HPNP2021

"Higgs as a Probe of New Physics" Special Edition 2021

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'Global' Electroweak Symmetric Vacuum

Minho Son

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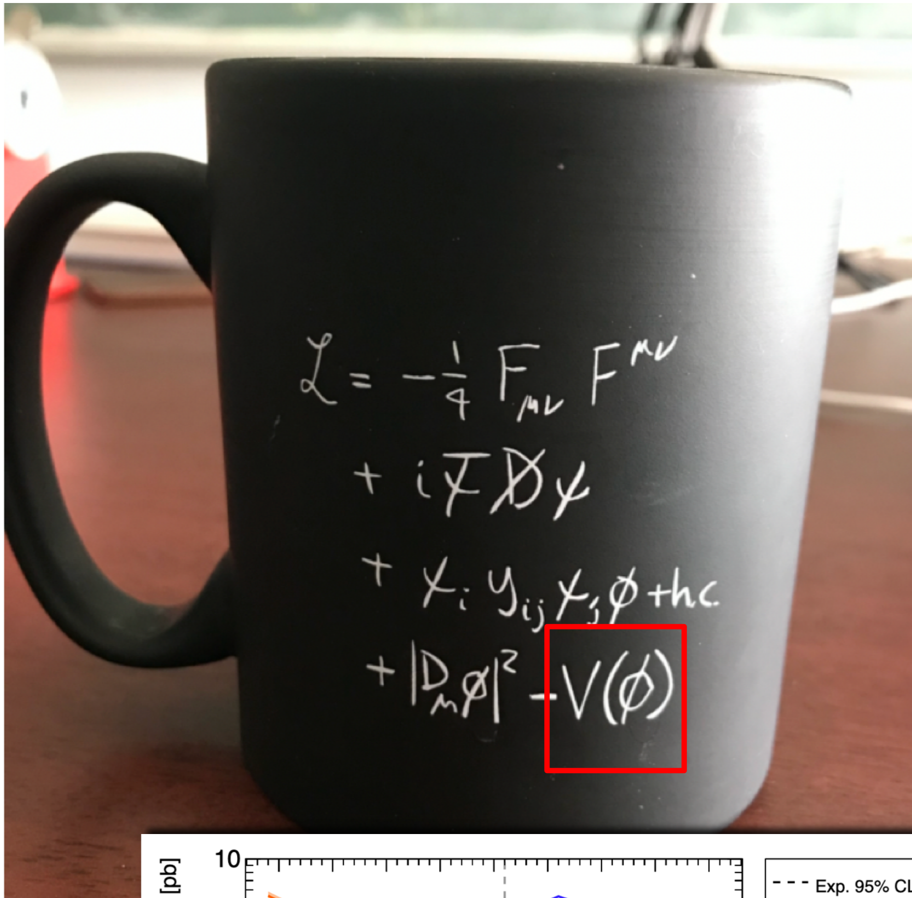
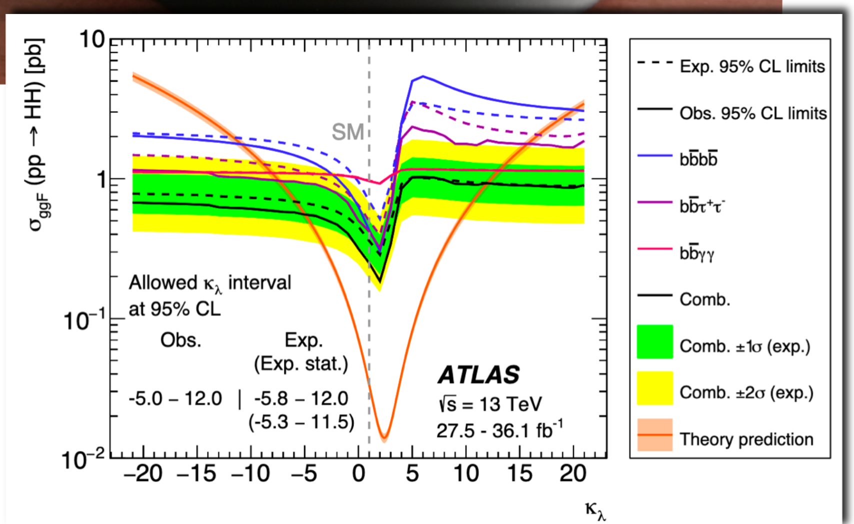
Yang Bai, Seung Lee, SON, Fang Ye, 2103.09819



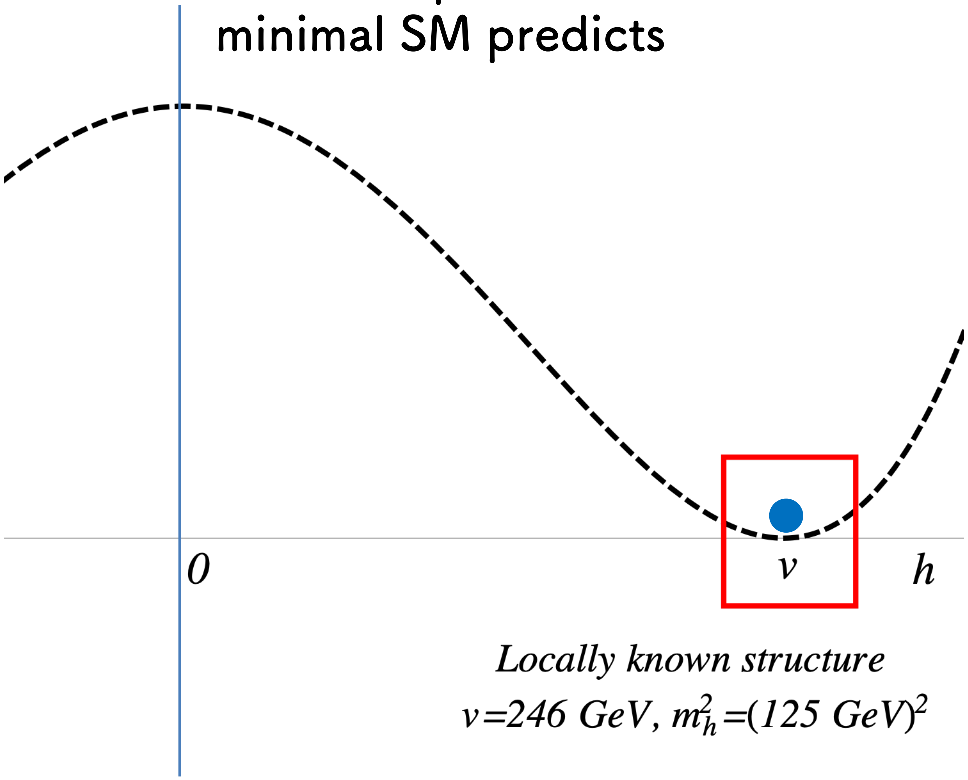


While the determination of the Higgs potential remains toughest, it is a unique place that still allows sizable New Physics near the EW scale

$$V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\lambda_3 h^3 + \frac{1}{4!}\lambda_4 h^4$$

$$\frac{\lambda_3}{\lambda_3^{SM}} \equiv \kappa_\lambda$$

This extrapolation is what minimal SM predicts



Typically this vacuum is required to be global

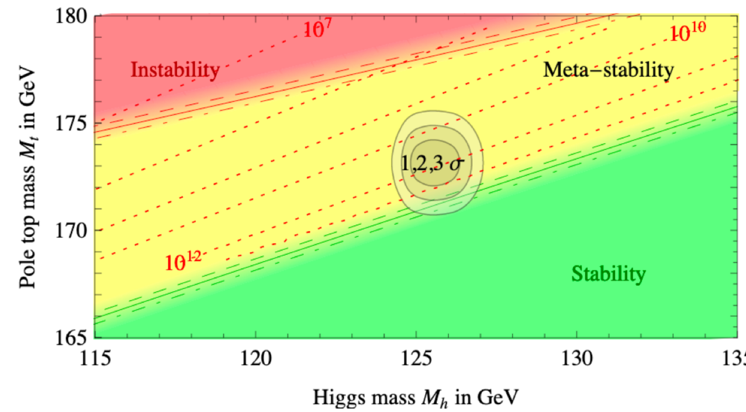
But
Given a limited information, it is hard to tell if this is really global vacuum

Locally known structure

$v = 246\ \mathrm{GeV},\ m_h^2 = (125\ \mathrm{GeV})^2$

From the viewpoint of Landscape of many vacua, e.g. in string theory, it might be more natural if our current Universe turns out to be sitting at a metastable vacuum

Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 13’

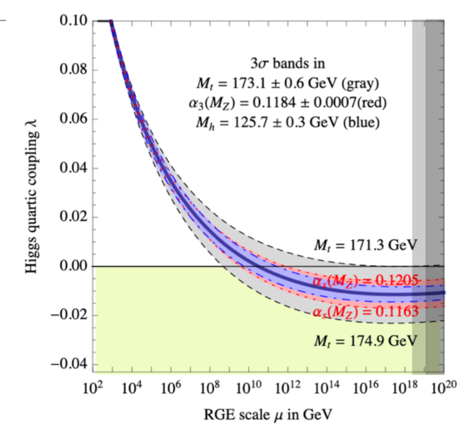


Instability at a large Higgs field might imply a new global vacuum

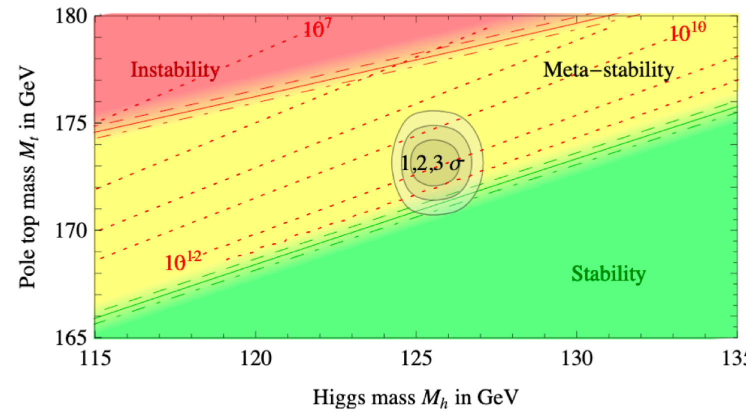
$$V_{\rm eff}(h) \sim \frac{\lambda_{\rm eff}(h)}{4} h^4$$

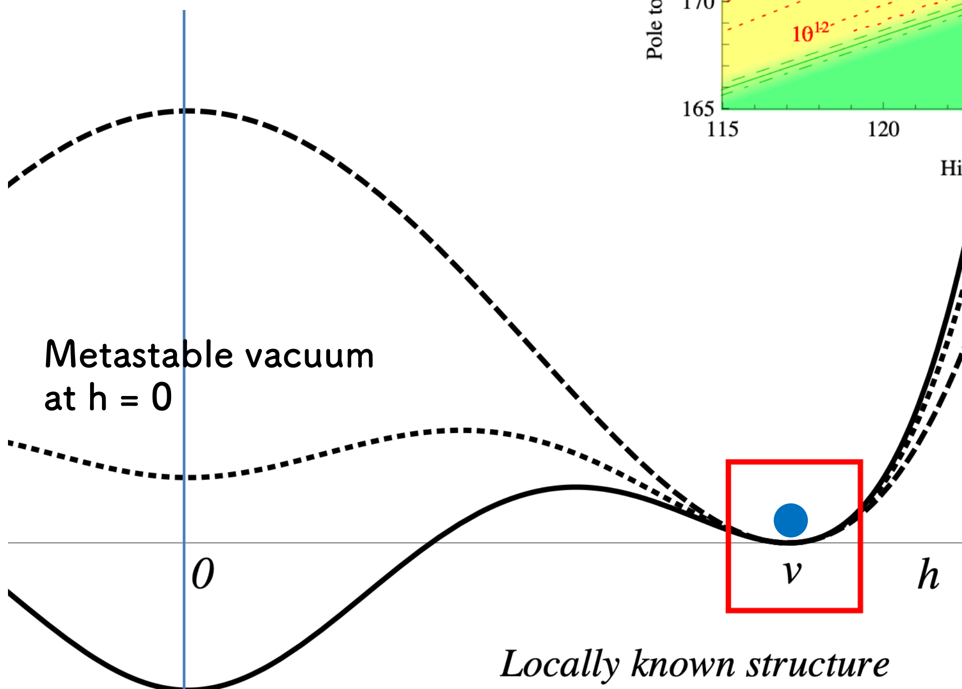
Locally known structure

v=246 GeV, m_h^2=(125 GeV)^2



Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 13'





Metastable vacuum
at h = 0

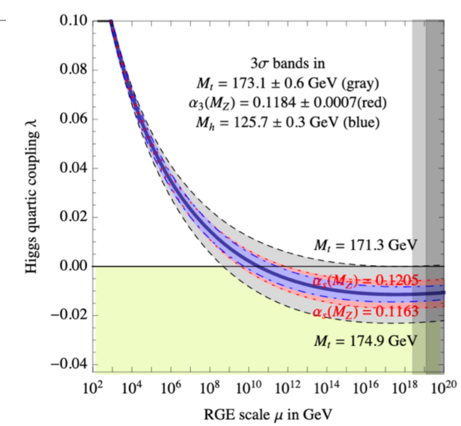
Less explored,
Not ruled out yet

Global vacuum
at h = 0

Locally known structure
v=246 GeV, m_h^2=(125 GeV)^2

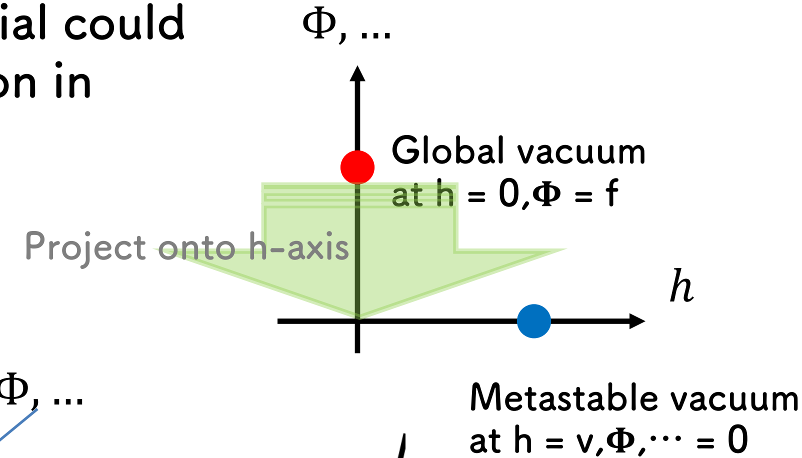
Instability at a large Higgs field might imply a new global vacuum

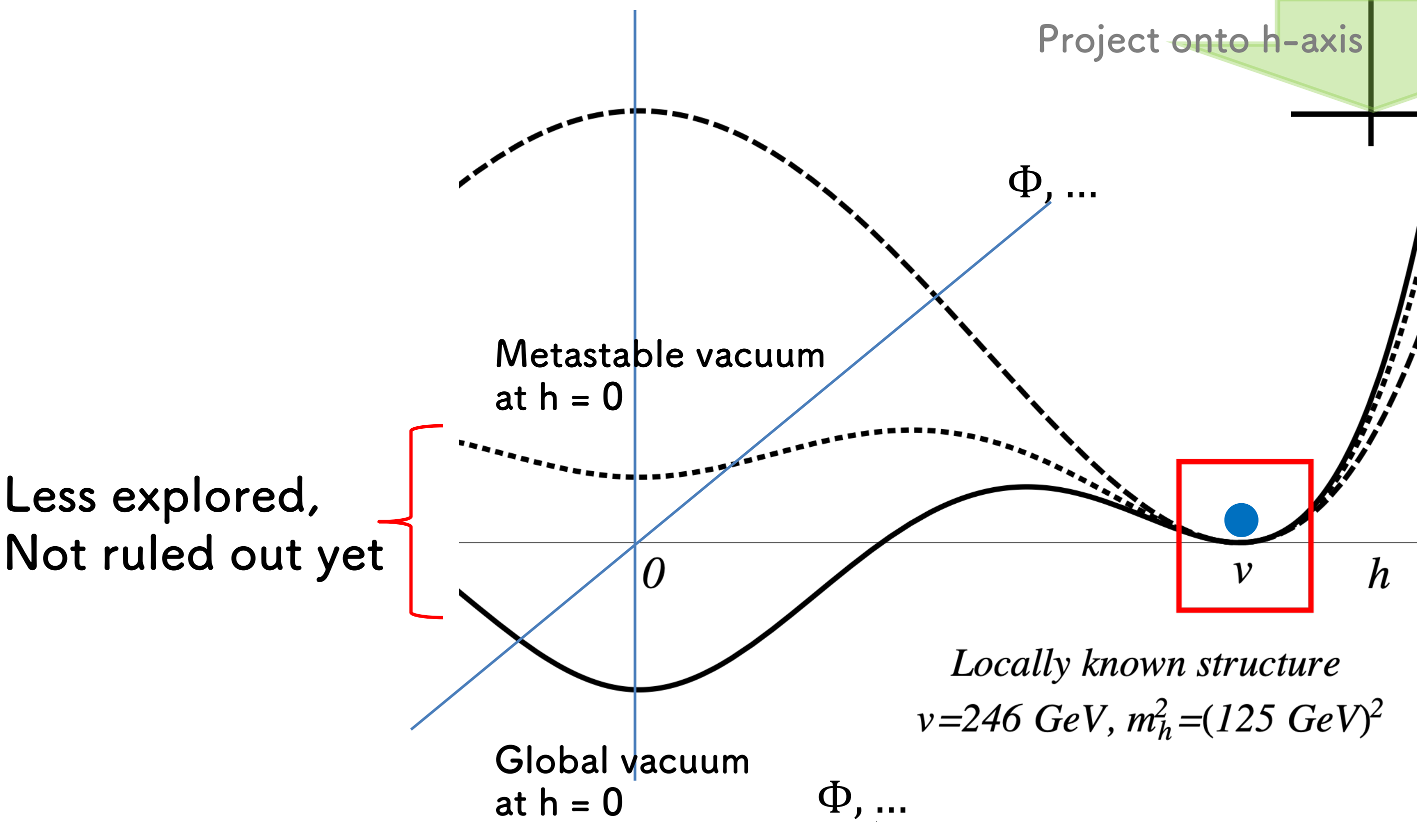
$$V_{\text{eff}}(h) \sim \frac{\lambda_{\text{eff}}(h)}{4} h^4$$



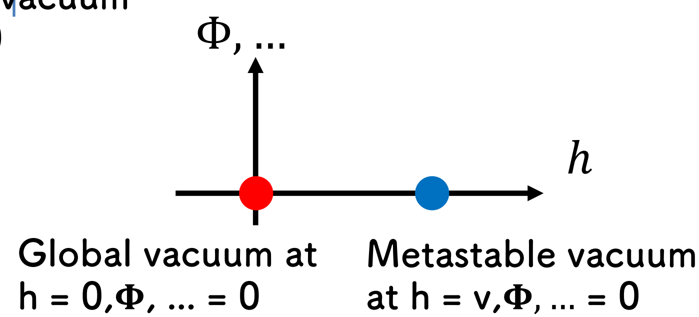
We examine this large field region with RGE in our model

The global vacuum along 1D Higgs potential could be projection of more complicated situation in multi-dimensional potential



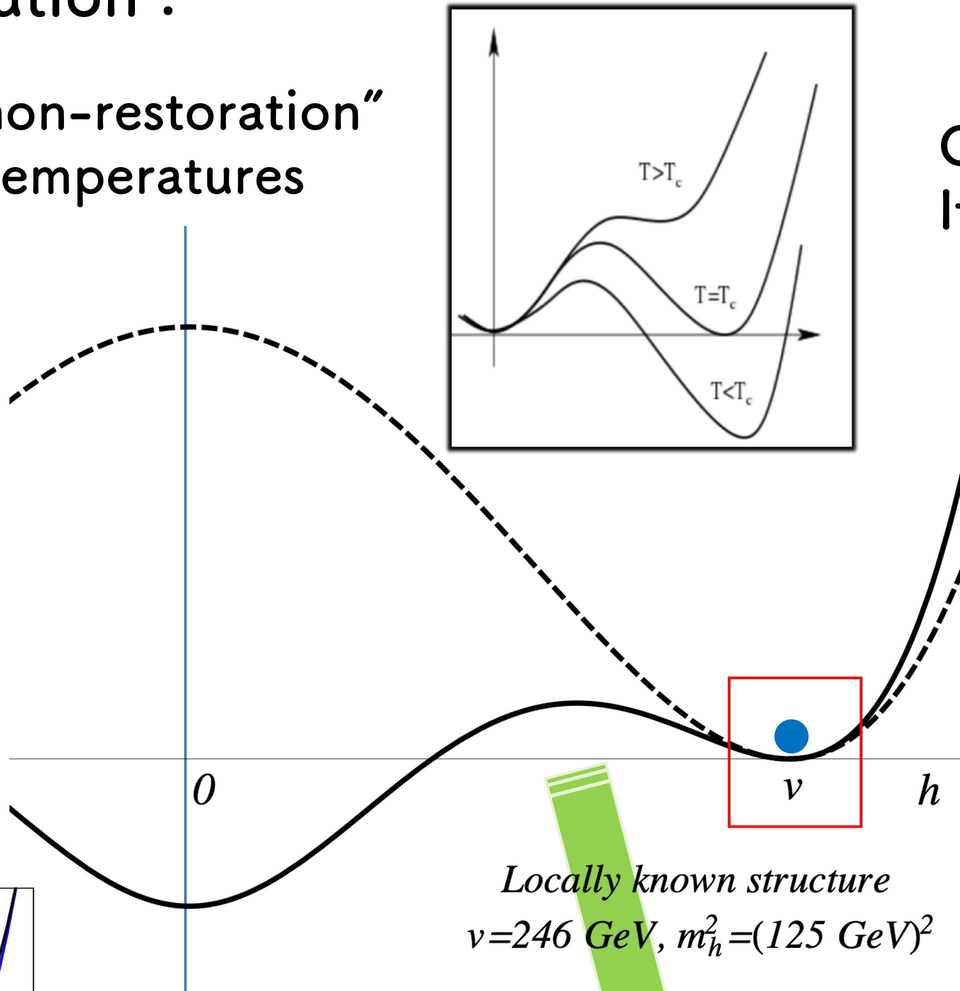


We focus on this :



Thermal evolution :

EW symmetry "non-restoration" (SNR) at finite temperatures

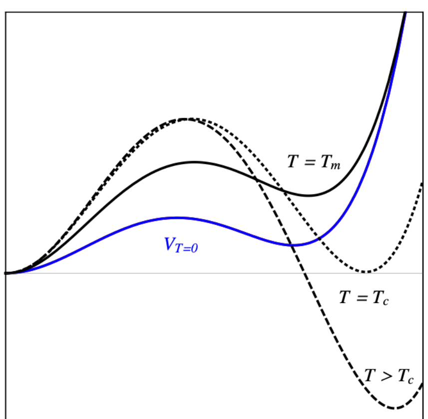


Optional SNR
If you want

Weinberg, PRD 74'
...
Meade, Ramani, PRL 19'
Baldes, Gervant, JHEP 18;
Glioti, Rattazzi, Vecchi, JHEP 19;
Matsedonskyi, Servant, JHEP 20'
Cao, Hashino, Li, Ren, Yu, 21'

SM-type

We focus on



Locally known structure
v=246 GeV, m_h^2=(125 GeV)^2

Evolving toward EW symmetry non-restoration

Bai, Lee, SON, Ye 21'

Non-optional SNR

; EW symmetry restoration postponed to a very high T

Higgs-portal

e.g. as simple toy-model for Landscape scenario

We introduce Higgs-portal coupling to SM singlets belongs to O(N) rep with a large N

(Simple toy-model for Landscape scenario)

$$V_{tree} = -\frac{\mu^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\lambda_{hs}}{2}h^2 S^2 + \frac{m_s^2}{2}S^2 + \frac{\lambda_s}{4}(S^2)^2 + \frac{\lambda_{h\phi}}{2}h^2\Phi^2 + \frac{m_\phi^2}{2}\Phi^2 + \frac{\lambda_s}{4}(\Phi^2)^2$$

$\lambda_{s\phi} \sim \lambda_{hs}\lambda_{h\phi}/16\pi^2$ $\quad \lambda_h, \lambda_s, \lambda_\phi, \lambda_{h\phi} > 0$

S, Φ belong to fundamental rep of $O(N_s)$, $O(N_\phi)$

Responsible for EW symmetry non-restoration due to $\lambda_{hs} < 0$

Responsible for lifting v=246 GeV to metastable vacuum via quantum correction

Stability at large fields

$$-\sqrt{\lambda_h}\sqrt{\lambda_s} < \lambda_{hs} < 0$$

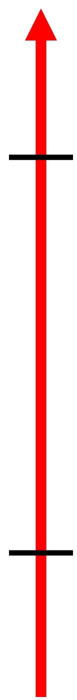
Simple diagrammatic NDA estimates for perturbativity

$$\frac{\sqrt{N_s}|\lambda_{hs}|}{16\pi^2}, \quad \frac{\sqrt{N_\phi}|\lambda_{h\phi}|}{16\pi^2}, \quad \frac{N_s\lambda_s}{16\pi^2}, \quad \frac{N_\phi\lambda_\phi}{16\pi^2} < \mathcal{O}(1)$$

See extra slides for RGE

We introduce Higgs-portal coupling to SM singlets belongs to O(N) rep with a large N

$$\Lambda_L = v \exp\left[\frac{16\pi^2}{\sqrt{8(2N_\phi + 4)}}\frac{1}{|\lambda_{h\phi}(v)|}\right]$$



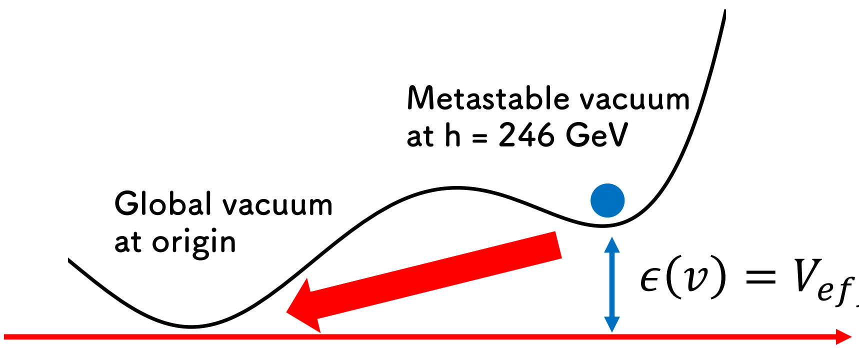
Λ_{UV} $\sim \Lambda_L \sim$ 120 TeV for $\lambda_{h\phi}$

Smallest Landau pole scale in our benchmark scenarios as $N_\phi \lambda_{h\phi}^2$ is constrained to exhibit EWS vacuum at h = 0

μ_{EW}

The complete set of conditions for Global EWS vacuum at h = 0 (metastable at h = 246 GeV)

$$V_{eff} = V_{tree} + V_{CW}$$



$$\epsilon(v) = V_{eff}(v) - V_{eff}(0) > 0$$

$$m_h^2(0) = \left.\frac{d^2 V_{eff}}{dh^2}\right|_{h=0} > 0$$

$$\Gamma_4 \approx \frac{1}{R^4}\left(\frac{S_4}{2\pi}\right)^2 \exp(-S_4) < H_0^4 \qquad : T \approx 0$$

: Long-lived enough vacuum than age of Universe

$$S_4 > S_4^{min} \approx 416$$

$$\Gamma_3 \approx T^4 \left[\frac{S_3(T)}{2\pi T}\right]^{\frac{3}{2}} \exp\left(-{}^{S_3(T)}/_{T}\right) \qquad : T \neq 0$$

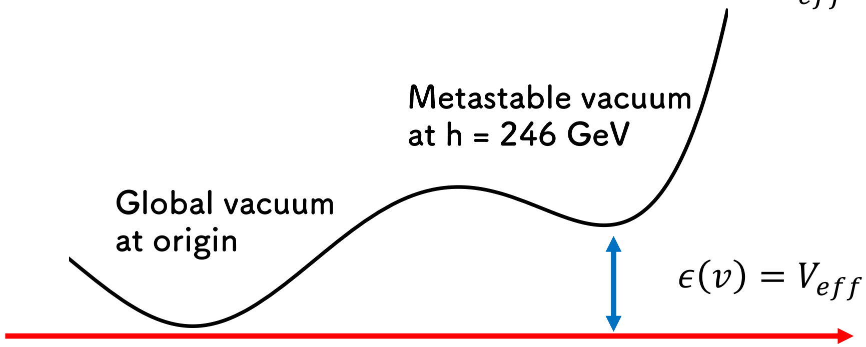
: No even a single supercritical bubble creation should allowed

$$(S_3(T)/T)_{min} > 339$$

Against quantum tunneling

$$\boldsymbol{T = 0}$$

Global EWS vacuum at h = 0



$$V_{eff} = V_{tree} + V_{CW}$$

$$V_{CW} = \sum_{X=S,\Phi} \frac{N_X}{64\pi^2}\left[m_X^4(h)\left(\ln\frac{m_X^2(h)}{m_X^2(v)} - \frac{3}{2}\right) + 2m_X^2(h)m_X^2(v)\right]$$

$$\epsilon(v) = V_{eff}(v) - V_{eff}(0) > 0$$

$$m_h^2(0) = \left.\frac{d^2V_{eff}}{dh^2}\right|_{h=0} > 0$$

$$m_h^2(0) = -\lambda_h v^2 + \boxed{\frac{N_s\lambda_{hs}}{16\pi^2}m_s^2\left[\ln\left(\frac{1}{1+\lambda_{hs}v^2/m_s^2}\right) + \frac{\lambda_{hs}v^2}{m_s^2}\right]} + \boxed{\frac{N_\phi\lambda_{h\phi}^2}{16\pi^2}v^2\left[\frac{m_\phi^2}{\lambda_{h\phi}v^2}\ln\left(\frac{m_\phi^2/\lambda_{h\phi}v^2}{m_\phi^2/\lambda_{h\phi}v^2+1}\right)+1\right]} > 0$$

We save S for finite-T part

We chose Φ to be responsible for lifting

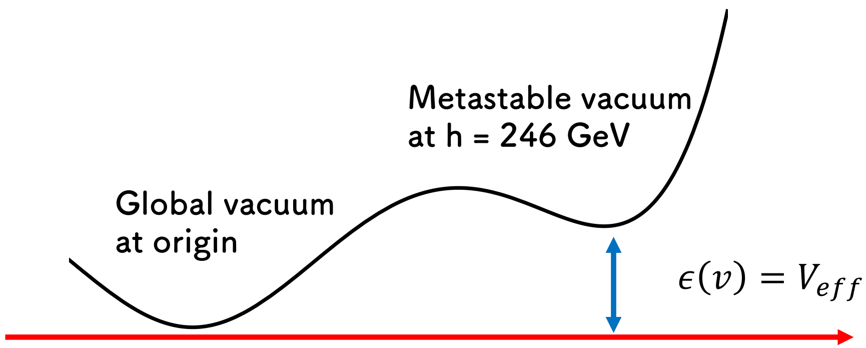
$$\epsilon(v) = -\frac{1}{4}\lambda_h v^2 + \boxed{\frac{N_s}{128\pi^2}m_s^4\left[\frac{\lambda_{hs}^2v^4}{m_s^4} - 2\frac{\lambda_{hs}v^2}{m_s^2} - 2\ln\left(\frac{1}{1+\lambda_{hs}v^2/m_s^2}\right)\right]}$$

$$+ \boxed{\frac{N_\phi\lambda_{h\phi}^2}{128\pi^2}v^4\left[1 - 2\frac{m_\phi^2}{\lambda_{h\phi}v^2} - 2\frac{m_\phi^4}{\lambda_{h\phi}^2v^4}\ln\left(\frac{m_\phi^2/\lambda_{h\phi}v^2}{m_\phi^2/\lambda_{h\phi}v^2+1}\right)\right]} > 0$$

$$m_s^2 \sim v^2\,, \quad |\lambda_{hs}| \ll 1\,, \quad \frac{m_\phi^2}{\lambda_{h\phi}v^2} \ll 1$$: asymmetric assignment to Φ, S

Global EWS vacuum at h = 0

$$m_s^2 \sim v^2\,,\quad |\lambda_{hs}| \ll 1\,,\quad \frac{m_\phi^2}{\lambda_{h\phi} v^2} \ll 1$$: our assumptions



$$\epsilon(v) = V_{eff}(v) - V_{eff}(0) > 0$$

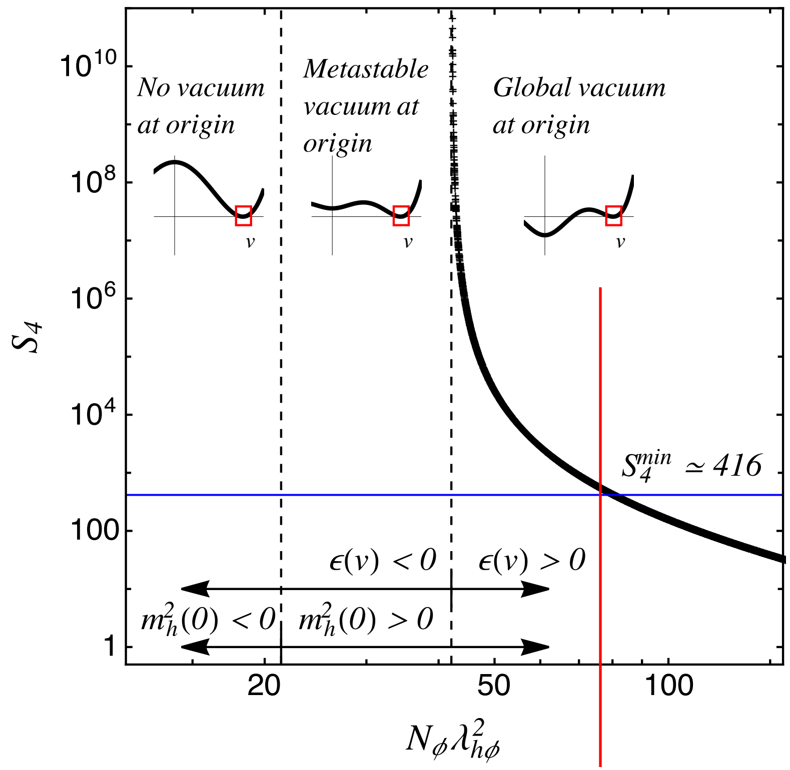
$$m_h^2(0) = \left.\frac{d^2 V_{eff}}{dh^2}\right|_{h=0} > 0 \qquad \approx -\frac{1}{4}\lambda_h v^2 + \frac{m_s^4 N_s}{192\pi^2}\left(\frac{\lambda_{hs} v^2}{m_s^2}\right)^3 + \frac{N_\phi \lambda_{h\phi}^2}{128\pi^2} v^4 > 0$$

$$\Rightarrow \quad N_\phi \lambda_{h\phi}^2 > 32\pi^2 \lambda_h \approx 41$$

$$\approx -\lambda_h v^2 + \frac{N_s \lambda_{hs}^3}{32\pi^2}\frac{v^4}{m_s^2} + \frac{N_\phi \lambda_{h\phi}^2}{16\pi^2} v^2 > 0$$

$$\Rightarrow \quad N_\phi \lambda_{h\phi}^2 > 16\pi^2 \lambda_h \approx 21$$

Global electroweak symmetric vacuum against quantum tunneling process



$N_\phi \lambda_{h\phi}^2 < 80$

$$\Gamma_4 \approx \frac{1}{R^4}\left(\frac{S_4}{2\pi}\right)^2 \exp(-S_4) < H_0^4 \qquad : T \approx 0$$

: Long-lived enough vacuum than age of Universe

$$S_4 > S_4^{min} \approx 416$$

Against thermal transition

$$T \neq 0$$

Thermal evolution of global EW symmetric vacuum & EW symmetry non-restoration (SNR)

To be consistent current metastable EW symmetry breaking vacuum

In the high T limit

: our numerical simulation does not assume high-T approximation

$$\Delta V_{thermal} = \frac{1}{24}\left(N_s\lambda_{hs} + N_\phi\lambda_{h\phi}\right)T^2h^2$$

$$+\frac{1}{24}\underbrace{[4\lambda_{hs} + (N_s+2)\lambda_s]}_{>0}T^2S^2 + \frac{1}{24}\left[4\lambda_{h\phi} + \left(N_\phi+2\right)\lambda_\phi\right]T^2\Phi^2 + \cdots$$

No saddle points in S and Φ direction

EW SNR

Option 1 : $N_s\lambda_{hs} + N_\phi\lambda_{h\phi} < 0$

→ **Prefers Asymmetric : $N_s \gg N_\phi$**

$$\frac{6.41}{\sqrt{N_\phi}} \approx \frac{4\pi\sqrt{2\lambda_h}}{\sqrt{N_\phi}} < \lambda_{h\phi} < -\frac{N_s}{N_\phi}\lambda_{hs}$$

Condition for global EWS vacuum at h = 0

Favors $\lambda_{h\phi} \lesssim \mathcal{O}(1)$ for $N_\phi \gtrsim 10^2$ (vs. $|\lambda_{hs}| \ll 1$)

Thermal evolution of global EW symmetric vacuum & EW symmetry non-restoration (SNR)

To be consistent current metastable EW symmetry breaking vacuum

In the high T limit

$$\Delta V_{thermal} = \frac{1}{24}(N_s\lambda_{hs} + N_\phi\lambda_{h\phi})T^2h^2 + \frac{1}{24}\underbrace{[4\lambda_{hs} + (N_s+2)\lambda_s]}_{>0}T^2S^2 + \frac{1}{24}[4\lambda_{h\phi} + (N_\phi+2)\lambda_\phi]T^2\Phi^2 + \cdots$$

EW SNR

Option 2 : neg. Higgs mass-sq from $V_{\rm ring}$

→ **Symmetric : $\boldsymbol{N_s = N_\phi}$ allowed**

Dominant contributions to negative Higgs mass squared from Φ and $N_s\lambda_{hs} + N_\phi\lambda_{h\phi} < 0$, or $\lambda_{h\phi} < -\frac{N_s}{N_\phi}\lambda_{hs}$

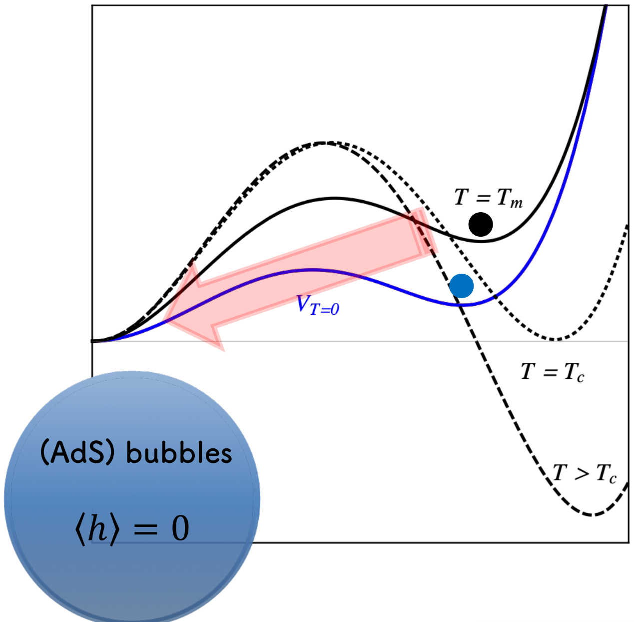
is not necessarily required

, but negative λ_{hs} still helps for SNR

$$V_{\rm ring} \approx -\frac{T^2h^2}{16\sqrt{3}\pi}\left[N_s\lambda_{hs}\sqrt{3\lambda_{hs} + (2+N_s)\lambda_s}\right] - \frac{T^2h^2}{16\sqrt{3}\pi}\left[N_\phi\lambda_{h\phi}\sqrt{3\lambda_{h\phi} + (2+N_\phi)\lambda_\phi}\right] \quad \text{: High-T limit}$$

$$\approx -\frac{N_sT^3}{96\pi}[4\lambda_{hs} + (2+N_s)\lambda_s]\sqrt{m_s^2 + \lambda_{hs}h^2} - \frac{N_\phi T^3}{96\pi}[4\lambda_{h\phi} + (2+N_\phi)\lambda_\phi]\sqrt{m_\phi^2 + \lambda_{h\phi}h^2} \quad \text{: Low-T limit}$$

Thick wall vs thin wall approximation



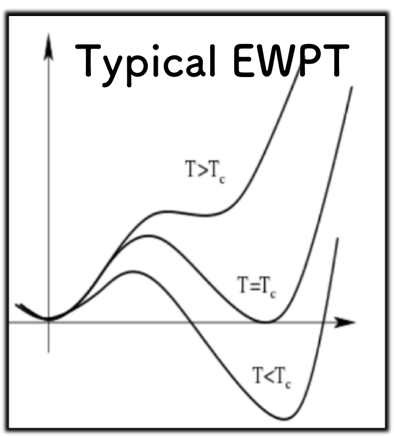
$\langle h \rangle \neq 0$

PT can occurs well before T=Tc, and thin-wall approximation is not necessarily justified

PT needs to be uncompleted against $\frac{S_3(T)}{T}$ (and S_4 as well)

$$\frac{S_3(T_m)}{T_m} \gtrsim \ln\left(M_{pl} T_m^2 t_0^3\right) + \frac{3}{2}\ln\left[\frac{2}{3}\ln\left(M_{pl} T_m^2 t_0^3\right)\right] \approx 339$$

$t_0 = 13.7$ Gyr, $T_m = 10$ GeV



PT occurs right after T = Tc where two vacua are almost degenerate, and thin-wall approximation is likely valid

PT is completed immediately

$$\frac{S_3(T_c)}{T_c} \lesssim 150$$

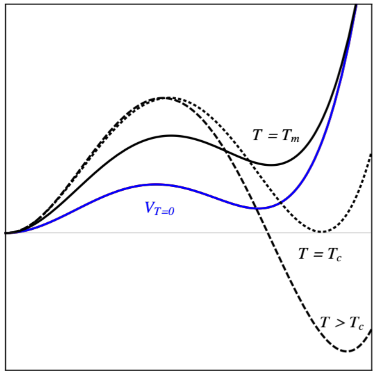
Super (sub) critical bubbles

Gleiser, Kolb, Watkins, Nucl.Phys.B 91'
Gleiser, Heckler, Kolb, Phys.Lett.B 97'

Espinosa, Giudice, Morgante, Riotto, Senatore, Strumia, JHEP 15'

Bubbles can be treated as a normal matter with a mass

We can adopt thin-wall approx for qualitative understanding



Volume energy   Surface energy

$$S_3 = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + V(h,T)\right] \sim -\frac{4}{3}\pi R^3 \epsilon(T) + 4\pi R^2 S_1(T)$$

$r = |\vec{x}|$

: favors expansion   : favors contraction

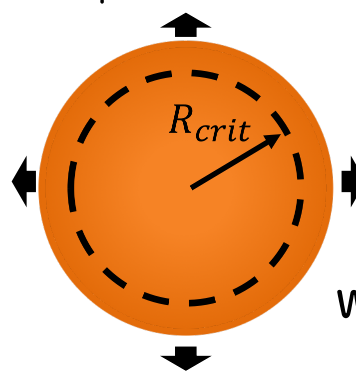
$$S_1 = \int_0^\infty dr \left[\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + V(h,T)\right]$$

Sub-critical

$$R_{crit} = \frac{2S_1(T)}{\epsilon(T)}$$

Will collapse

Super-critical



Will expand

sub-critical bubbles with smaller R will be freq generated and collapse afterward

Total energy contained inside the bubble is roughly

$$\epsilon(v)(R_0 = v_w t_0)^3$$

Super (sub) critical bubbles

Gleiser, Kolb, Watkins, Nucl.Phys.B 91'
Gleiser, Heckler, Kolb, Phys.Lett.B 97'

Alternative approach
Espinosa, Giudice, Morgante, Riotto, Senatore, Strumia, JHEP 15'

Bubbles can be treated as a normal matter with a mass

We can adopt thin-wall approx for qualitative understanding

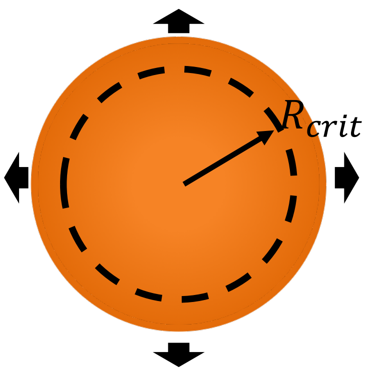
Volume energy — Surface energy

$$S_3 = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + V(h,T)\right] \sim -\frac{4}{3}\pi R^3 \epsilon(T) + 4\pi R^2 S_1(T)$$

$r = |\vec{x}|$

Volume energy: favors expansion — Surface energy: favors contraction

Super-critical bubble and uncompleted phase transition



$$R_{crit} = \frac{2S_1(T)}{\epsilon(T)}$$

Fraction of space (for a volume V) not occupied by the bubbles

$$f(t) \sim \exp(-\Gamma_3 \cdot V) = \exp\left(-\frac{4\pi}{3}\int_{t_c}^{t} dt' v_w^3 (t-t')^3 \Gamma_3(t')\right)$$

where $\Gamma_3 \approx T^4 \left[\frac{S_3(T)}{2\pi T}\right]^{\frac{3}{2}} \exp\left(-{S_3(T)}/{T}\right)$

$$f(t_0) \sim 1 \rightarrow \quad \frac{S_3(T_m)}{T_m} \gtrsim \ln\left(M_{pl} T_m^2 t_0^3\right) + \frac{3}{2}\ln\left[\frac{2}{3}\ln\left(M_{pl} T_m^2 t_0^3\right)\right] \approx 339$$

$t_0 = 13.7$ Gyr, $T_m = 10$ GeV

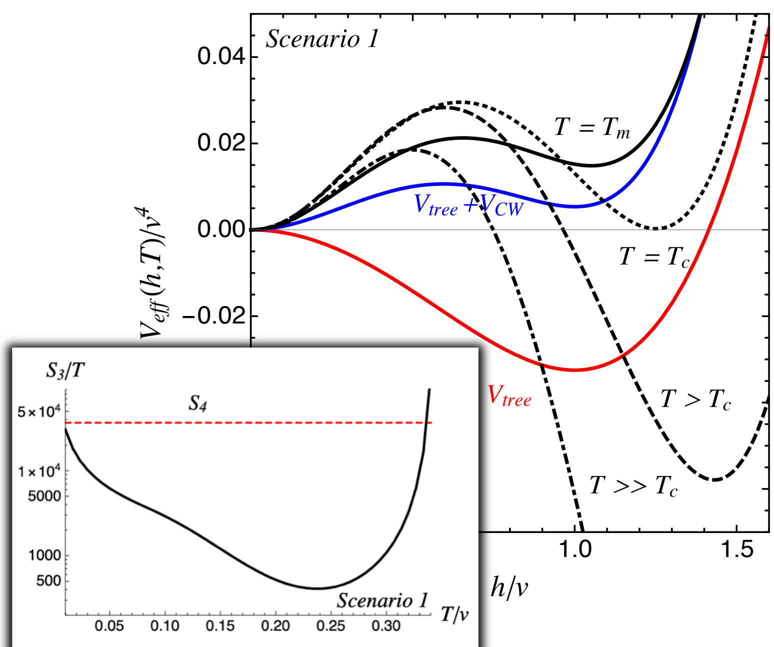
Benchmark scenarios & numerical scans

Benchmark scenarios

$$m_s^2 \sim v^2\,, \quad |\lambda_{hs}| \ll 1\,, \quad \frac{m_\phi^2}{\lambda_{h\phi} v^2} \ll 1\,, \quad \frac{6.41}{\sqrt{N_\phi}} \approx \frac{4\pi\sqrt{2\lambda_h}}{\sqrt{N_\phi}} < \lambda_{h\phi} < -\frac{N_s}{N_\phi}\lambda_{hs}$$

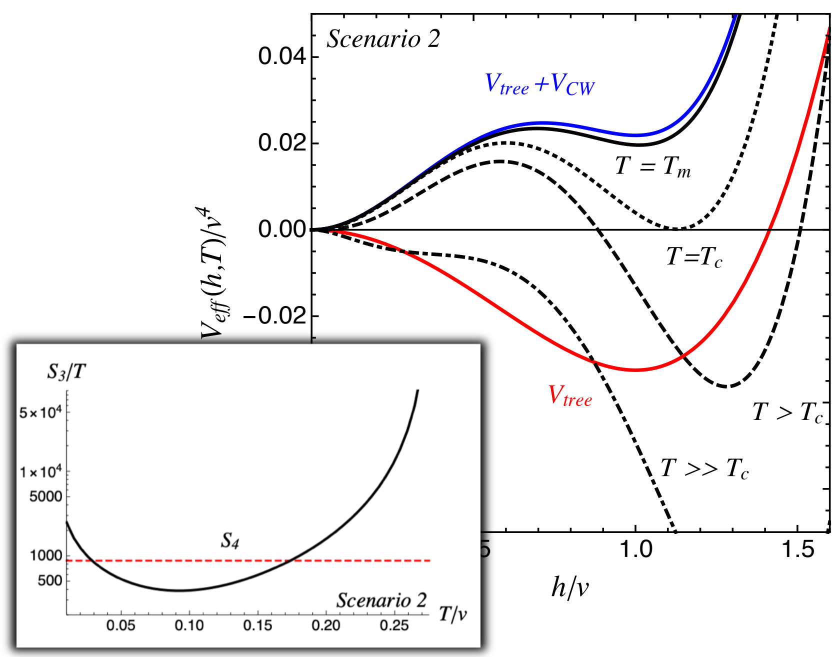
	λ_{hs}	$\lambda_{h\phi}$	λ_s	λ_ϕ	m_s	$\alpha = \frac{m_\phi^2}{\lambda_{h\phi} v^2}$	N_s	N_ϕ	S_4	$\left(\frac{S_3}{T}\right)_{\min}$	$\frac{T_{\min}}{v}$	$\frac{T_c}{v}$
1	-0.1	0.70	$5 \cdot 10^{-4}$	10^{-4}	246	0.001	1500	100	36680	409	0.234	0.343
2	-0.1	0.83	0.1	0.1	246	0.001	100	100	879	386	0.095	0.278

Asymmetric : $N_s \gg N_\phi$



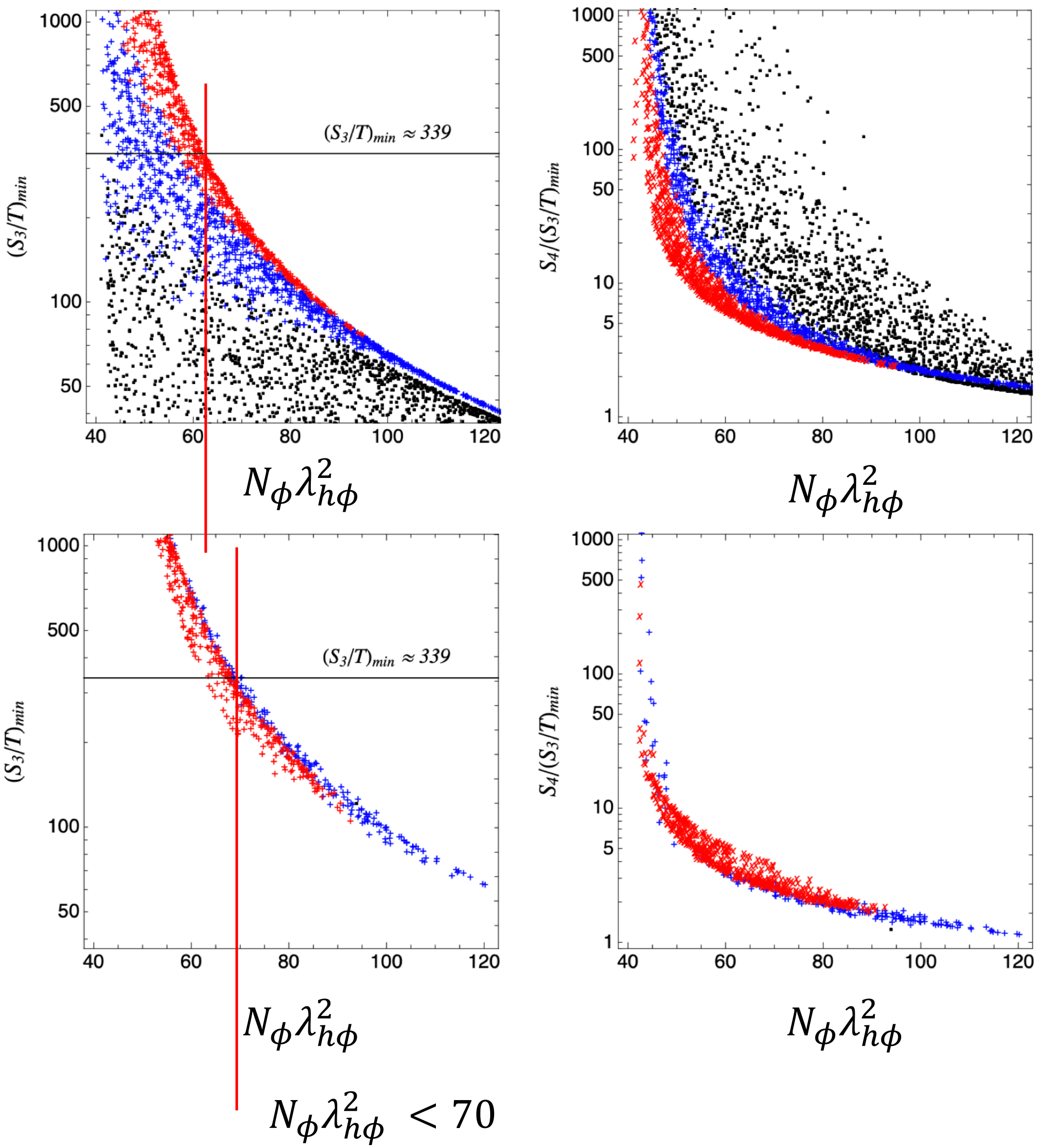
Non-monotonic evolution

Symmetric : $N_s = N_\phi$



Monotonic evolution

Numerical scans in the vicinity of two benchmark points



Asymmetric : $N_s \gg N_\phi$

$\lambda_{h\phi} = [0.40,1.10]$, $N_\phi = [30,200]$

$N_s = [1000,1500]$

Varying other parameters (e.g. m_s) has minor effect on upper limit of $N_\phi \lambda_{h\phi^2}$

Symmetric : $N_s = N_\phi$

$\lambda_{h\phi} = [0.40,1.10]$, $N_\phi = [30,200]$

$N_s = [30,200]$

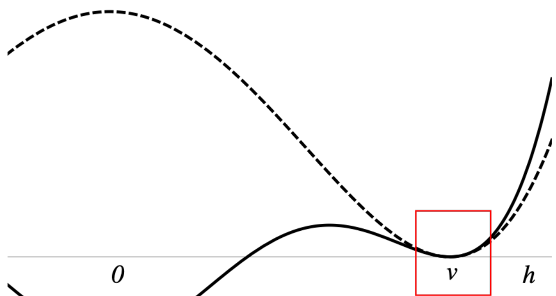
Varying other parameters (e.g. m_s, $\lambda_{s,\phi}$) has minor effect on upper limit of $N_\phi \lambda_{h\phi^2}$

Testing ….

Collider Phenomenology

1. Higgs cubic self-coupling

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \lambda_3 v h^3 + \frac{1}{4!} \lambda_4 h^4$$



Locally known structure
v=246 GeV, m_h^2=(125 GeV)^2

$$\lambda_3 \sim 6\lambda_h + \frac{N_\phi \lambda_{h\phi}^2}{4\pi^2} + \frac{N_s \lambda_{hs}^2}{4\pi^2} \frac{\lambda_{hs} v^2}{m_s^2}$$

$$41 \; < \; N_\phi \lambda_{h\phi}^2 \; < \; 80 \quad (70)$$

$: m_h^2(0), \epsilon(v) > 0$

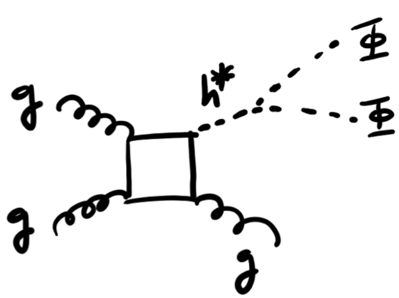
Global EWS vacuum at T = 0	Global EWS vacuum at $T \neq 0$
$: S_4 > 416$	$: S_3(T_m)/T_m > 339$

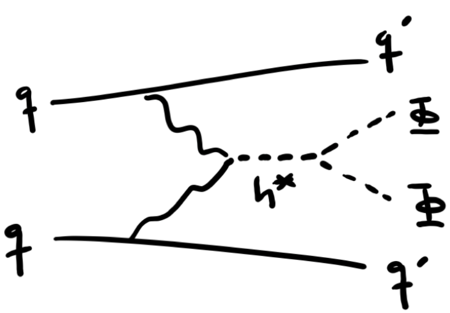
Expected : $2.3 < \dfrac{\lambda_3}{\lambda_3^{SM}} < 3.6 \quad (3.3)$

2. Missing Et + jets

$41 \; < \; N_\phi \lambda_{h\phi}^2 \; < \; 80 \quad (70)$, $m_\phi^{\text{phys}} > m_h/2$ satisfied

$(m_\phi^{\text{phys}\,2} = m_\phi^2 + \lambda_{h\phi} v^2)$





$$\sigma(pp \to \Phi\Phi + \text{jets})$$

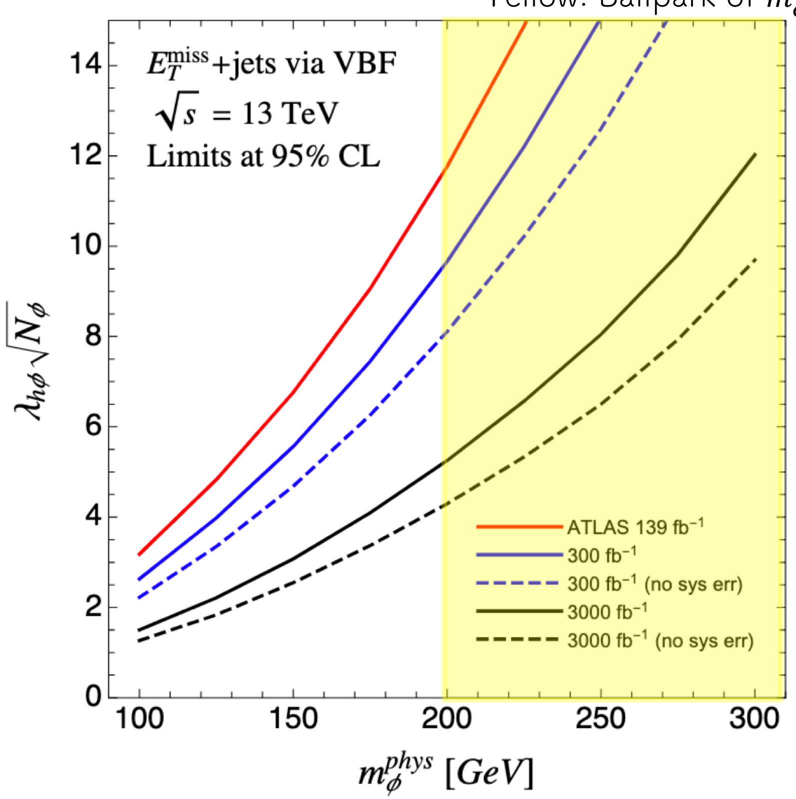
$$= N_\phi \lambda_{h\phi}^2 \cdot \sigma(\text{with } \lambda_{h\phi}\sqrt{N_\phi} = 1)$$

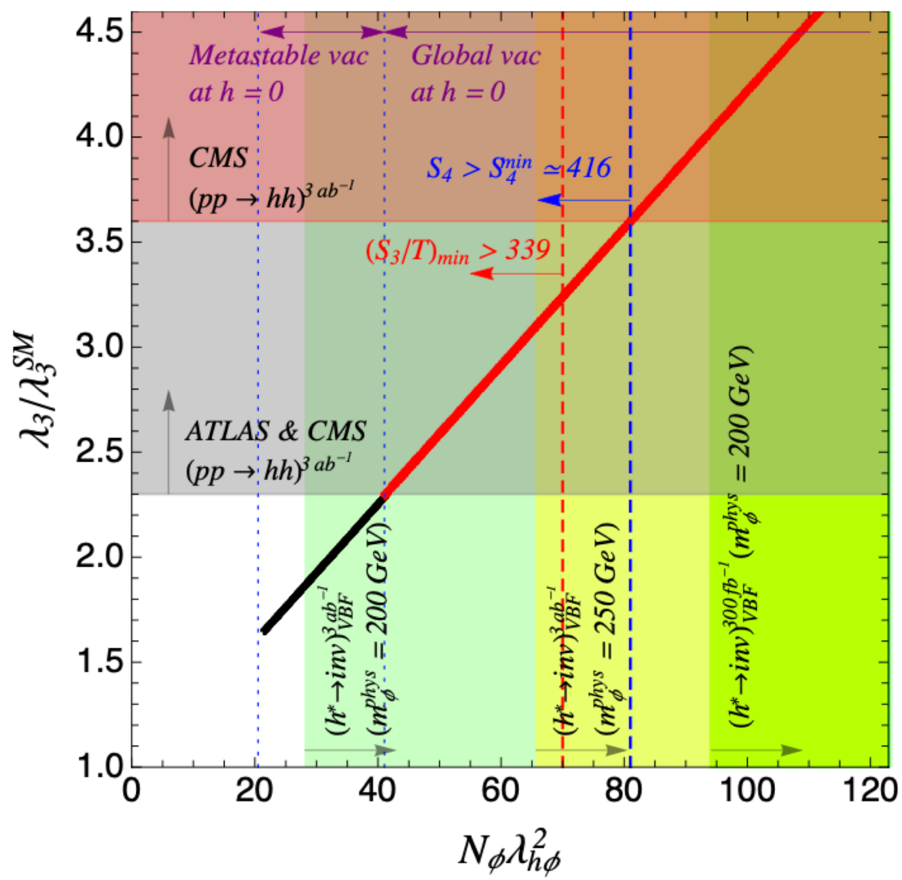
Higgs cubic self-coupling vs Missing Et + jets

$$2.3 < \frac{\lambda_3}{\lambda_3^{SM}} < 3.6\ (3.3)\,, \quad 41 < N_\phi \lambda_{h\phi}^2 < 80 \quad (70)$$

ATLAS, inv Higgs boson decays with VBF, 13TeV, 139/fb
ATLAS-CONF-2020-008

Yellow: Ballpark of $m_\phi^{\rm phys}$





Similar studies at 14 TeV and future colliders
Craig, Lou, McCullough, Thalapillil, 16'
Ruhdorfer, Salvioni, Weiler, 20'

Summary and future direction

Global EWS vacuum has been less explored

1. More natural from viewpoint of Landscape
2. More natural with electroweak symmetry non-restoration

Global EWS vacuum is testable in near future

1. Higgs self-couplings
2. Invisible decay of off-shell Higgs

We initiated only one simple model and there could be many variants and related physics

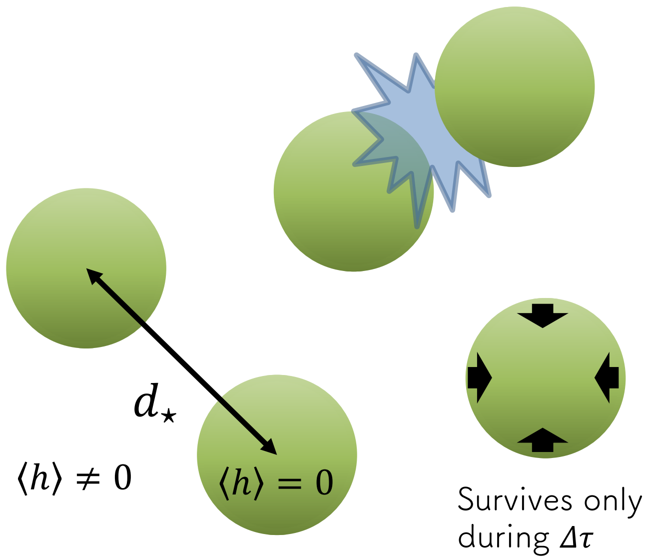
Many variants:

1. More fields
2. Tree vs loop-induced
3. ⋯

Related physics:

1. Dark Matter
2. Baryogenesis
3. EWS bubbles in the sky
4. Gravitational Waves
5. ⋯

Sub-critical bubbles



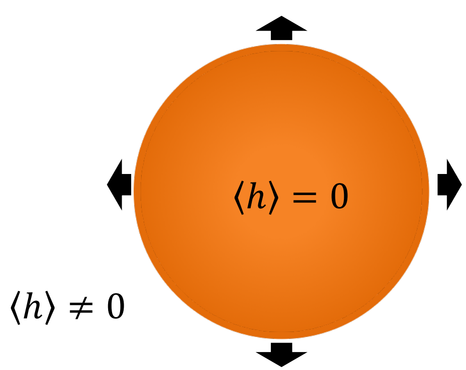
Can collisions between subcritical bubbles create detectable gravitational waves (before being disappeared) ?

Looks like unlikely

$$d_\star \sim n_{\text{bubble}}^{-1/3} \sim \left[\int_{t_\star}^{t} dt' \Gamma(t') f(t')\right]^{-1/3} \gg \Delta\tau$$

Can baryon asymmetry be generated inside bubbles ?

Super-critical bubbles



Can we slow down the wall velocity ?

e.g. $v_w \ll 1$

If yes, we might look for EWS bubbles in the sky ?

No instability at a large Higgs field

$$16\pi^2\beta_{\lambda_h} \approx 12y_t^2\lambda_h + 24\,\lambda_h^2 \boxed{- 6y_t^4 + 2N_s\lambda_{hs}^2 + 2N_\phi\lambda_{h\phi}^2}$$

No instability at a large Higgs field is induced

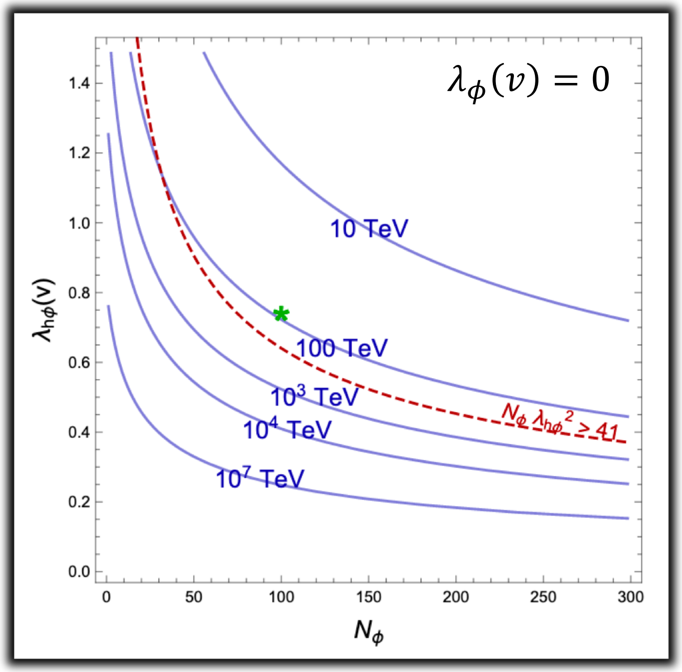
Landau pole scale ~ cutoff scale of our EFT

$$16\pi^2\beta_{\lambda_{hs}} \approx (2N_s + 4)\lambda_{hs}\lambda_s + 8\lambda_{hs}^2$$

$$16\pi^2\beta_{\lambda_s} \approx 8\lambda_{hs}^2 + (2N_s + 4)\lambda_s^2$$

$$16\pi^2\beta_{\lambda_{h\phi}} \approx (2N_\phi + 4)\lambda_{h\phi}\lambda_\phi + 8\lambda_{h\phi}^2$$

$$16\pi^2\beta_{\lambda_\phi} \approx 8\lambda_{h\phi}^2 + (2N_\phi + 4)\lambda_\phi^2$$



$$\Lambda_L = v\exp\left[\frac{16\pi^2}{\sqrt{8(2N_s + 4)}}\frac{1}{|\lambda_{hs}(v)|}\right]$$

$\sim 2.3 \times 10^{19}$ GeV

$$\Lambda_L = v\exp\left[\frac{16\pi^2}{\sqrt{8(2N_\phi + 4)}}\frac{1}{|\lambda_{h\phi}(v)|}\right]$$

~ 120 TeV for $N_\phi\lambda_{h\phi}^2 > 32\pi^2\lambda_h \approx 41$