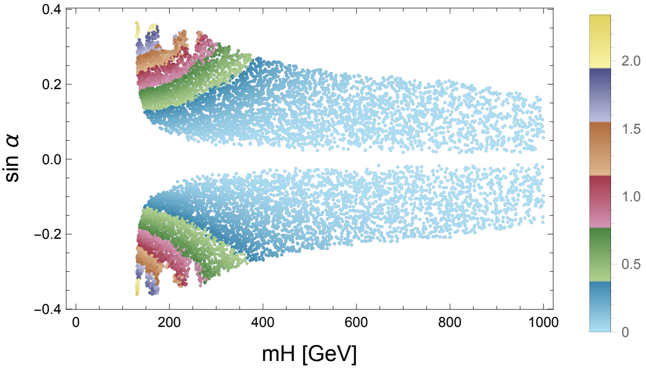
$m_H = 125\,\mathrm{GeV}$

"typical" size of corrections

[beware of "inverse" $\tan\beta$ definition !!]

The future...

... is colorful...



$\sigma(pp \rightarrow h\,H)[\text{fb}]$, 13 TeV LHC

[in collaboration with A. Papaefstathiou, J. Zurita; in preparation]

Summary

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG (cf. also YR3, Snowmass report)
- constraints on **maximal mixing** from m_W **at NLO** ($m_H \in [200\,\mathrm{GeV}; 800\,\mathrm{GeV}]$), **experimental searches and fits** ($m_{H,h} \leq 200\,\mathrm{GeV}$) and/ or **running couplings** ($m_H \geq 800\,\mathrm{GeV}$)
- **quite narrow widths wrt SM-like Higgses** in this mass range $\Rightarrow$ **better theoretical handle**
- quite large suppression from current experimental/ theoretical constraints

!!! still, large numbers could have been produced already !!!

$\Longrightarrow$ **STAY TUNED** $\Longleftarrow$

Appendix

Coupling and mass relations

$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \qquad (1)$$

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

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \qquad (3)$$

$$\cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \qquad (4)$$

Comments on constraints - 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 ?

⇒ check at relative low scale (cf next slide)

⇒ 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 ($\sim 10^8\,\mathrm{GeV}$)
- 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...)

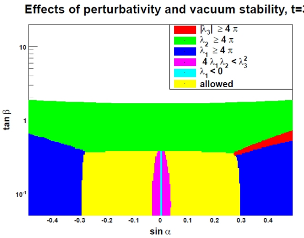
- RGEs for this model well-known (cf eg Schabinger, Wells)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM,break}} \sim 6.3 \times 10^{10}\,\text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 1.2 \times 10^{11}\,\text{GeV}$

(higher scales $\Longleftrightarrow$ stronger constraints)

- **obvious: for $m_H \sim 125\,\text{GeV}$, breakdown "immediate"** when going to $\mu_{\text{run}} > v$

$\Rightarrow$ disregard constraints from running in this case

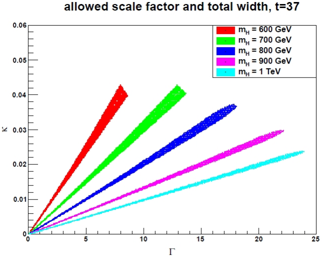
Limits for $m_H \geq 600\,\mathrm{GeV}$



Limits in $\sin\alpha$, $\tan\beta$ plane,

$m_H = 600\,\mathrm{GeV}$ including all bounds

$\Longrightarrow$



limits on κ, Γ plane from all constraints

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

(sideremark: here, 1 σ constraint on mixing from μ; relaxed and improved in newer work, just as an example here)

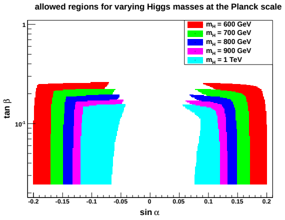
Limits in numbers; high mass scenario

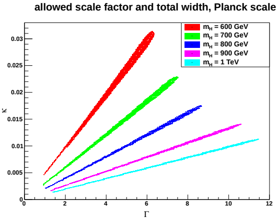
m_H[GeV]	$\lvert\sin\alpha\rvert$	source upper limit	$(\tan\beta)_{max}$
1000	[0.020; 0.16]	$\lambda_1$perturbativity	0.21
800	[0.028; 0.20]	m_W at NLO/ $\lambda_1$perturbativity	0.26
600	[0.038; 0.22]	m_W at NLO	0.36
400	[0.057; 0.26]	m_W at NLO	0.54
200	[0.092; 0.43]	m_W at NLO	1.08
180	[0.10; 0.46]	126 GeV signal strength	1.20
160	[0.12; 0.46]	126 GeV signal strength	1.34
140	[0.17; 0.34]	$h \to \ell^+\ell^-\ell^+\ell^-$	1.54

- $\sin\alpha_{\mathbf{min}}$ always from **vacuum stability**
- $\tan\beta_{\mathbf{max}}$ always from **perturbativity of** λ_2

Limits at Planck scale

assume that the model is valid up to $\mu_{\rm run} \sim 10^{19}\,\mathrm{GeV}$
(not always well motivated)





- naturally: **parameter space more restricted**
- translates to $\kappa \lesssim 0.03$ **for** $m_H = 600\,\mathrm{GeV}$ (25 % decrease)
- now: μ no longer relevant, only constraint from perturbativity of $\lambda_1,\,\lambda_2$

Could we have seen them ??

all numbers below: $\sqrt{S_{\text{hadr}}} = 8\,\text{TeV},\ \int \mathcal{L} = 23\,\text{fb}^{-1}$

m_H [GeV]	κ_{max}	#gg ~	κ'_{max}	#gg ~
200	0.18	**3×10^4**	0	0
300	0.076	**6×10^3**	0.038	**3×10^3**
400	0.053	**4×10^3**	0.021	**1×10^3**
500	0.047	**1×10^3**	0.015	**440**
600	0.039	**470**	0.012	140
700	0.035	180	0.010	50
800	0.033	80	0.009	20
900	0.027	40	0.007	10
1000	0.021	15	0.005	4

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

for $m_H \lesssim 600\,\text{GeV}$, may could already have been produced which are not excluded by current searches !!

What about the "inverse" scenario, ie. $m_H = 125.7\,\mathrm{GeV}$

mainly ruled out by LEP and/ or χ^2 fit from HiggsSignals
however, *still* large number produced due to large $\sigma_{gg\to h}$

$m_h[\mathrm{GeV}]$	$\lvert\sin\alpha\rvert_{\text{min, exp}}$	$\lvert\sin\alpha\rvert_{\text{min, }2\sigma}$	$(\tan\beta)_{\max}$	$\#gg\sim$
110	0.82	0.89	9.2	10^5
100	0.86	$--$	10.1	10^5
90	0.91	$--$	11.2	10^5
80	0.98	$--$	12.6	10^4
70	0.99	$--$	14.4	10^4
60	0.98	$\gtrsim 0.99$	16.8	10^4
50	0.99	$\gtrsim 0.99$	20.2	10^4
40	0.99	$\gtrsim 0.99$	25.2	10^4

Table : Upper limit on $\tan\beta$ from perturbative unitarity. ($--$ means no additional constraint)

(side remark: for $m_h \gtrsim 60\,\mathrm{GeV}$, $\tan\beta$ irrelevant for collider observables)

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)
- new tool in the MadGraph environment (Artoisenet ea, 06/13): QCD-part of NLO
- complete higher orders: would need to be implemented in respective tools (I am not aware of any at the moment)

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

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

$$H \to h\,h \to \ldots$$

- **widely discussed in the literature**
  (for recent work, cf Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz; Cooper, Konstantinidis, Lambourne, Wardrope; ...)
- **HOWEVER** in our scan, WW **always dominant**

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

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \rightarrow 2$ scattering amplitudes for $s \rightarrow \infty$
- we considered:

$$WW,\, ZZ,\, HH,\, Hh,\, hh \rightarrow WW,\, ZZ,\, HH,\, Hh,\, hh$$

- 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

  (Literature: Lee/ Quigg/ Thacker, Phys. Rev. D 16, 1519 (1977))

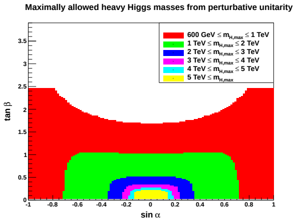
  (in the end: all "beaten" by perturbativity of running couplings)

Comments on constraints (1) - Perturbativity issues

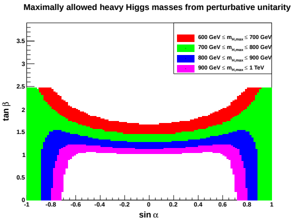
- we tested: **maximal m_H** from PU

  $\Longrightarrow$ **strongest constraints from $H\,H \rightarrow H\,H$** $\Longleftarrow$

- rule of thumb (exact for $\alpha = 0$): $\tan^2\beta \leq \frac{16\,\pi\,v^2}{3\,m_H^2}$



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed m_H from PU



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed $m_H \leq 1\,\mathrm{TeV}$ from PU

$\Longrightarrow$ **for realistic $\sin\alpha$ and our m_H range, $\tan\beta \lesssim 8$**

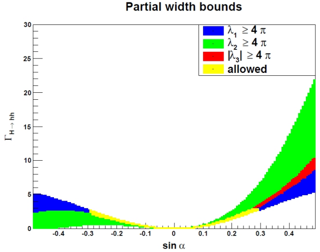
Comments on constraints (2) - running couplings and vacuum

1. **perturbativity:** $|\lambda_{1,2,3}(\mu_{\text{run}})| \leq 4\,\pi$
2. **potential bounded from below:** $\lambda_1, \lambda_2 > 0$
3. **potential has local minimum:** $4\lambda_1\lambda_2 - \lambda_3^2 > 0$

$\Longrightarrow$ need (2), can debate about (1), (3) at all scales $\Longleftarrow$

Limits on κ, Γ_{tot}

limits on $\Gamma_{H\to h\,h}$, $m_H = 600\,\mathrm{GeV}$

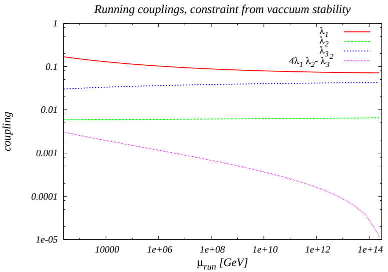


Limits on $\Gamma_{H\to h\,h}$ from perturbativity

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

RGE running: a caveat (1)

- important for **collider constraints:** **maximal value of** $|\sin\alpha|$
- important for **vacuum stability:** **minimal value of** $|\sin\alpha|$
- important here: $4\,\lambda_1\,\lambda_2 \;\geq\; \lambda_3^2$
- **sometimes:** this is **(nearly) violated** for running over large scales

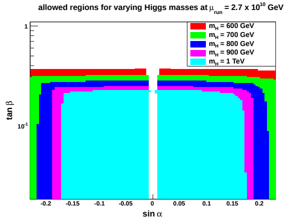


RGE running: a caveat (2)

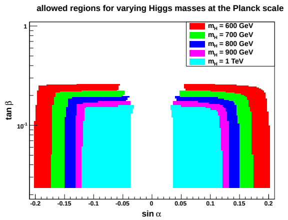
⇒ could in principle argue that **higher orders are needed**

⇒ one possible way to **quantify: neglect this condition**

⇒ now $|\sin\alpha|_{\mathrm{min}}$ follows from $\lambda_1 \geq 0$.



low scale, third condition neglected



Planck scale, third condition neglected

⇒ back to vacuum stability problem of SM ⇐

no important consequences for discovery prospects

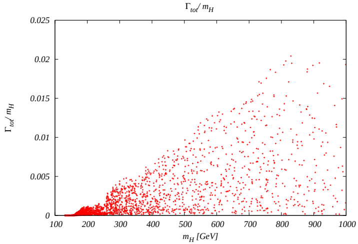
RGE running: variation of input parameters

- especially in sensitive cases, but also otherwise:
  check robustness against input parameters
- here: especially important in decoupling (ie SM-like) case
  (cf. various discussions in the literature...)
- our check:
  vary $\alpha_s(m_Z)$, $y_t(m_t)$ for 1 σ around central values
- main impact: **on vacuum stability,** ie $\lambda_1 > 0$ condition
- **no significant change in $\kappa_{max}(m_H)$, ...**

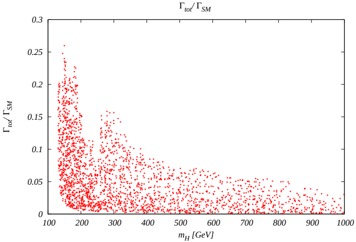
$\Rightarrow$ **not relevant for collider studies** (at this stage...)

Interim comment on total width

- Total width greatly reduced



width over mass



suppression factor of width

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

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

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

⇒ **might be OK for a rough estimate**

- another point: "sideband" complications vanish

⇒ **low-mass case: interference effects ?**
(currently limited from signal strength fits (via Γ_{inv}))