On the Validity of the Effective Potential and the Precision of Higgs Self Couplings

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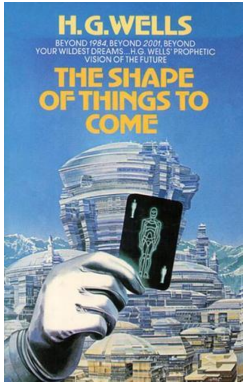
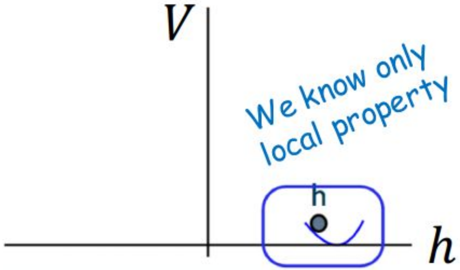
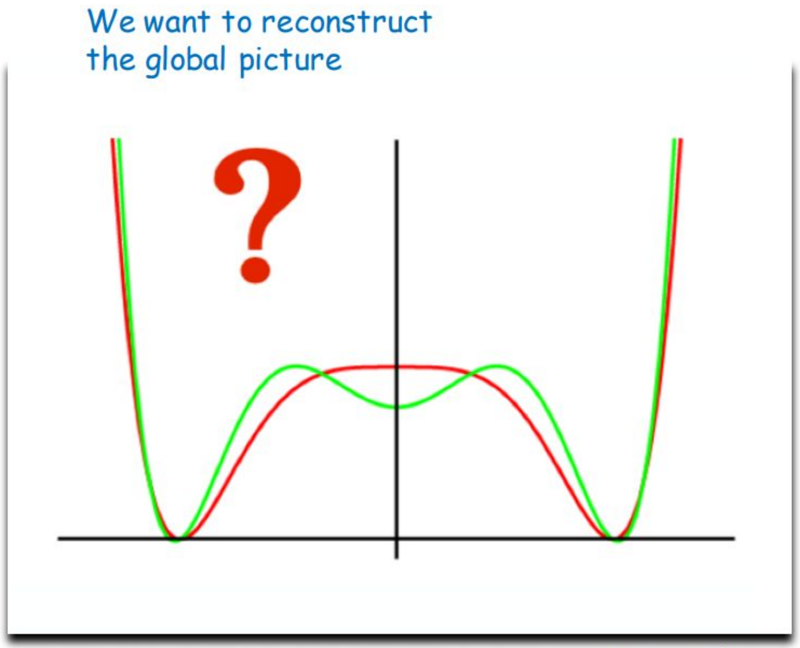
Work done with Minho Son, Seung J Lee

Based on arXiv:1709.03232

The Shape of Things to come





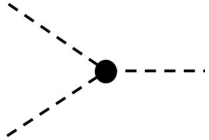


$$V_h = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 + d_4 \frac{1}{24}\left(\frac{3\, m_h^2}{v^2}\right) h^4$$

measured

Unknown!! - c_3=d_3=1 (SM) - measurement needed to test the validity of SM

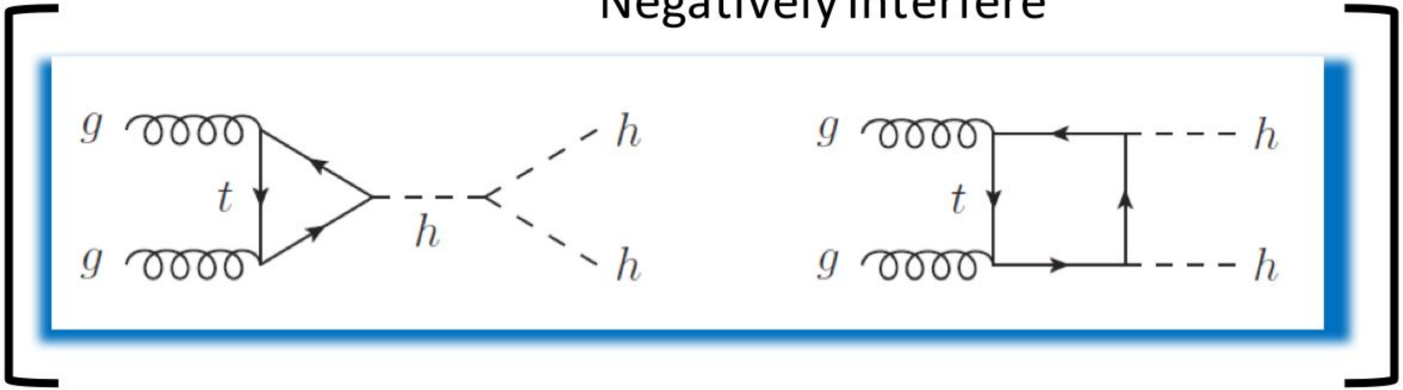
Can Higgs potential be tested by self coupling measurements?



- ➔ Cubic higgs self coupling
- ➔ HH production via gluon fusion is the best channel

Negatively Interfere

σ



$\sim$ 40 fb @14 TeV

$\times$ BR

Very small signal rate

$$\sim \frac{m_h^2}{\hat{s}}$$

Threshold region = big backgrounds

Nothing to discuss about Higgs self coupling using current data

ATL-PHYS-PUB-2014-019

$b\bar{b}\gamma\gamma$ by ATLAS

Cubic coupling @ HL LHC using 3000/fb

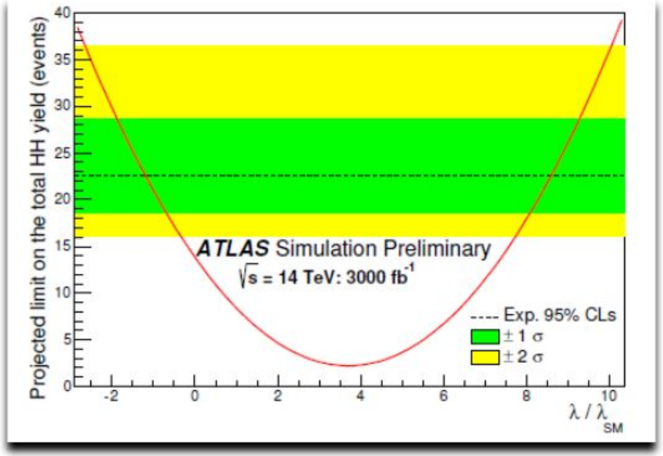
- ✓ Very tough process

  $b\bar{b}\gamma\gamma$ (0.264%)

  Seems to be the best channel so far

  We would see only ~ 10 events by the end of HL LHC

Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4



an exclusion at 95% C.L. of BSM models with $\lambda_3/\lambda_{3,SM} \leq -1.3$ and $\lambda_3/\lambda_{3,SM} \geq 8.7$

Similarly for $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$ by CMS

CMS FTR-15-002-pas

Nothing to discuss about Higgs self coupling using current data

Cubic coupling @ HL LHC using 3000/fb

- ✓ Very tough process

  $b\bar{b}\gamma\gamma$ (0.264%)

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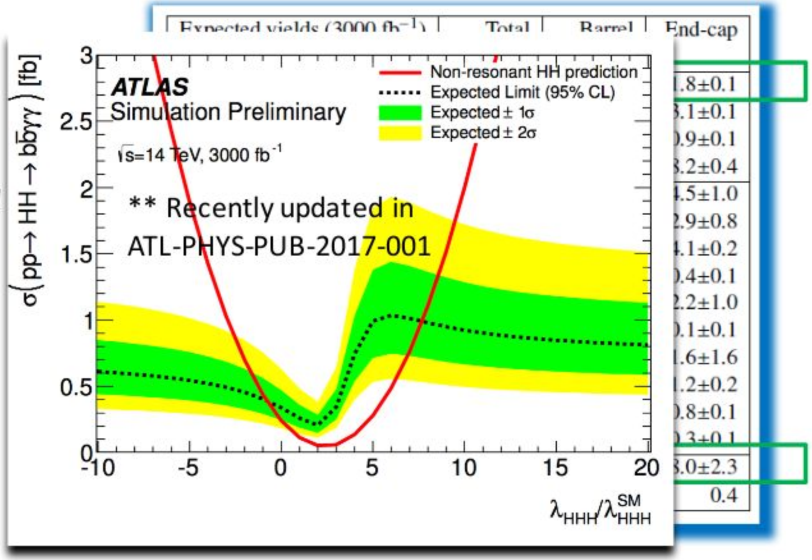
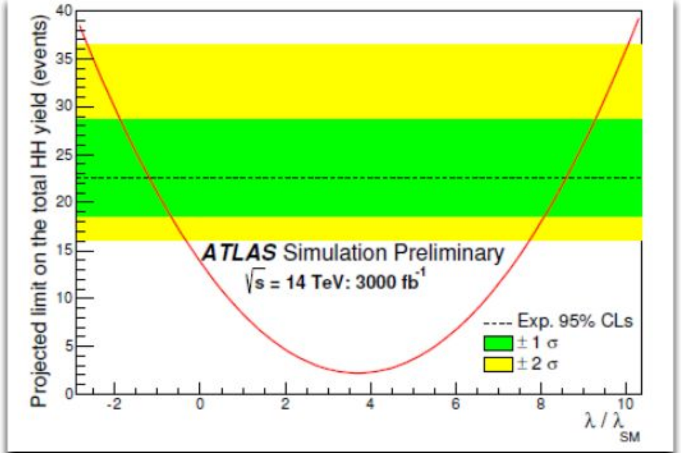
  We would see only ~ 10 events by the end

$b\bar{b}\gamma\gamma$ by ATLAS



** Recently updated in ATL-PHYS-PUB-2017-001

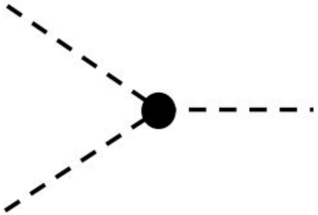


$-0.8 < \lambda/\lambda_{SM} < 7.7$ at 95% CL (excl.)

Similarly for $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$ by CMS

CMS FTR-15-002-pas

Cubic coupling @ 100 TeV using 30/ab



- ✓ $b\bar{b}\gamma\gamma$ becomes Golden channel at 100 TeV pp collider

$40\times$ enhanced xsec due to PDF

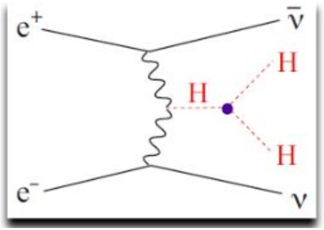
Barr, Dolan, Englert, Lima, M.Spannowsky 15'
Contino, Azatov, Panico, SON 15'
H. He, J. Ren, W. Yao 16'
Physics at 100 TeV

Contino, Panico, Papaefstathiou, Selvaggi, SON
in progress

$\sim$ 3.4 % is possible with 30 ab^{-1}

Physics at 100 TeV, arXiv:1606.09408

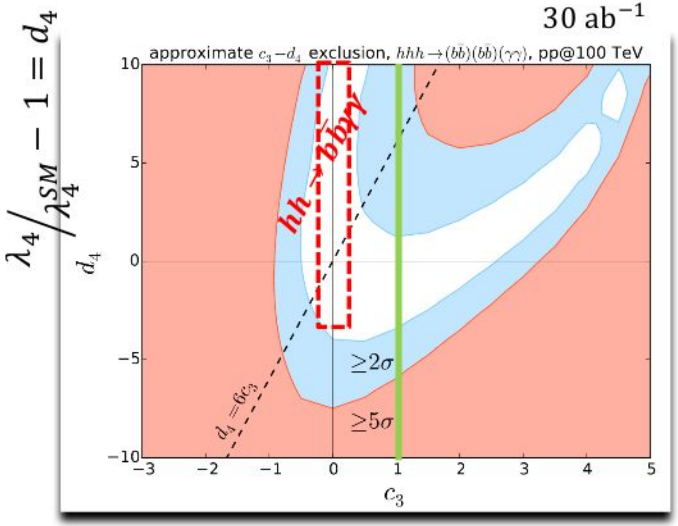
- ✓ ILC via VBF at 1 TeV 8 ab^{-1} ~10%



J. Tian, LC-REP-2013-003 M. Kurata,
LC-REP-2014-025 C. Duerig, Ph.D. thesis at DESY, 2016
HHàbbbb, bbWW* combination

Quartic coupling @ 100 TeV

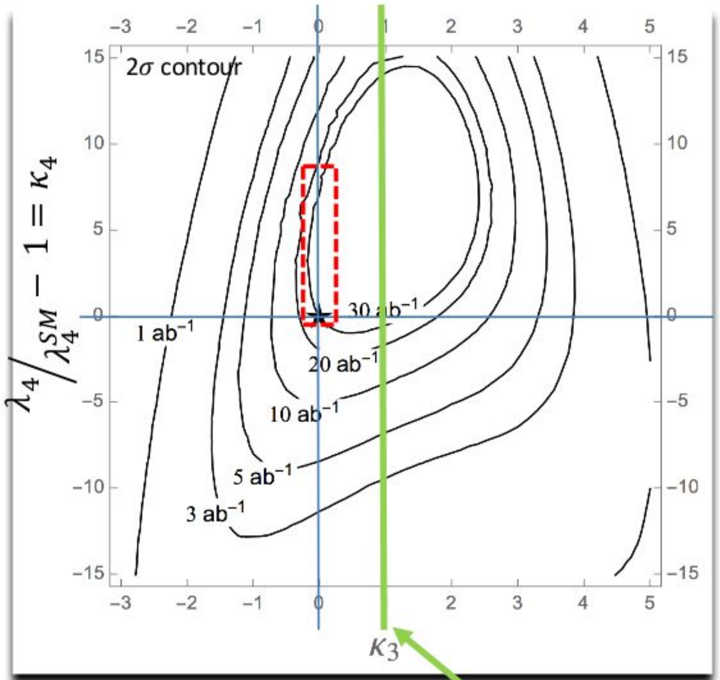
$hhh \to b\bar{b}b\bar{b}\gamma\gamma$ BR=0.232 %



Papaefstathiou, Sakurai 15'

$\lambda_3 / \lambda_3^{SM} - 1 = c_3$

$hhh \to b\bar{b}b\bar{b}\tau^+\tau^-$ $BR = 6.46\ \%$



$\lambda_3 / \lambda_3^{SM} - 1 = \kappa_3$

Fuks, Kim, Lee 16'

✓ If we observe cubic ~ $\mathcal{O}(1)$ @ HL LHC or 100 TeV, then quartic from 100 TeV is very useful

What if we observe a large κ_3 at HL LHC?

Dynamics of EWPT

Mass param, μ^2

$$V_{\rm EFF}(\varphi, T) = D(T^2 - T_0^2)\varphi^2 - (ET + e)\varphi^3 + \bar{\lambda}\varphi^4 + \cdots$$

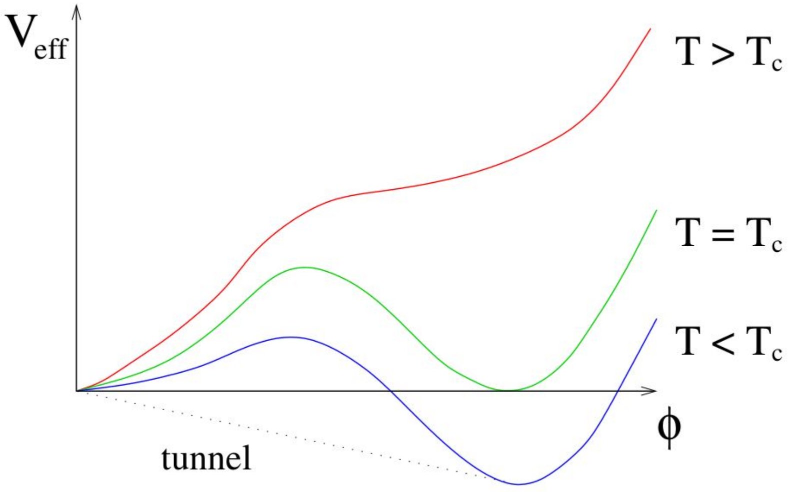
Higgs background field

Thermal mass

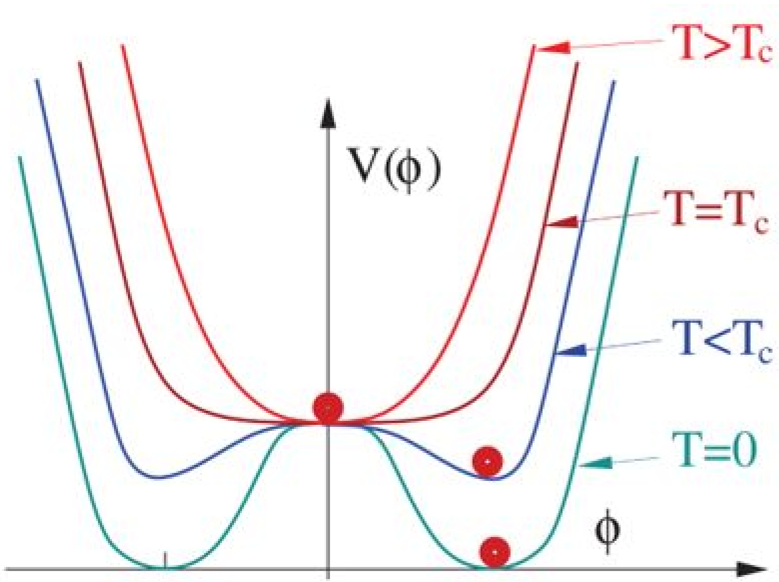
Triggers PT

Higgs self coupling

- ➔ In SM, e =0 while in BSM its nonzero
- ➔ E is generated at loop level (SM & BSM)
- ➔ (ET+e) and $\bar{\lambda}$ decide the nature of EWPT
- ➔ II order PT - both E and e vanish
- ➔ I order PT occurs with E>0 and/ro e>0
- ➔ I order PT has interesting consequences
- ➔ Eg: - baryogenesis (more about this later)



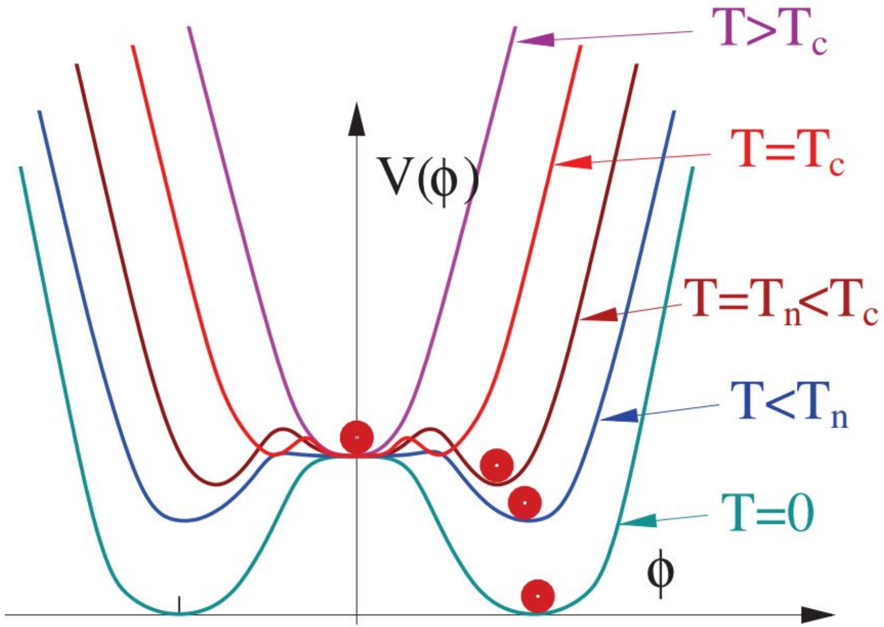
In SM , with m_H = 125 GeV , Numerical simulations suggest a crossover



- ➔ Field,Φ develops a vev when T< Tc
- ➔ Φ rolls smoothly from zero to nonzero value
- ➔ Such transitions are always in thermal equilibrium
- ➔ System remembers nothing about the unbroken phase
- ➔ Cosmologically uninteresting

K. Kajantie, et al. PRL 77 (1996) 2887, F. Karsch, et al. NPPS 53 (1997) 623, Y. Aoki et al., PRD 56 (1997) 3860 M. Gurtler et al., PRD 56 (1997) 3888

In BSM, we can have first order phase transitions



- @Tc all 3 minima become equal
- Φ is still trapped in the origin but secondary minima is energetically favorable
- At Tn potential barrier is small
- Φ tunnels to true vacuum
- Out of equilibrium processes
- Relevant for cosmology

Phase transition model classes

I. Thermally Driven - new particles in early universe plasma

- barrier formation via thermal loop effects associated with bosonic zero modes

IA. barrier from light scalar via thermal cubic terms

IIB. from heavy particles with large coupling to Higgs field

II. Tree-Level Driven - BSM physics

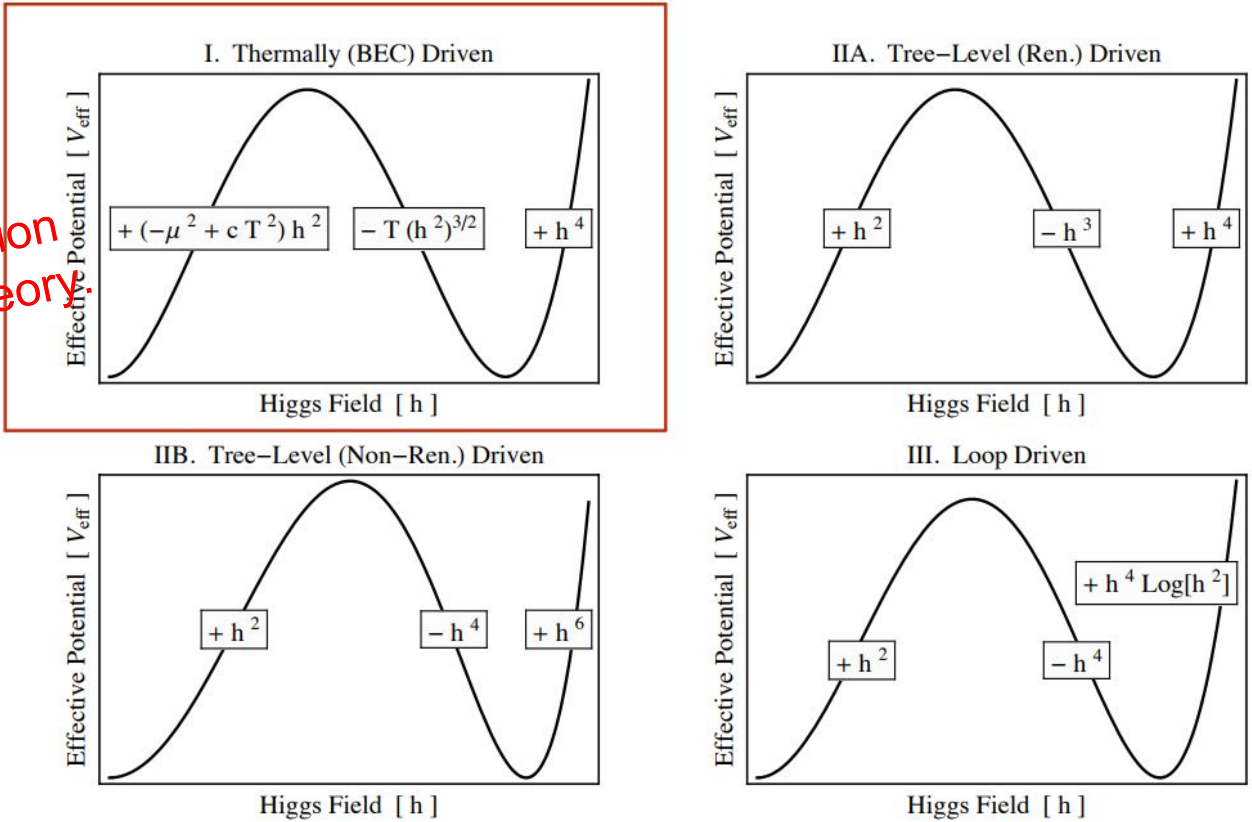
IIA. Renormalizable Operators - effective h^3 operator from extra scalars which acquire nonzero vevs during EWPT eg:- SM+ real singlet

IIB. Non-Renormalizable Operators. - higher dimensional operators like h^6

III. Loop Driven

- Eq:- quartic correction of form $h^4 \ln h^2$ - which competes with unstable $-h^4$ term

Extensions to Higgs

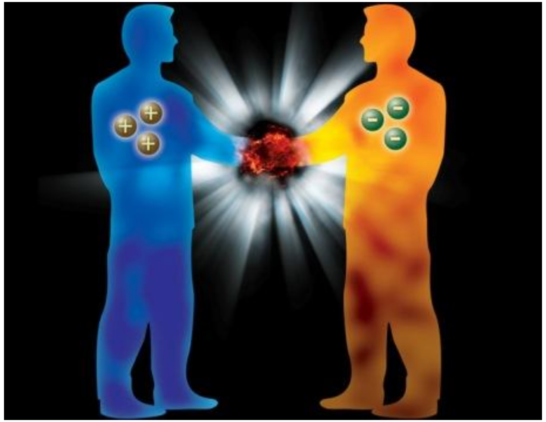


Requires precision thermal field theory.

Chung et.al.1209.1819

Baryogenesis

- ➔ Evidence from cosmology: $\frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \quad \text{(Planck)}$
- ➔ Sakharov's 3 conditions (1967), for baryogenesis
  - ◆ Baryon number violation
  - ◆ C and CP violation
  - ◆ Out of equilibrium
- ➔ EW baryogenesis is one of the potential solutions
- ➔ Need new physics because in SM:
  - ◆ EW phase transition is a crossover, instead of 1 st order
  - ◆ CP violation is too small



Criteria for baryon number violation

Baryon number can be violated by non-perturbative EW processes

Unstable solutions of S_{EFF} i.e sphalerons interpolate b/w topologically distinct vacua

Sphaleron energy depends on shape of potential away from the minimum

Litmus test for its global structure !!!

For successful EWBG, EW sphaleron processes are out of equilibrium in broken phase

- washout avoidance condition

$$\frac{v\,(T_{PT})}{T_{PT}} \gtrsim 1 \times \left(\frac{E_{sph,0}}{9\ \text{TeV}}\right)^{-1} \in [0.6,\ 1.4] \Rightarrow$$

Strong first order PT

No unique value ⇒ adds to uncertainty on Higgs self coupling

Testability

➔ LHC is running!

➔ What's the sensitivity of HL-LHC, 100 TeV pp colliders, and future e+ e- colliders to the region of parameter space where SFOPT is allowed?

➔ Gravitational waves: Bubble collisions

Overview of effective potential at Finite T

The effective potential

Truncated Full Dressing (TFD): We call this Prescription A

: thermal mass Π_i is still obtained in the high-T approximation

$$V_{eff} = V_{tree} + V_{CW}[m_i^2(h) + \Pi_i] + V_T[m_i^2(h) + \Pi_i]$$

$$V_T = \sum_{i=\mathrm{B,F}} (-1)^{F_i} \frac{g_i T^4}{2\pi^2} \int_0^\infty dx\, x^2 \log\left[1 \mp \exp\left(-\sqrt{x^2 + {(m_i^2(h) + \Pi_i)}/{T^2}}\right)\right]$$

$$m_i^2(h) = m^2 + \mathrm{coupling} \times h^2$$

For $v_c \gtrsim T_c$ and $\gtrsim \mathcal{O}(1)$ coupling,
integral needs to be exactly evaluated

✓ Validity of High-T approximation/Validity of perturbation

: not rigorously addressed in most literature in the context of BSM physics

Curtin, Meade, Ramani 16' for a recent discussion

We do not intend to clarify this problem in this talk,
but just point out a few observations in the process of reproducing others.

In the High-T approximation

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

We call this Prescription B

$$\begin{cases} V_{CW} = \sum_{i=t,W,Z,h,G,\cdots} (-1)^{F_i} \frac{g_i}{64\pi^2} \left[m_i^4(h) \left(\log \frac{m_i^2(h)}{m_i^2(v)} - \frac{3}{2} \right) + 2 m_i^2(h) m_i^2(v) \right] \\ V_T = \sum_{i=\mathrm{B,F}} (-1)^{F_i} \frac{g_i T^4}{2\pi^2} J_{B/F} \left(\frac{m_i^2(h)}{T^2} \right) \\ V_{ring} = \sum_{i=\mathrm{bosons}} \frac{\bar{g}_i T}{12\pi} \left[m_i^3(h) - \left(m_i^2(h) + \Pi_i(T) \right)^{\frac{3}{2}} \right] \end{cases}$$

$$x^2 = \frac{m^2}{T^2} \ll 1$$

1st order PT via thermal effect

$$J_B(x^2) \approx -\frac{\pi^4}{45} + \frac{\pi^2}{12} x^2 - \frac{\pi}{6} x^3 - \frac{1}{32} x^4 \log\left(\frac{x^2}{c_b} \right)$$

$$J_F(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24} x^2 - \frac{1}{32} x^4 \log\left(\frac{x^2}{c_f} \right)$$

$$J_{B/F}(x^2) = \int_0^\infty dy\, y^2 \log[1 \mp \exp(-\sqrt{y^2 + x^2})]$$

The effective potential

Truncated Full Dressing (TFD): We call this Prescription A

: thermal mass Π_i is still obtained in the high-T approximation

$$V_{eff} = V_{tree} + V_{CW}[m_i^2(h) + \Pi_i] + V_T[m_i^2(h) + \Pi_i]$$

$$V_T(m_i^2(\phi), T) = \sum_i (-1)^{F_i} \frac{g_i T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right)$$

$$J_B(\alpha^2) \equiv J_B(\alpha^2;\, n) = -\sum_{k=1}^{n} \frac{1}{k^2} \alpha^2 K_2(\alpha\, k)\ ,$$

$$J_F(\alpha^2) \equiv J_F(\alpha^2;\, n) = -\sum_{k=1}^{n} \frac{(-1)^k}{k^2} \alpha^2 K_2(\alpha\, k)\ ,$$

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Benchmark Scenarios

Most commonly considered frameworks

$$V_{eff} = \sum_{i=t,W,Z,h,G,\,\boxed{\text{BSM}}} V_i$$

No mixing with Higgs
: less constrained

Mixes with Higgs
: strongly constrained

Higgs portal:
new scalar S

- Z_2-symmetry, e.g. $\langle S \rangle = 0$ vs $\langle S \rangle \neq 0$
- N_s: multiplicity E.g. can help with weak coupling
- … .

Effective Field Theory:
higher-dimensional operators

$\mathcal{O}_H = (\partial |H|^2)^2$ vs $\mathcal{O}_6 = |H|^6$

Higgs decay
: strongly constrained

Higgs self coupling
: poorly constrained

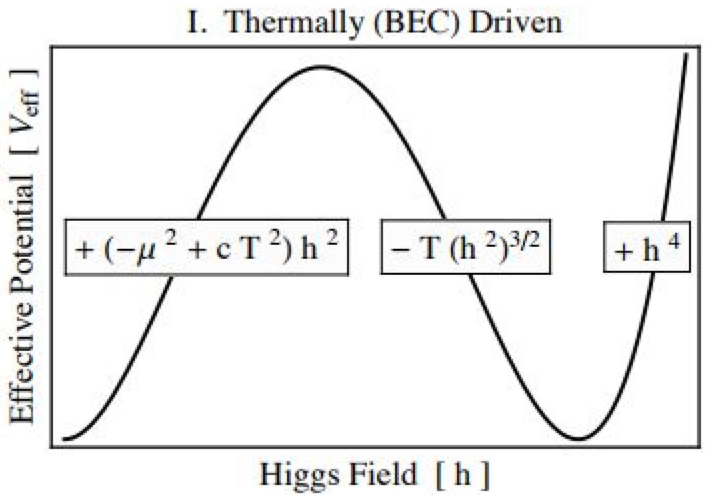
- Weakly coupled theory
- Strongly coupled theory

PGB vs non-pGB
Higgs Portal

$\mathcal{O}_H \ll \mathcal{O}_6$ possible

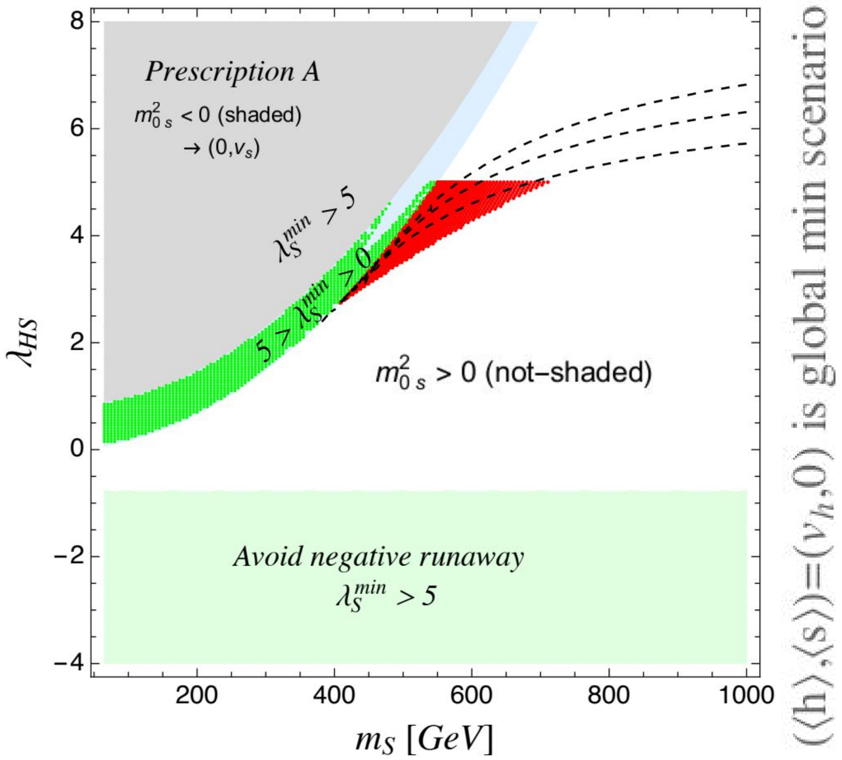
Azatov, Contino, Panico, Son 15’

Higgs portal



Higgs Portal → SM+Singlet

$$V_{tree} = -\frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS}h^2S^2 + \frac{1}{2}m_{0\,s}^2 S^2 + \frac{1}{4}\lambda_S S^4$$



Based on naïve criterion, existence of degenerate vacua, with $v_c/T_c > 1$ * Note cutoff $\lambda_{HS} > 5$ by hand

1. One-step strong 1st phase transition (dotted RED)

$$V(0,0) \rightarrow V(v,0) \quad , \langle S \rangle = 0$$

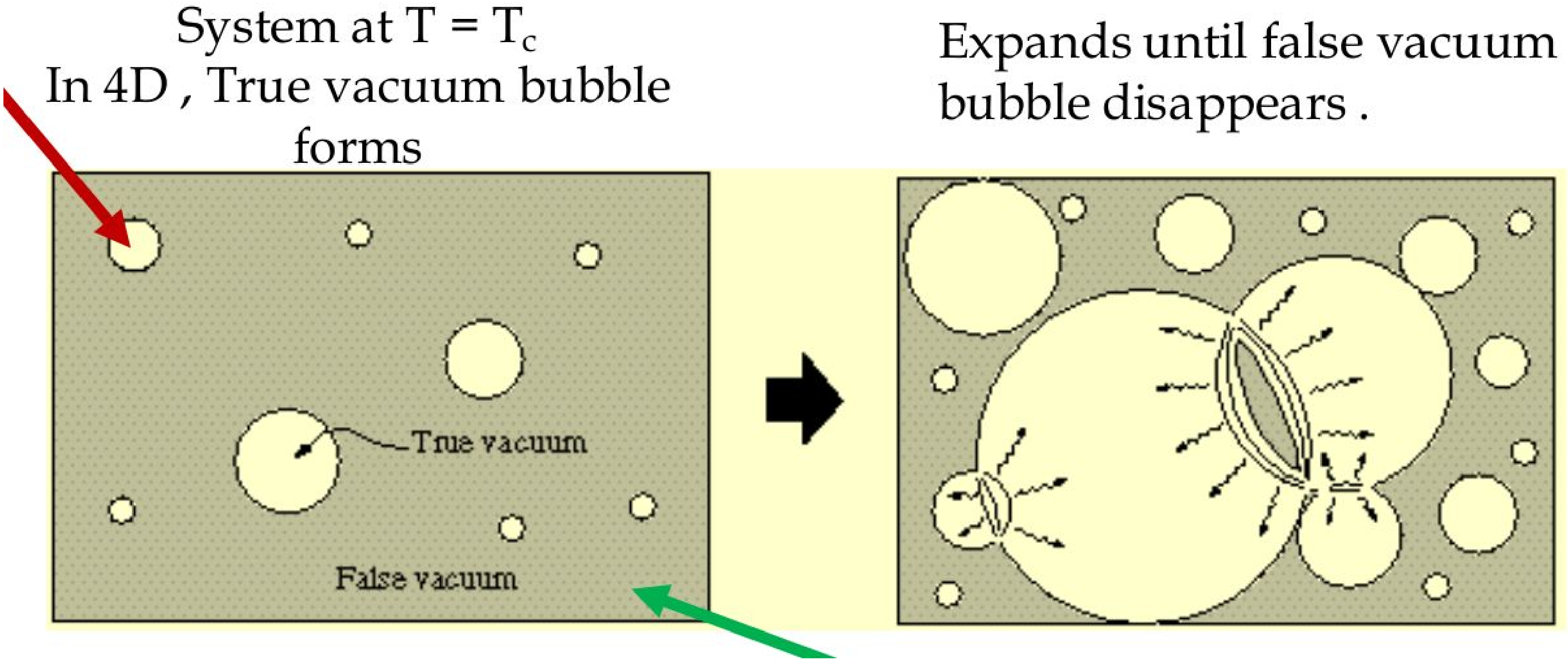
2. Two-step strong 1st phase transition (dotted GREEN)

$$V(0,0) \rightarrow V(0,v_s) \rightarrow V(v,0)$$

$$V(0,v_s) > V(v,0) \rightarrow$$

$$\lambda_S > \lambda_S^{\min} \equiv \lambda \frac{m_{0\,s}^4}{m^4} = \frac{2(m_S^2 - v^2\lambda_{HS})^2}{m_h^2 v^2}$$

At low temperatures, or at the interior of a bubble in the cooling universe, there exists a "true vacuum" (broken phase)



At high temperatures, or far away from the bubble, "false vacuum"

Bubble nucleation

As the Universe continues to cool, bubbles of the broken-minimum phase are nucleated.

Nucleation probability per unit time per unit volume at temperature T is given by

$$P \sim T^4 \exp(-S_3/T)$$

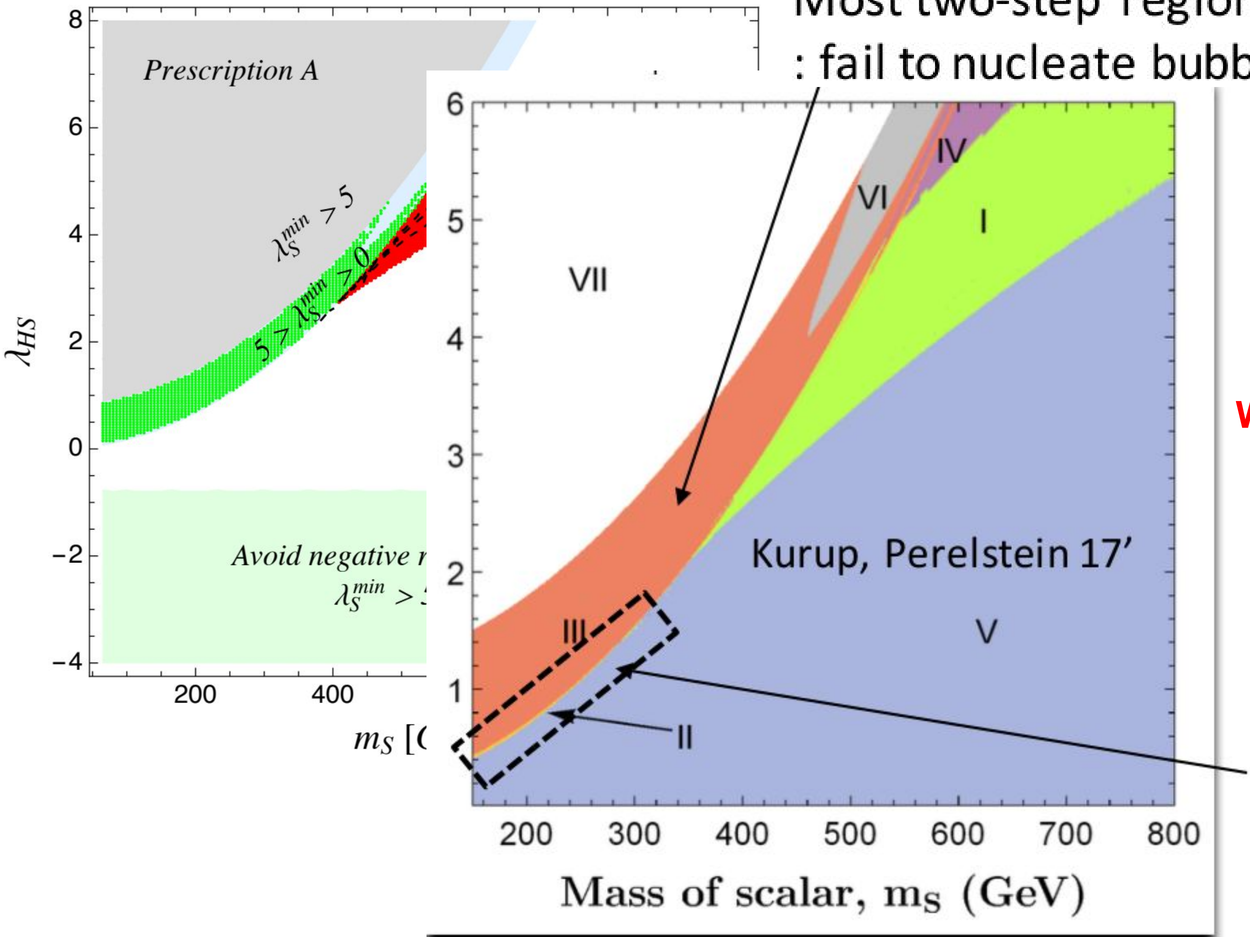
S_3 is the bubble action

Nucleation temperature T_N is the temperature at which the nucleation probability per Hubble volume becomes of order one; for electroweak phase transition, this corresponds to $S_3/T_N \approx 100$.

To avoid washout $v(T_N)/T_N > 1$

Two step PT

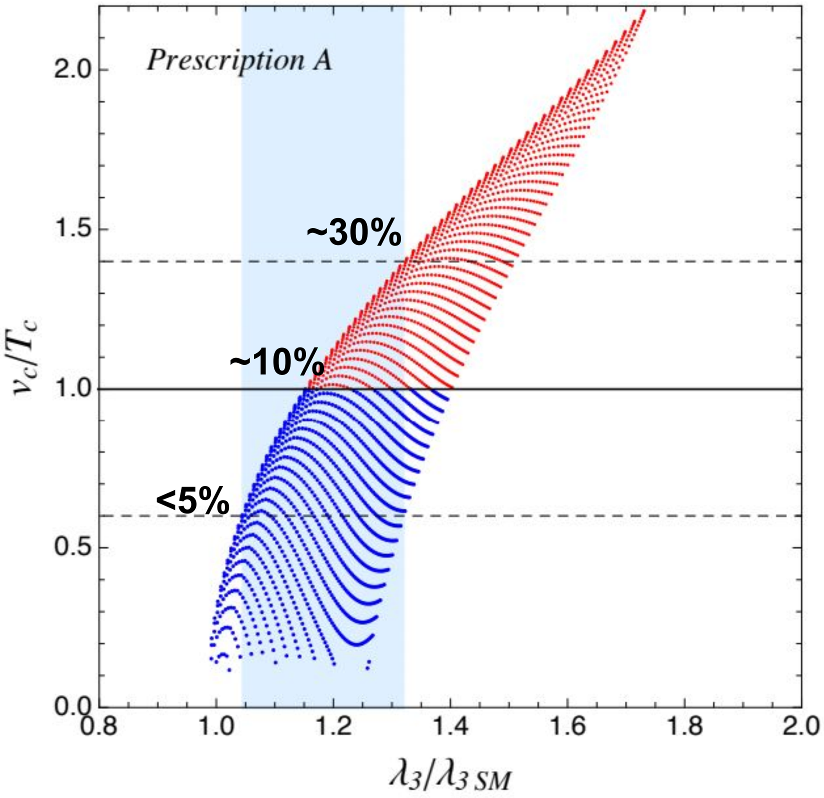
Most two-step region (III) is gone
: fail to nucleate bubbles

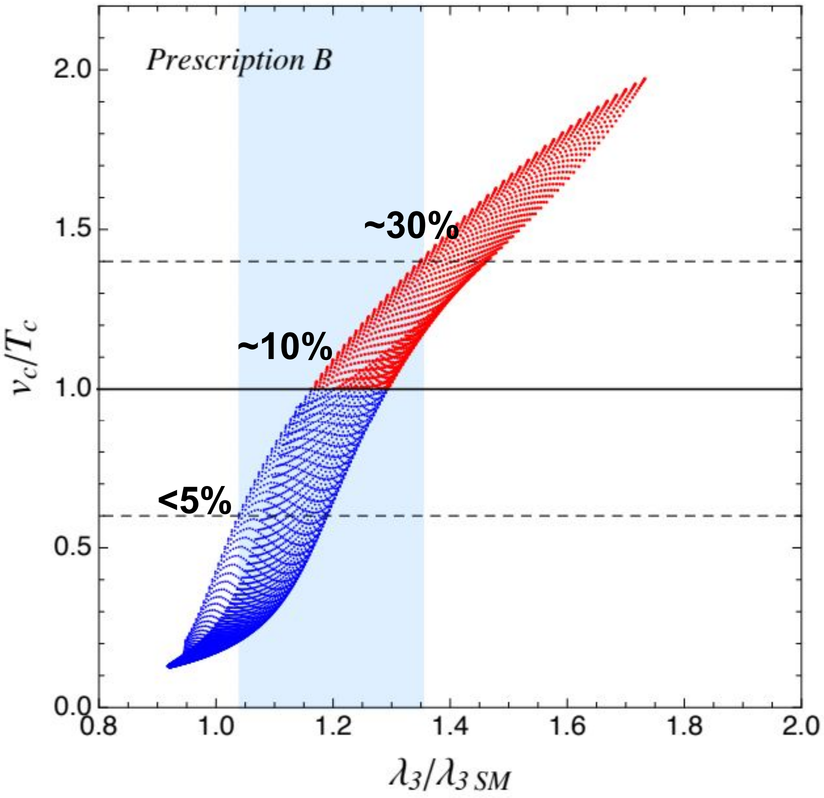


We will focus on the one-step PT

Tiny two-step region
: fine-tuned to live here

Precision of the Higgs self couplings





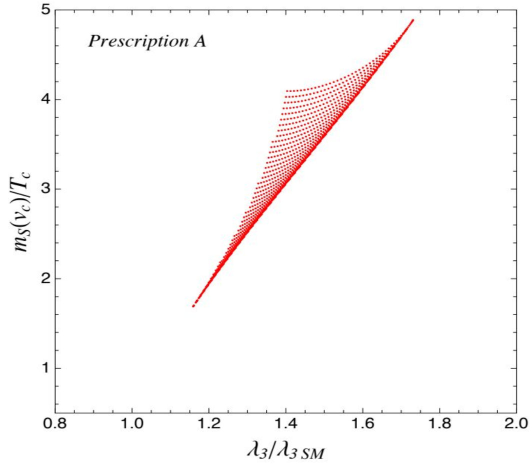
- ✓ Depending on the criteria on ${}^{v_c}/_{T_c}$, the target precision can fluctuate by $\mathcal{O}(1)$ amout

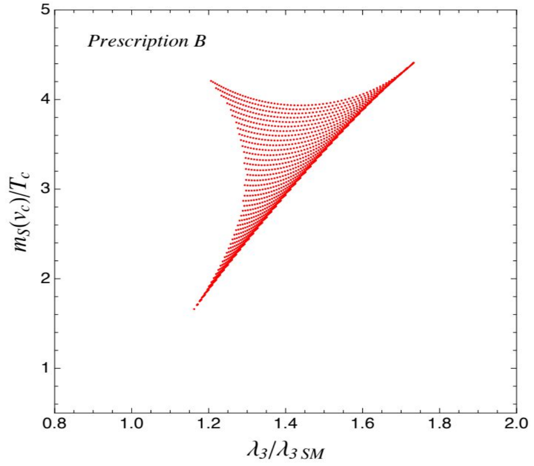
- ✓ ~ 10% deviation of the Higgs
- ✓ Achievable @100 TeV pp collider and ILC

Validity of High-T approximation

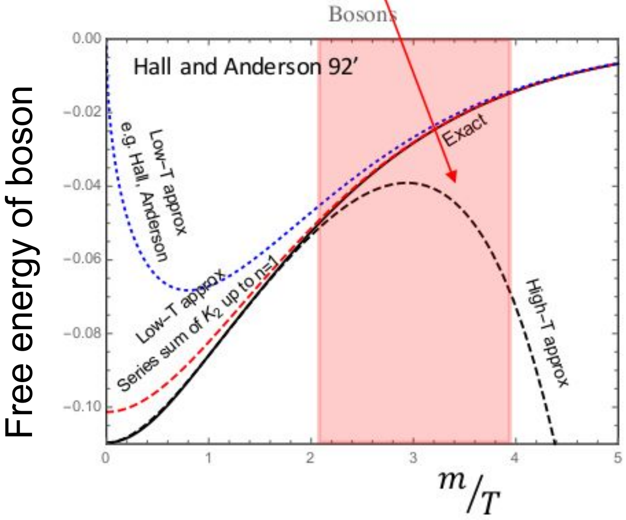
High-T approx. fails

(The issue is more pronounced in two step PT)





** $\frac{m_s(v)+\Pi}{T_c}$ will be even bigger λ_3/λ_3^{SM}



$$x^2 = \frac{m^2}{T^2} \ll 1: \text{High T approximation}$$

$$J_B(x^2) \approx -\frac{\pi^4}{45} + \frac{\pi^2}{12}x^2 - \frac{\pi}{6}x^3 - \frac{1}{32}x^4 \log\left(\frac{x^2}{c_b}\right)$$

$$J_F(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}x^2 - \frac{1}{32}x^4 \log\left(\frac{x^2}{c_f}\right)$$

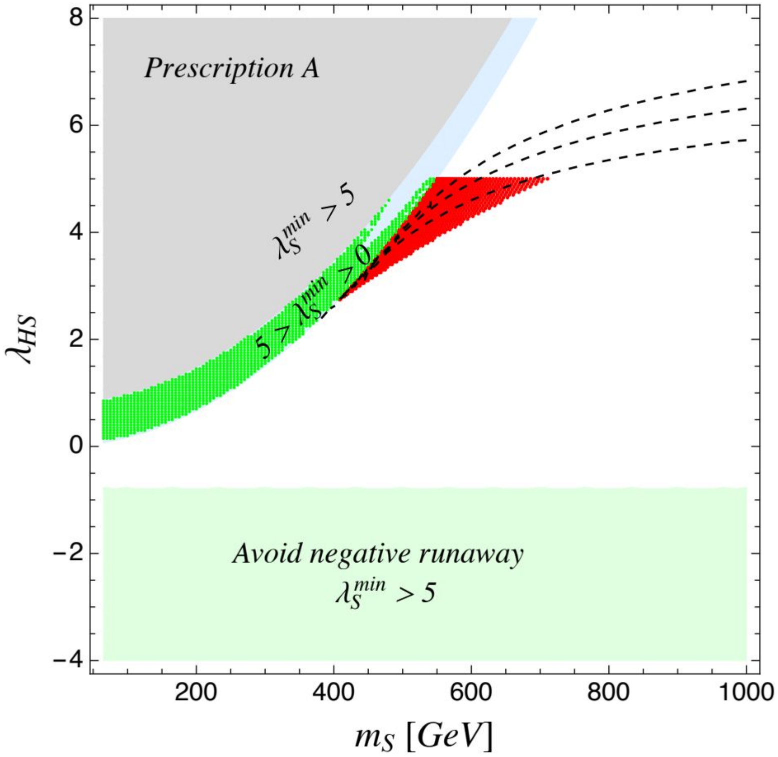
$$x^2 = \frac{m^2}{T^2} \gg 1: \text{Low T approximation}$$

$$J_B(x^2; n) = -\sum_{k=1}^{n} \frac{1}{k^2} x^2 K_2(x\,k)$$

$$J_F(x^2; n) = -\sum_{k=1}^{n} \frac{(-1)^k}{k^2} x^2 K_2(x\,k)$$

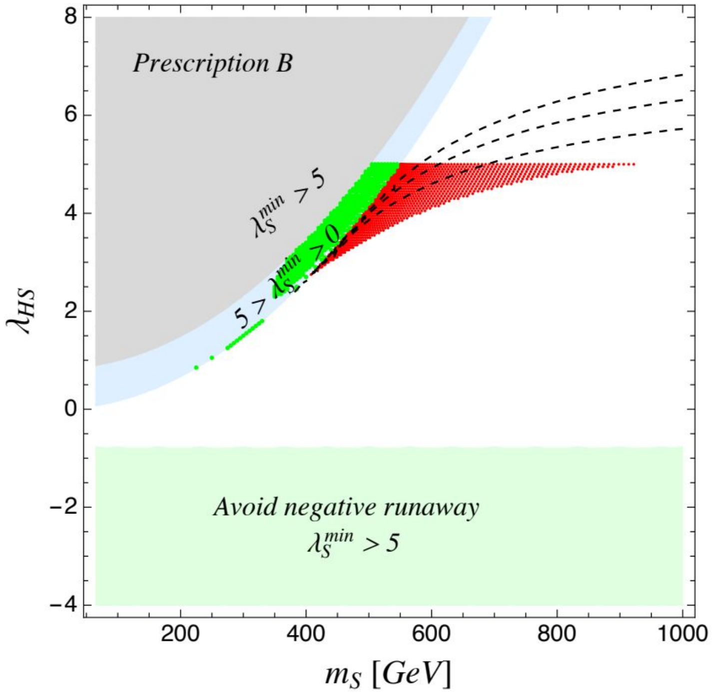
Consistent TFD

Sane Thermal term expansion



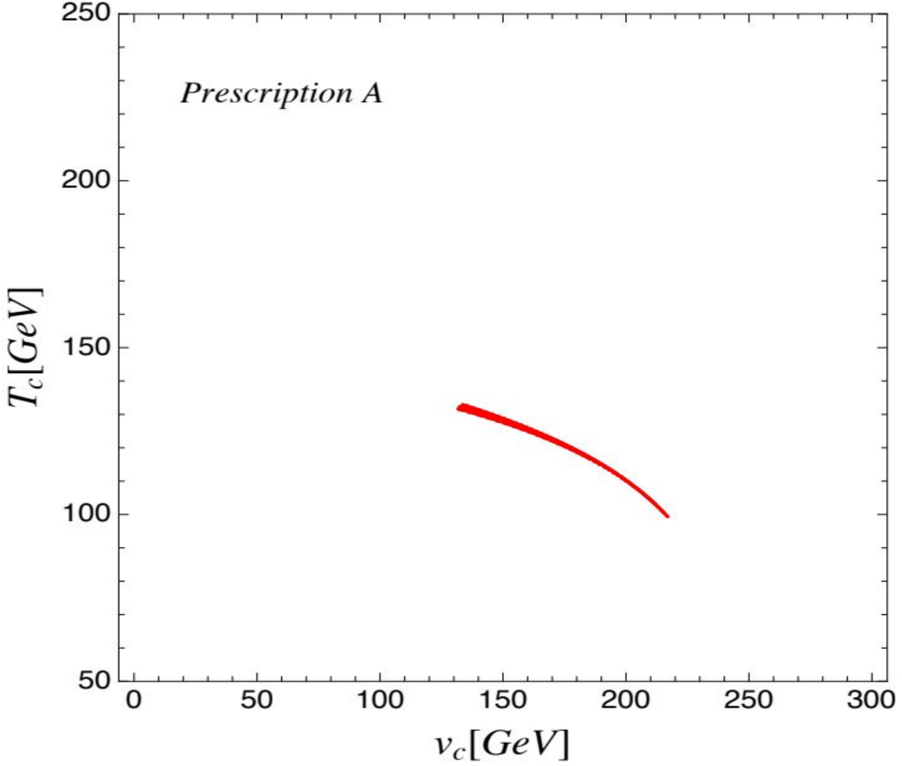
Pseudo Full Dressing

Exact T

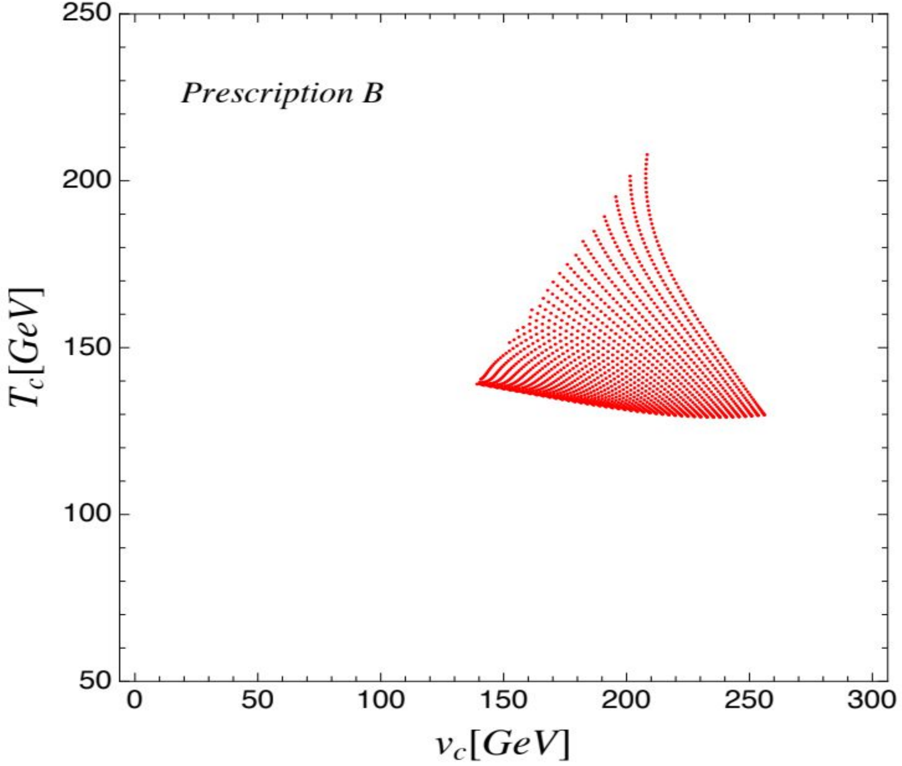


The results look similar in these plots

Consistent TFD

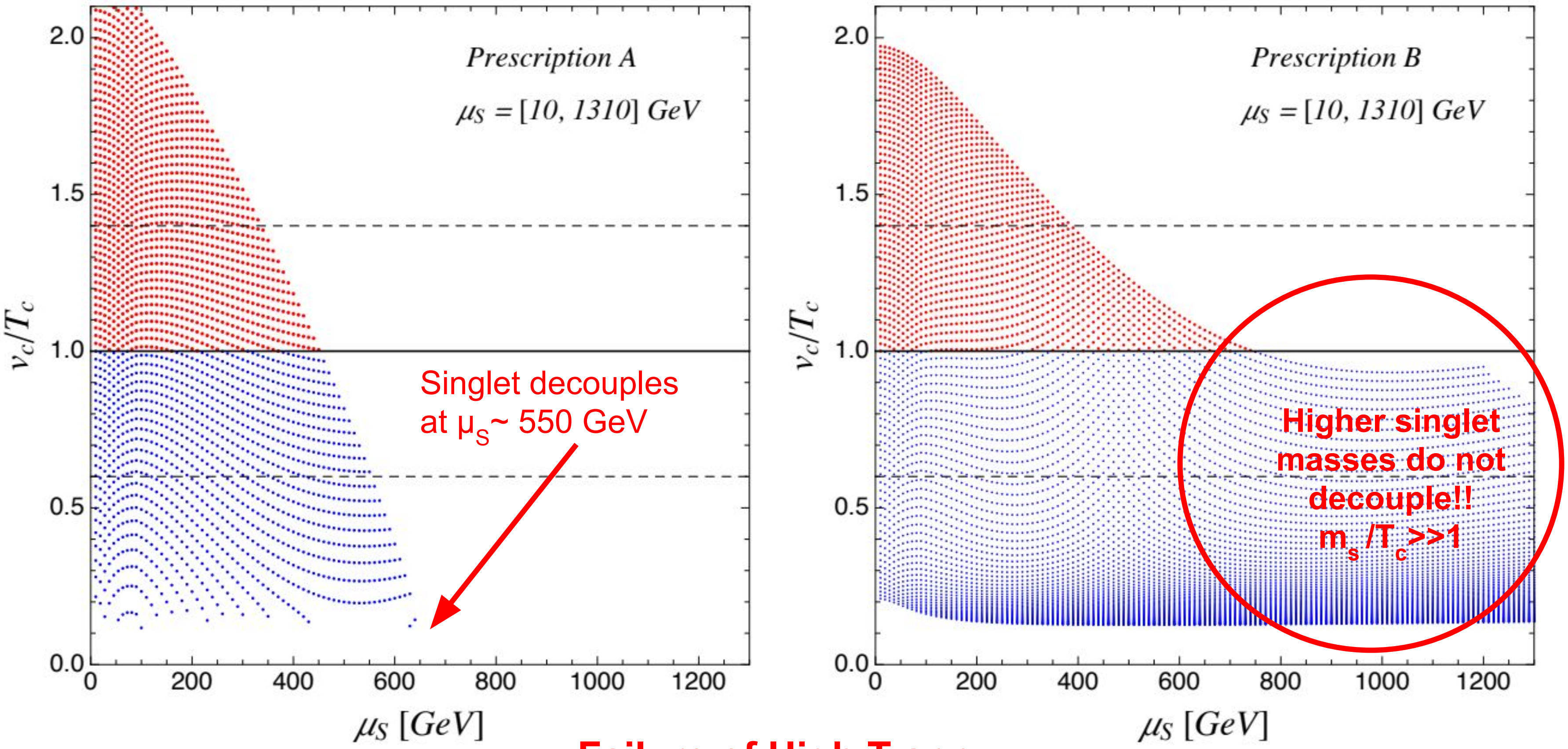


Pseudo Full Dressing



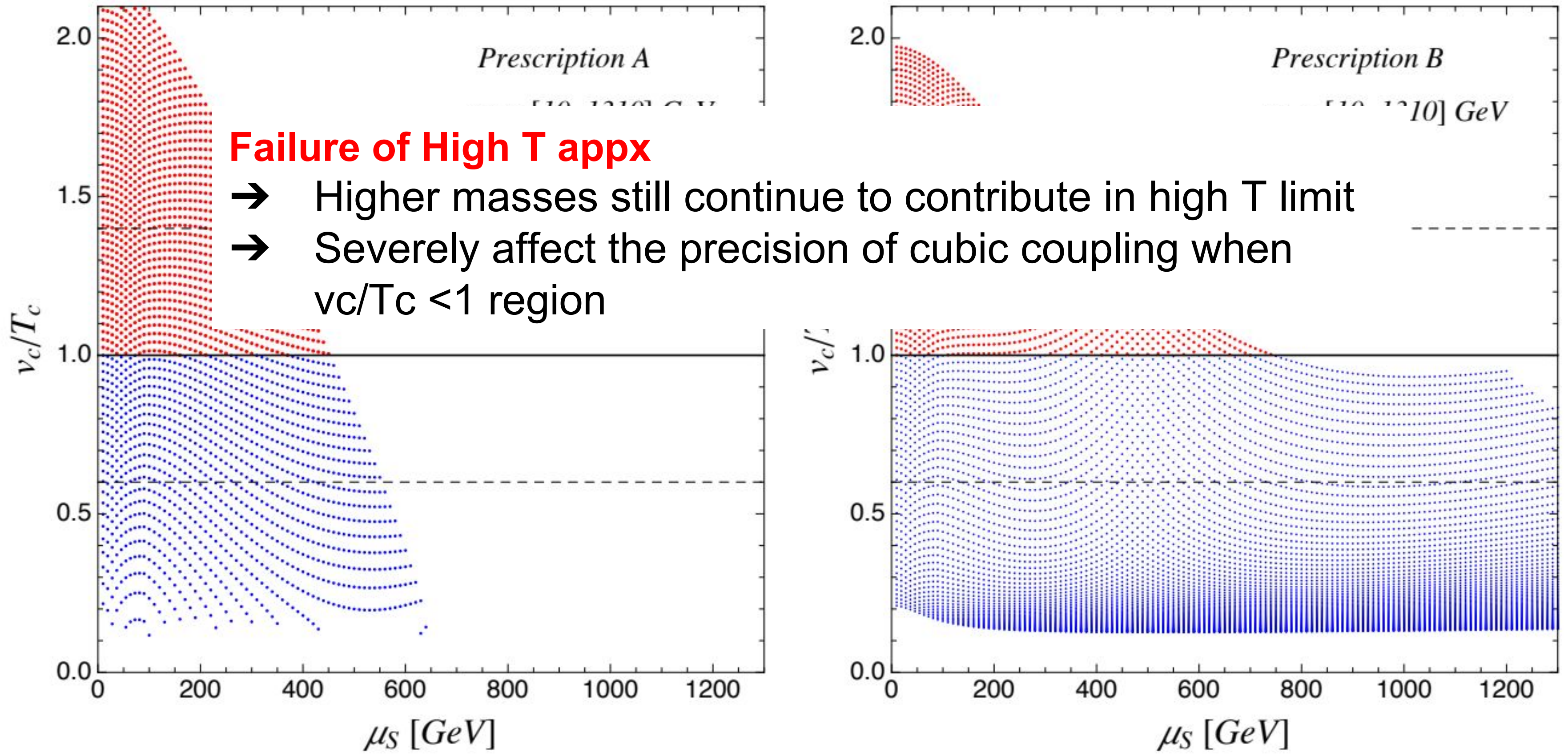
- ✓ More focused
- ✓ $v_c < v$=246 GeV is satisfied better

Decoupling of higher singlet masses for one-step PT



Failure of High T appx

Decoupling of higher singlet masses for one-step PT



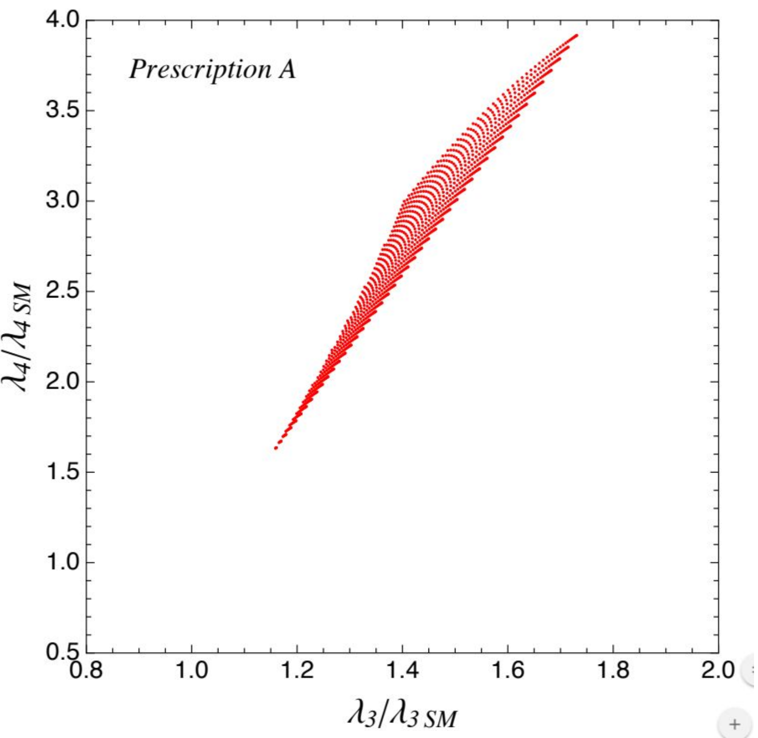
Failure of High T appx

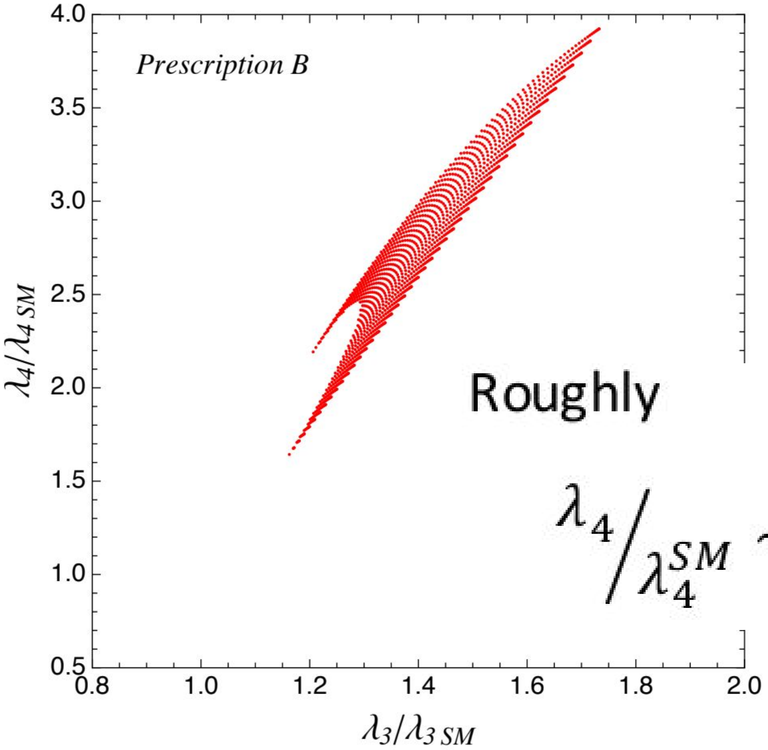
➔ Higher masses still continue to contribute in high T limit

➔ Severely affect the precision of cubic coupling when vc/Tc <1 region

Cubic vs. Quartic

$$V(h) = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6} \left(\frac{3\, m_h^2}{v} \right) h^3 + d_4 \frac{1}{24} \left(\frac{3\, m_h^2}{v^2} \right) h^4$$

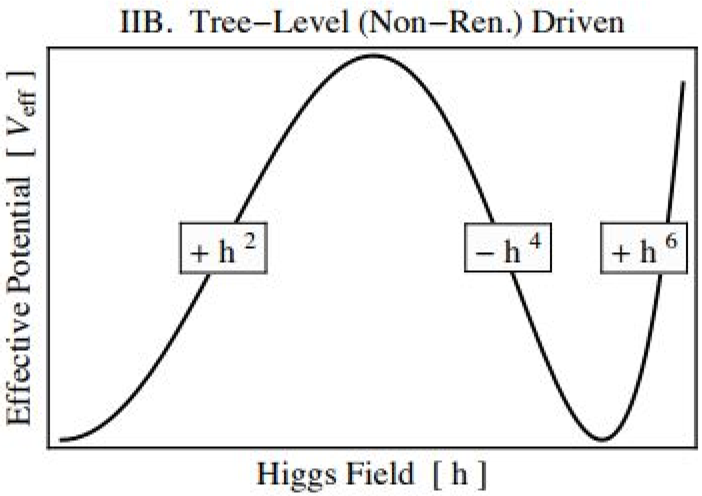




Roughly

$$\lambda_4 / \lambda_4^{SM} \sim 2\ \lambda_3 / \lambda_3^{SM}$$

EFT - higher dimension operators



1^{st} order phase transition in EFT approach

E.g. dim-6 operator

$$V_{EFT} = m^2|H|^2 + \lambda|H|^4 + \frac{c_6}{v^2}\frac{m_h^2}{2\,v^2}|H|^6$$

$$V_{EFT} = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{8}\,\frac{c_6}{v^2}\frac{m_h^2}{2\,v^2}h^6$$

$$0 = \frac{dV_{EFT}}{dh}\Big|_{h=v} = m^2 + \lambda h^2 + \frac{3c_6 m_h^2}{8v^4}h^4\Big|_{h=v}$$

$$m_h^2 \equiv \frac{d^2V_{EFT}}{dh^2}\Big|_{h=v} = m^2 + 3\lambda h^2 + \frac{15}{8}c_6 m_h^2$$

$$m^2 = -\frac{m_h^2}{2}\left(1 - \frac{3}{4}c_6\right)$$

$$\lambda = \frac{m_h^2}{2v^2}\left(1 - \frac{3}{2}c_6\right)$$

$$\lambda_3 \equiv \frac{d^3V_{EFT}}{dh^3}\Big|_{h=v} = \frac{3m_h^2}{v}(1 + c_6)$$

$$\lambda_4 \equiv \frac{d^4V_{EFT}}{dh^4}\Big|_{h=v} = \frac{3m_h^2}{v^2}(1 + 6\,c_6)$$

$$\lambda_3 / \lambda_3^{SM} = 1 + c_6$$

$$\lambda_4 / \lambda_4^{SM} = 1 + 6\,c_6$$

1st order phase transition in EFT approach

Nobel, Perelstein 08'
Delaunay, Grojean, Wells, 08'
Huang, Joglekar, Li, Wagner 15'
Chung, Long, Wang 16'
....

E.g. dim-6 operator

$$V_{EFT} = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{8}\frac{c_6}{v^2}\frac{m_h^2}{2\,v^2}h^6$$

(m^2, λ, c_6) 3 diff. local curvatures
: 1st order PT becomes in principle possible

When keeping only T^2-term as thermal effect, $m^2(T) = m^2 + aT^2$,
the analytic solution is possible

$\left.\frac{dV_{eff}}{dh}\right|_{h=v_c,\,T=T_c} = 0$ Should be extreme point

$V(v_c, T_c) = V(0, T_c)$ Degeneracy of the vaccua

$$v_c^2 = -\frac{4m^2(T_c)}{\lambda} = -\frac{2\lambda v^4}{c_6 m_h^2}$$

$$c_6 = \frac{2}{3}\frac{1}{1-\frac{2}{3}\frac{v_c^2}{v^2}}$$

$v_c^2 < v^2$ & $\lambda < 0$ ⇒ $\frac{2}{3} < c_6 < 2$

$$\lambda = \frac{m_h^2}{2v^2}\left(1 - \frac{3}{2}c_6\right)$$

Re-summed higher-dim operators

$$V_{tree} = -\mu^2|H|^2 + \lambda|H|^4 + \sum_{n=1}^{\infty} \frac{c_{4+2n}}{v^{2n}} \frac{m_h^2}{2v^2}|H|^{4+2n}$$

$$c_{4+2n} \;=\; c\,(v/f)^{2n} \;\text{ with }\; c \;\sim\; \mathcal{O}(1)$$

NDA scaling for all coeff

$$V_{tree} = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{1}{8}\frac{c}{f^2}\frac{m_h^2}{2v^2}h^6 \frac{1}{1-\frac{h^2}{2f^2}}$$

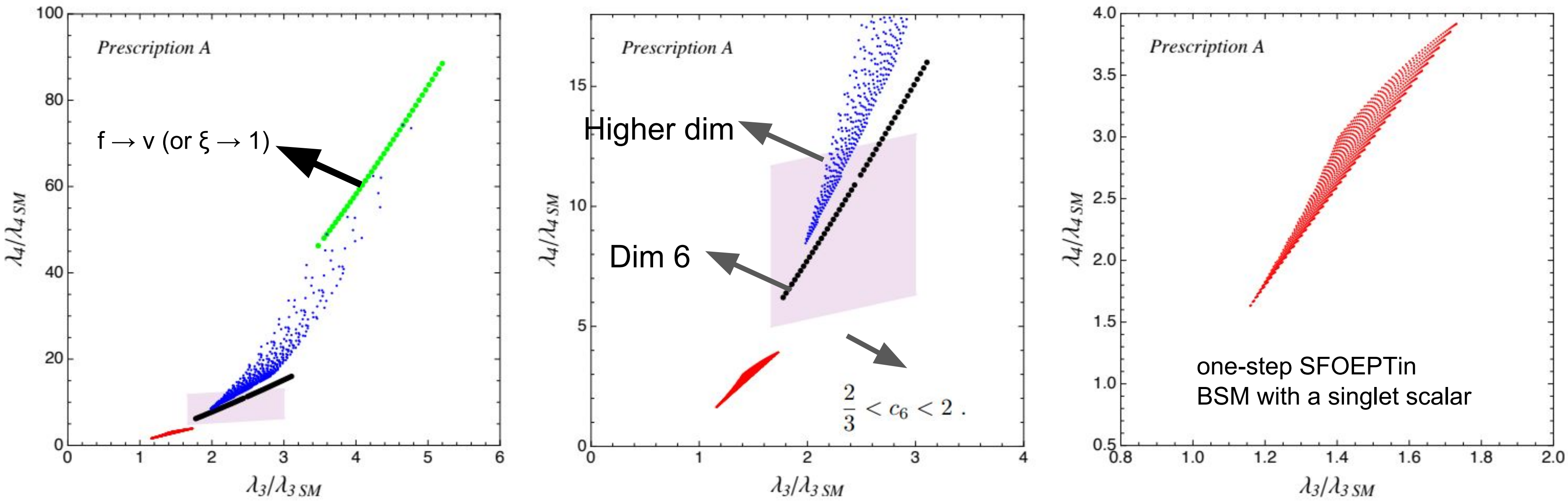
$$\lambda_3 = \left.\frac{d^3V_{tree}(h)}{dh^3}\right|_{h=v} = \frac{3m_h^2}{v}\left[1+16\,c\,\frac{\xi}{(2-\xi)^4}\right]$$

$$\lambda_4 = \left.\frac{d^4V_{tree}(h)}{dh^4}\right|_{h=v} = \frac{3m_h^2}{v^2}\left[1+32\,c\,\frac{(6+\xi)\xi}{(2-\xi)^5}\right]$$

Deviation in quartic is Bigger than cubic by $2(6+\xi)/(2-\xi)$

BSM Map in Higgs self coupling space

We wish to add more interesting BSM scenarios



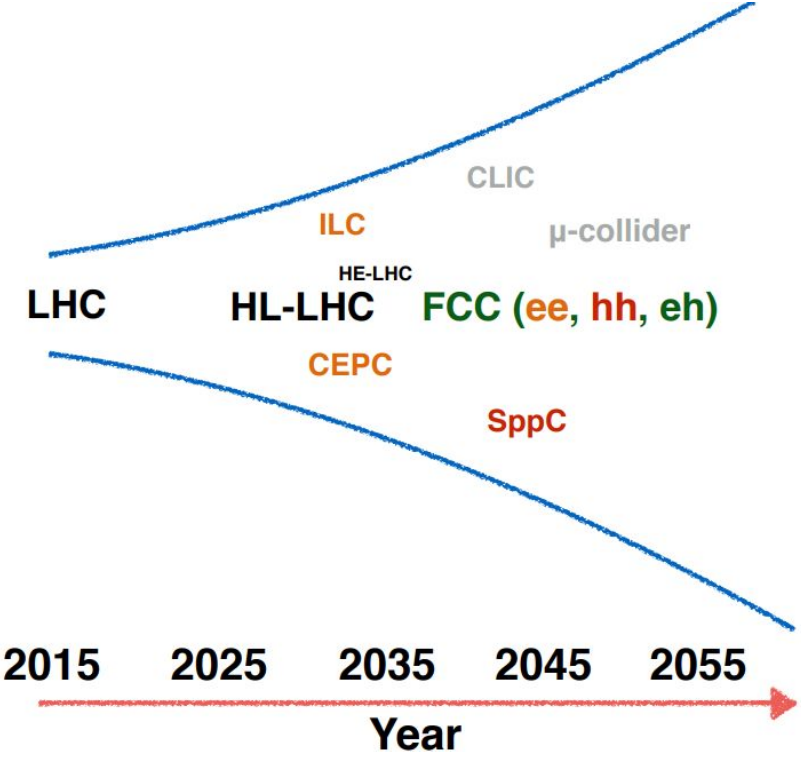
- ➔ HL-LHC has sensitivity 0f $\lambda_3/\lambda_{3,SM} - 1$ at 68%CL has two intervals, [−1.0, 1.8] ∪ [3.5, 5.1]
- ➔ Interval around SM can test O(1) deviations and exclude EFT cases

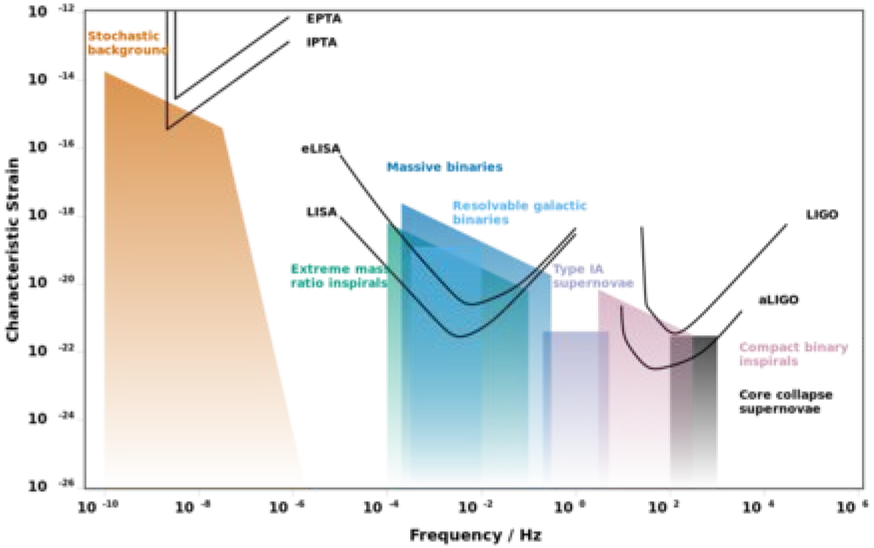
Lessons

- ➔ Break-down of the high-temperature approximation is more pronounced in the two-step SFOEPT.
- ➔ Criteria for SFOEPT?
  - ◆ v_c/T_c > 1 (1.4) requires the measurement of the coupling at ~ 15% (35%) precision achievable at ILC (via VBF process at higher c.o.m energy) and 100 TeV pp collider,
  - ◆ more stronger criteria, v_c/T_c > 0.6 requires ~ 5% precision of λ_3 which is likely plausible only at 100 TeV pp collider
- ➔ Various BSM scenarios can appear in different islands in (λ_3 , λ_4) space
  - ◆ λ_4 could be important to distinguish different scenarios, and it has chance @ 100 TeV in case that a large deviation of λ_3 , is observed
- ➔ What if we observe any hint of Strong 1 st order Phase Transition?
  - ◆ Likely strongly coupled dynamics not far away from EW scale ?
- ➔ Very strong EWPT could generate a stochastic background of gravitational waves - signal is potentially within reach of future space-based gravitational wave interferometers, such as eLISA

Grojean et al' 99, Beniwal et al ' 17, Huang et. al. '17

The Road Ahead





Future is bright!!

Backup slides

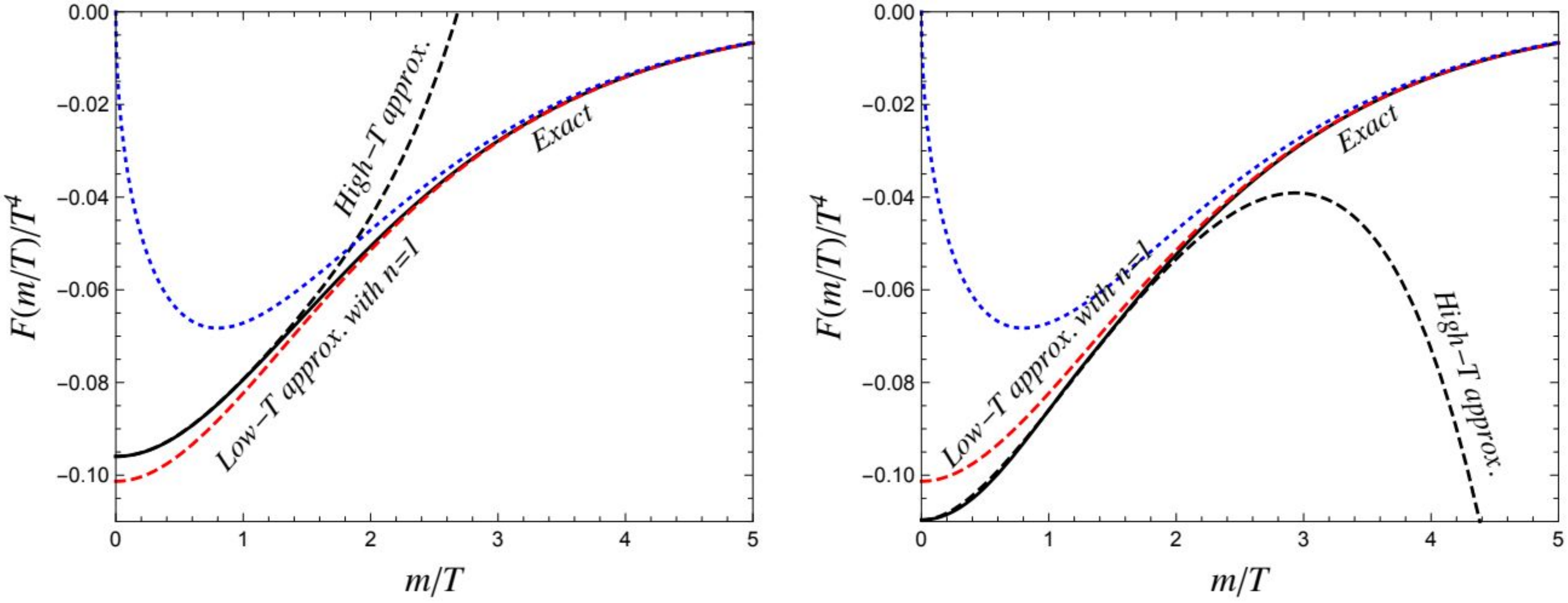


FIG. 1: Free energy for the fermions (left) and bosons (right) as a function of m/T in the high-T approximation (black-dashed), low-T approximation in Eq. (9) (red-dashed) with $n = 1$, and in the exact form (black-solid). The dotted-blue line is the low-T approximation with the approximated K_2 as in [42].

Simulation details - SM extension with the scalar singlet

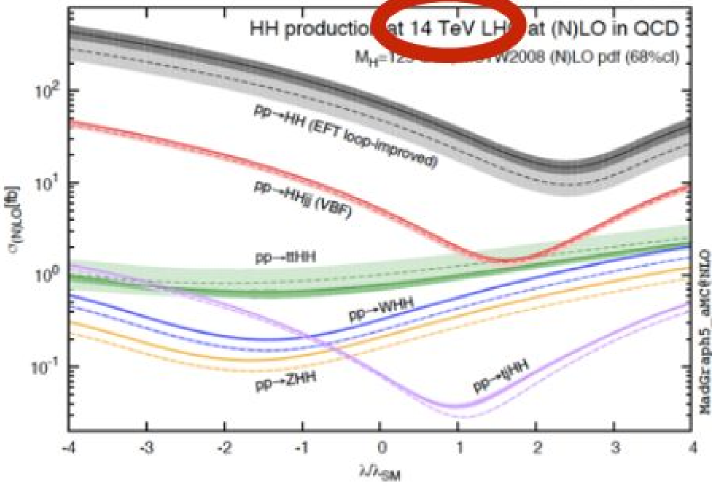
- ➔ For the one-step phase transition the quartic coupling λ_S does not play much role directly in the phenomenology apart from ensuring the stability of the potential at a large field.
- ➔ Fix λ_S =0 and scan over μ_S = [10, 1310] GeV (in steps of 10 GeV) and λ_{HS} = [0, 5] (in steps of 0.05).
- ➔ For two-step cascade, the λ_S needs to stay above the minimum $\lambda_{\text{min } S}$ so that (v, 0) remains the global minimum.
- ➔ Scan intervals m_S = [65, 700] GeV (in steps of 5 GeV) and λ_{HS} = [0, 5] (in steps of 0.05) for a few choices of λ_S, parameterized as $\lambda_S = \lambda_{\text{min } S} + \delta S$.
- ➔ Assume: singlet mass is heavier than roughly mh/2 to avoid the Higgs decays to the singlet scalar.
- ➔ Impose arbitrary hard cutoffs $\lambda_{HS} < 5$ and $\lambda_S < 5$ (smaller than 4π which is the typical unitarity bound), to avoid the strongly coupled regime.

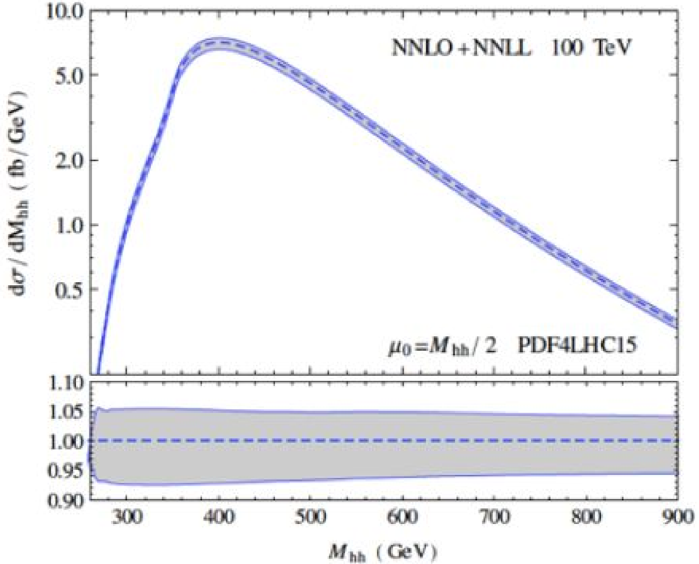
➡ Probing triple-Higgs coupling with double Higgs production

- Consistency of check of EWSB
- Reconstructing the Higgs potential
- Sensitivity through yields and kinematics
- Large enhancement through BSM possible
- Exhaustive program at the (HL-)LHC

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

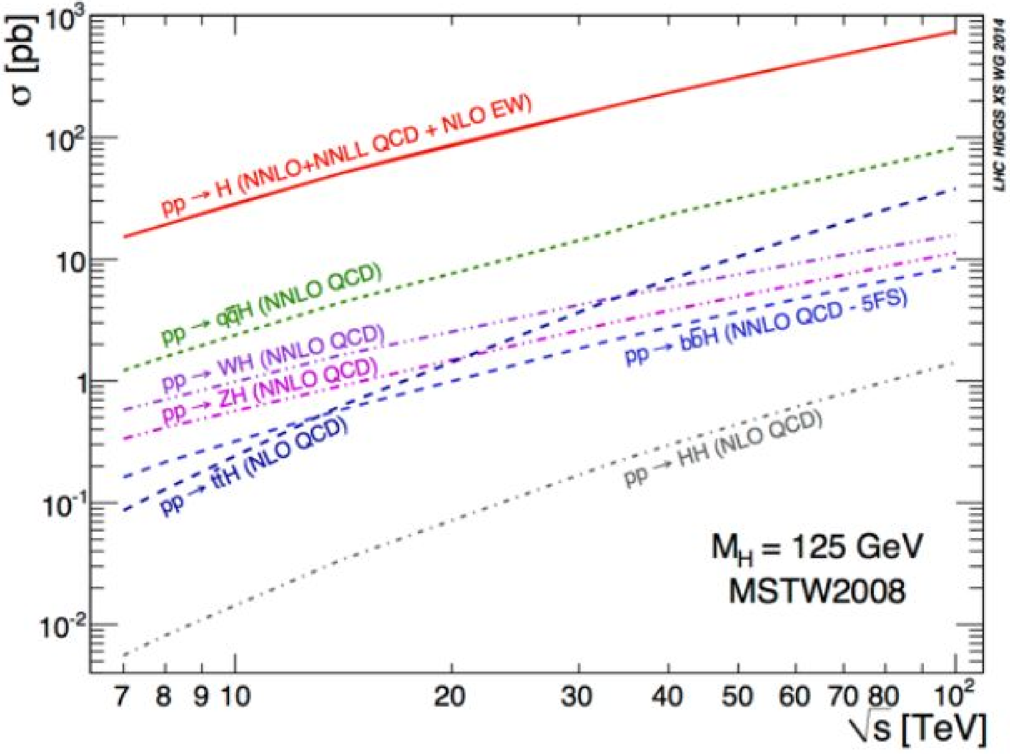
EFT Lagrangian





Dihiggs production

Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\overline{b} + b\overline{b}$	33%	40,000
$b\overline{b} + W^+W^-$	25%	31,000
$b\overline{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\overline{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\overline{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Table 1: Branching ratios for different HH final states, and their corresponding approximate expected yields in 3000 fb^{-1} of data before any event selection is applied, assuming a total production cross section of 40.8 fb and $m_H = 125$ GeV.

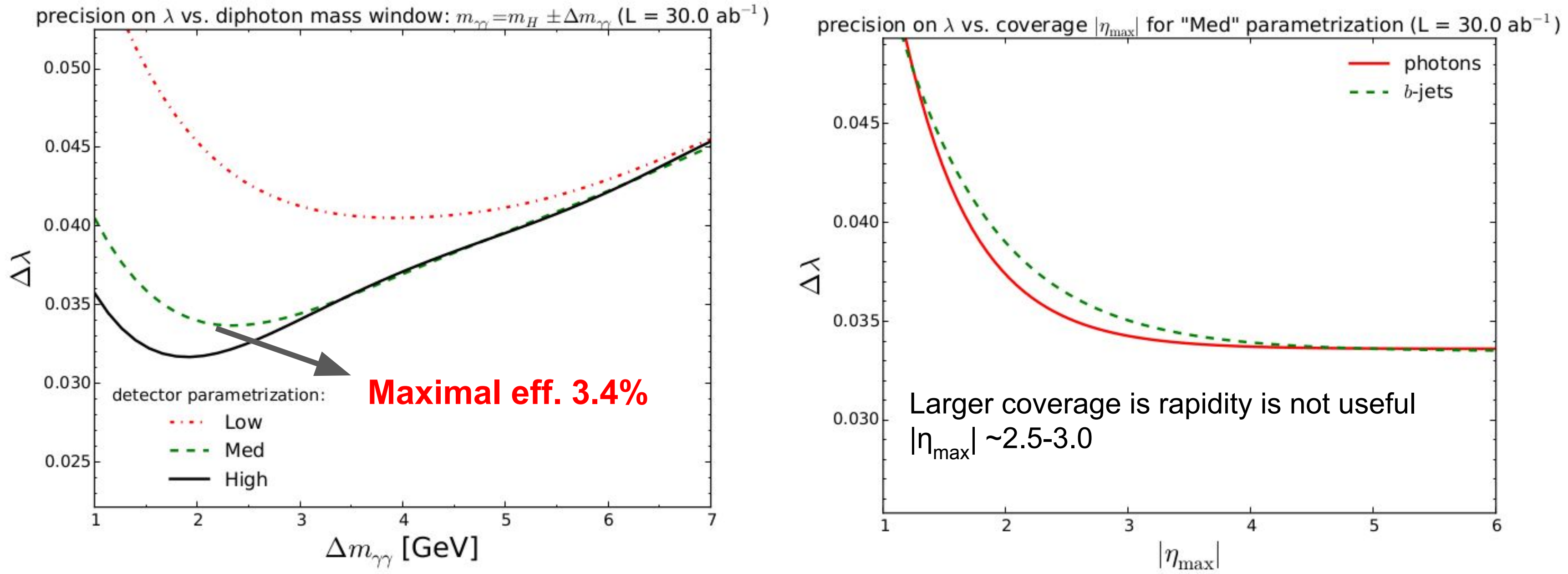
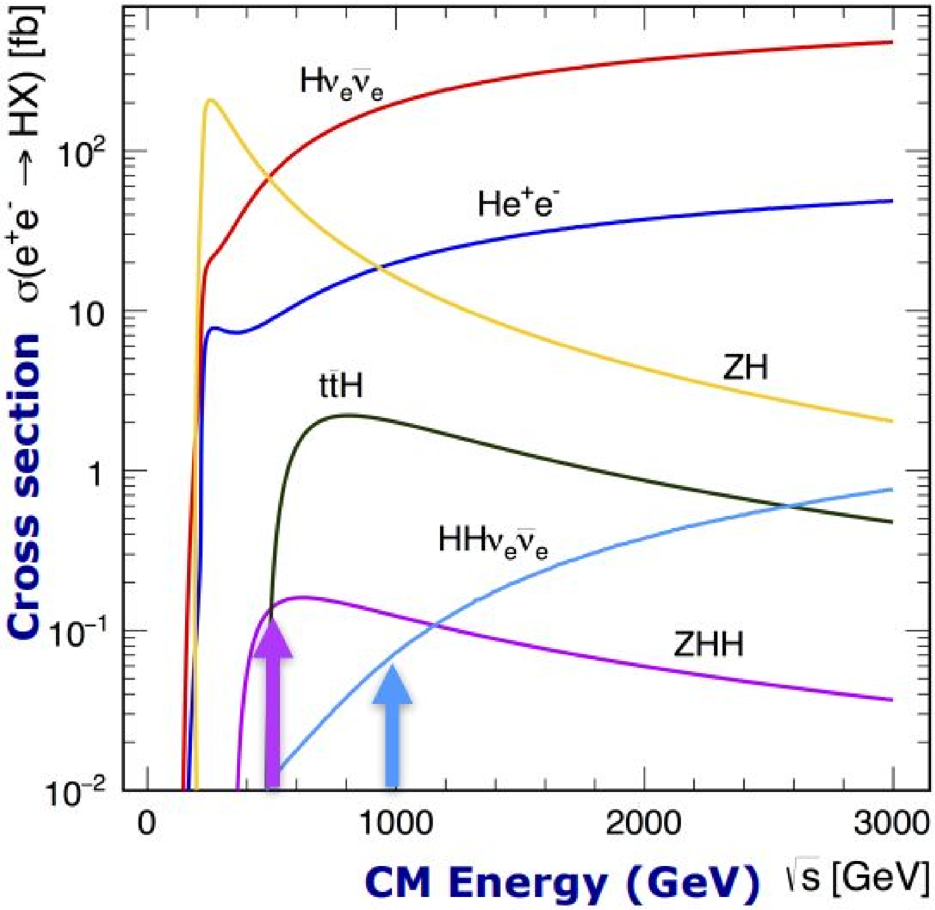
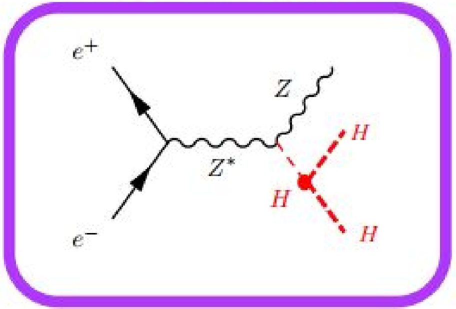


Fig. 65: Estimated precision on the measurement of the Higgs trilinear self-coupling. The left panel shows to result as a function of the cut on the invariant mass os the photon pair $\Delta m_{\gamma\gamma}$ for the three detector benchmark scenarios, "Low" (dot-dashed red), "Medium" (dashed green) and "High" (solid black). In the right panel the result is shown as a function of the cut on the maximal rapidity of the reconstructed objects η_{max} assuming the "Medium" detector benchmark (the solid red and dashed green curves correspond to a variation of the photon and b-jets acceptances respectively). All the results have been obtained for an integrated luminosity of 30 ab^{-1}.

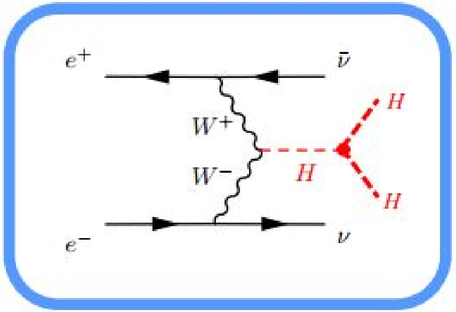


Double Higgs Production:

e+e- → ZHH

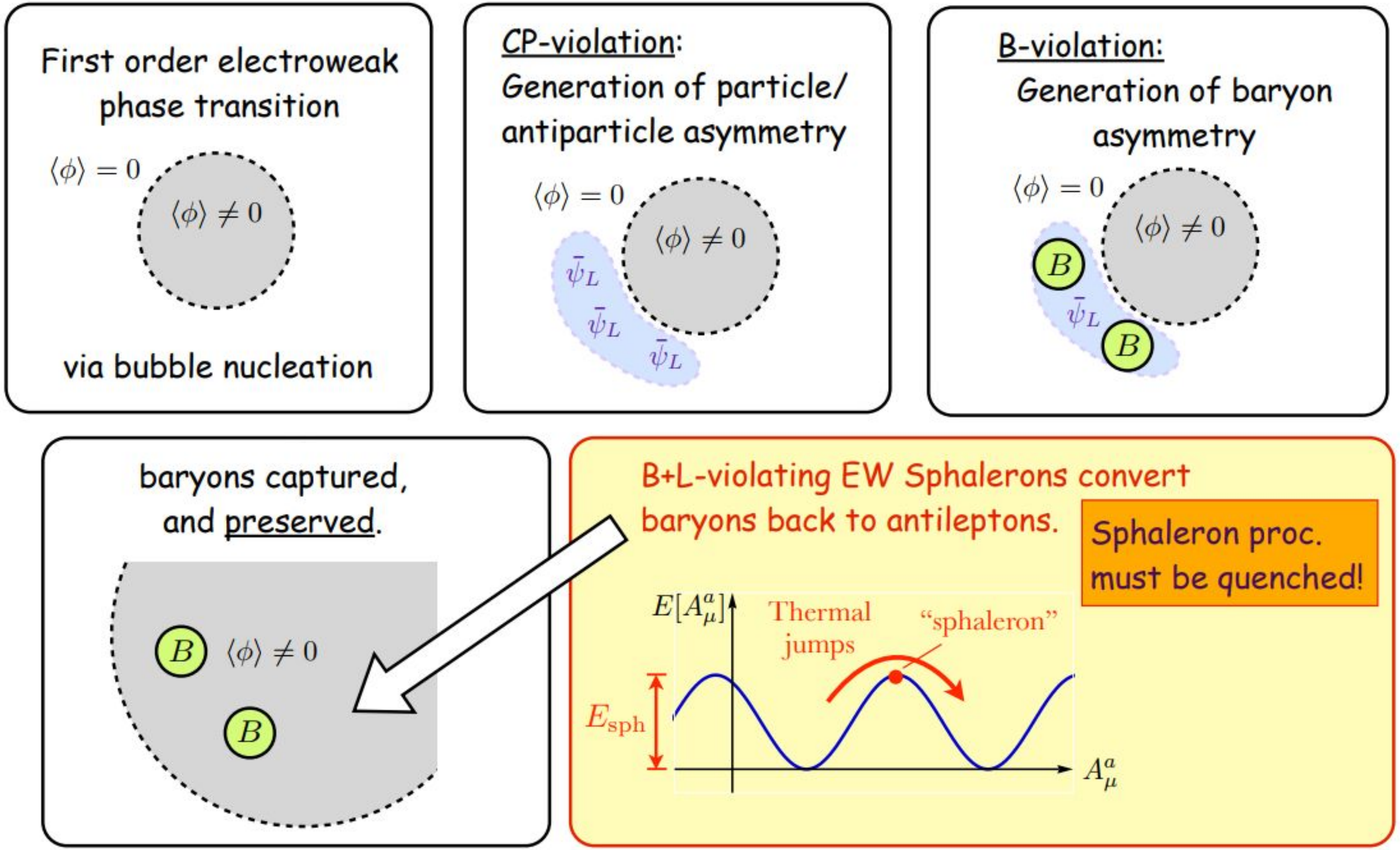


e+e- → vvHH



Require at least ~500 GeV for the direct measurement of the triple-Higgs coupling via double Higgs production.

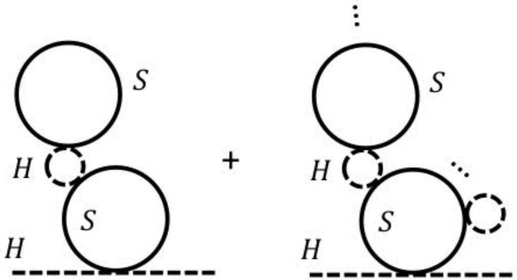
Baryogenesis ...*in a nutshell*



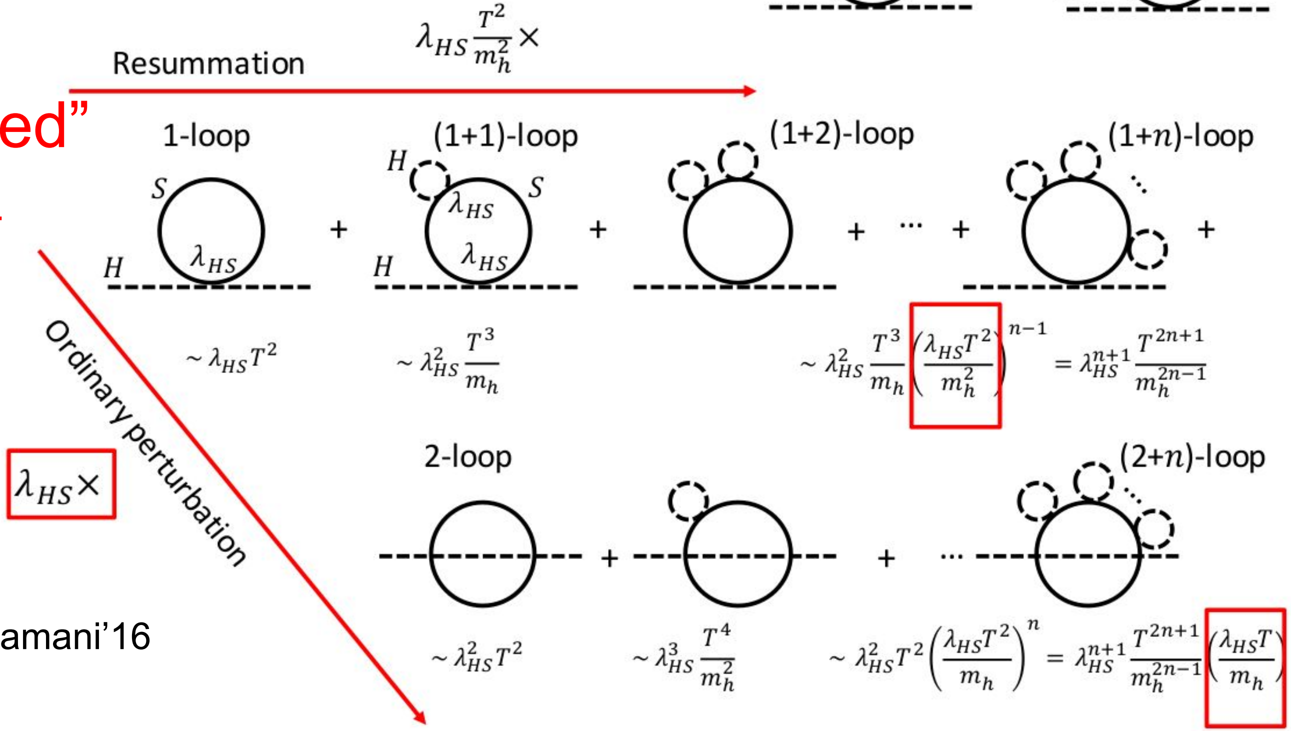
Strong 1st order phase transition
$\leftrightarrow \quad \lambda_{HS} \sim \mathcal{O}(1)$ for $N_S = 1$

The perturbation breaks down ? It looks like

$\lambda_4 \sim 0.13$, and we assumed $\lambda_S \sim 0$, ignored overall m_h^2/m_S^2 factor



“ring-improved” version of V_T



Curitn, Meade, Ramani’16