Electroweak Phase Transition in the Two-Higgs-Doublet Model

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Outline

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Motivation

[Morrissey, Ramsey-Musolf '12]

- Electroweak Baryogenesis (EWBG): generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition
- Sakharov conditions [Sakharov '67]
  - departure from thermal equilibrium
  - baryon number violating processes
  - *C*- and *CP*-violating processes
- further condition: phase transition (PT) must be (strong) first order

  $\rightarrow$ expanding bubbles with broken phase inside, symmetric phase outside

In the SM: [see e.g. Morrissey, Ramsey-Musolf '12 and references therein]

- Sakharov conditions fulfilled
- a strong phase transition only occurs, if [Shaposhnikov et. al. '87, '95][Jansen '95]

$$m_h \lesssim 70 \text{ GeV}$$

- *CP*-violation induced by CKM-matrix too small

Introduction

Motivation

$\Rightarrow$ New Physics required $\rightarrow$ Two-Higgs-Doublet Model (2HDM)

- analyses of EWBG in the 2HDM with old exclusion bounds

  [Cline, Lemieux '97][Fromme, Huber, Seniuch '06][Cline, Kainulainen, Trott '11]

  [Dorsch, Huber, No '13][Dorsch, Huber, Mimasu, No '14]

  $\rightarrow$ update to newest bounds
- mixing angles of the Higgs sector of the 2HDM never considered in the renormalization so far

  $\rightarrow$ consider them for the first time
- new treatment of the Goldstone bosons in the renormalization
- detailed analysis of implications of the requirement for a strong phase transition on collider observables

Two-Higgs-Doublet Model

- extend the SM Higgs sector by a second Higgs doublet

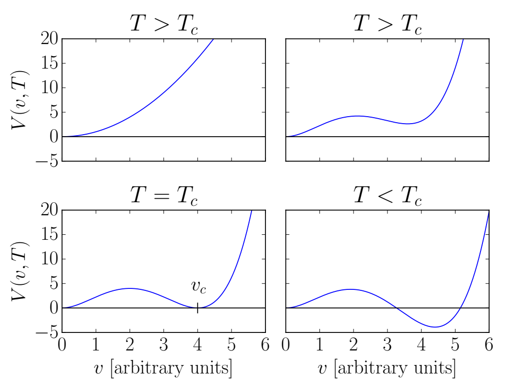
$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]$$

- new Higgs bosons, five in total: h, H, A, H^+, H^-
  $\rightarrow$ impact on the phase transition
- m_{12}^2, λ_5 can in principle be complex
  $\rightarrow$ new sources of *CP*-violation
- coupling of fermions to Higgs bosons:
  Type I: all fermions to Φ_2
  Type II: up-type to Φ_2, down-type and leptons to Φ_1
- two sets of input parameters: either parameters in V_{tree} or

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ \alpha,\ \tan\beta,\ v$$

Electroweak Phase Transition

- requirement for successful EWBG: PT of strong first order



- determine v for given T, criterion for a PT to be strong: [e.g. Quiros '99 and references therein]

$$\frac{v_c}{T_c} \geq 1$$

Calculation

Effective Potential at Finite Temperature at the One-Loop Level

[excellent review e.g. in Quiros '99]

- ingredients:
  - tree-level potential
  - Coleman-Weinberg potential [Coleman, Weinberg '73]
  - temperature potential
  - counterterm potential
- position of the global minimum, Higgs masses and mixing angles preserved at tree-level values
- minimization to find the global minimum at given temperature ($\rightarrow$ vacuum expectation value (VEV))
- determination of the critical temperature and the corresponding VEV

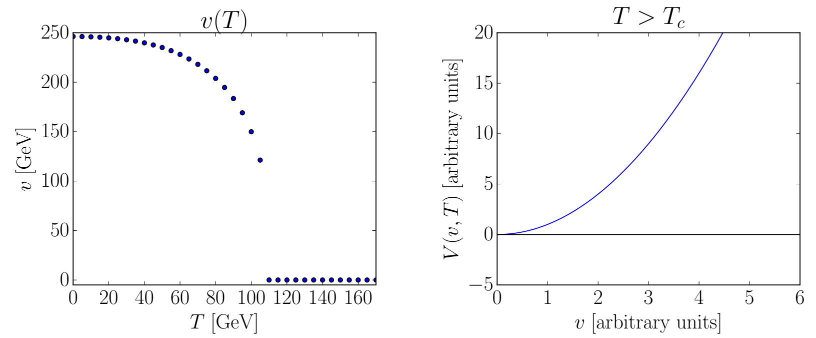
Calculation

Tools and Constraints

- two independent calculations and implementations (C++ and Mathematica)
- `ScannerS`: Scan over the parameter space, boundedness from below and tree-level perturbative unitarity [Coimbra, Sampaio, Santos '13][Ferreira, Guedes, Sampaio, Santos '14]
- S, T, U parameters for electroweak precision observables
- $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{Hadrons})$ and $B \to X_s\gamma$
- Higgs exclusion bounds checked by `HiggsBounds` [Bechtle, Heinemeyer, Weiglein et al. '08, '11, '13]
- Higgs rates checked via `SusHi` and `HDECAY` [Harlander, Liebler, Mantler '12][Harlander, Mühlleitner, Rathsman, Spira, Stal '13][Djouadi, Kalinowski, Spira '97 + Mühlleitner][Butterworth et al. '10]
- extensive scans over the parameter space of the 2HDM

Results

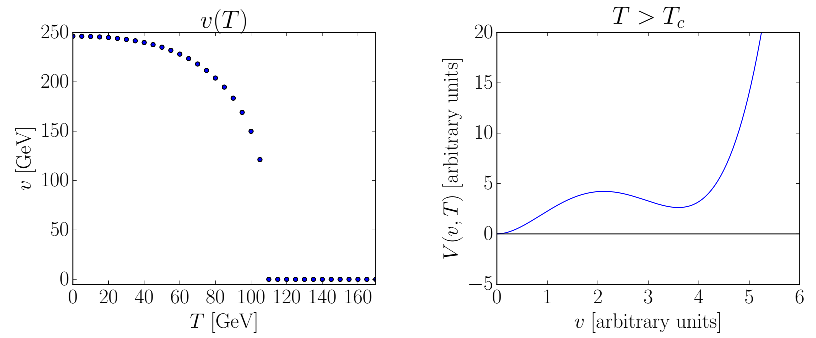
$T > T_c$



- global minimum of the potential at $v = 0$, electroweak symmetry unbroken

Results

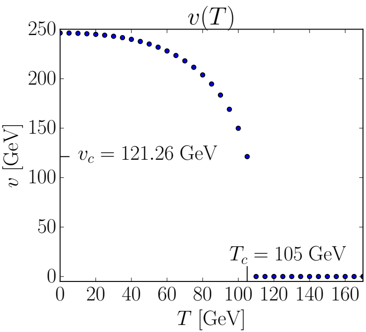
$T > T_c$

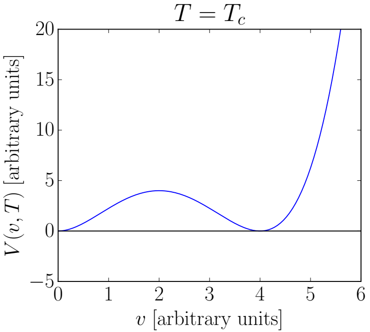


- global minimum of the potential still at $v = 0$, electroweak symmetry unbroken

Results

$T = T_c$

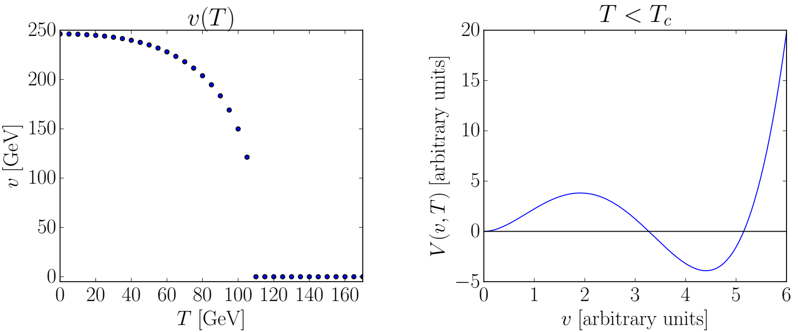




- degenerate minima, determination of v_c and T_c by the position and height of the jump
- $\frac{v_c}{T_c} = 1.15 \Rightarrow$ strong first order PT

Results

$T < T_c$

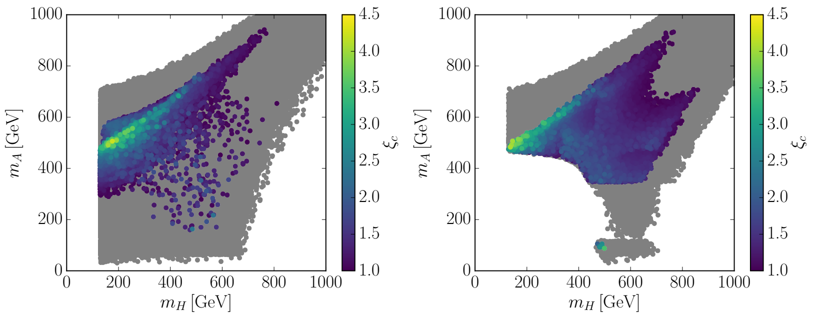


- finite non-zero v, electroweak symmetry broken

Comparison of the 2HDM Types

[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]

Type I | Type II

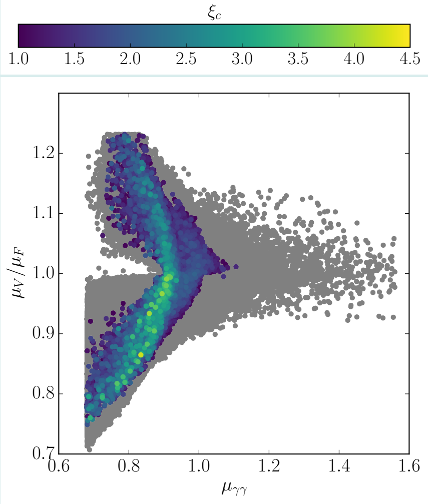


- $\xi_c = v_c/T_c$
- $m_h = 125.09$ GeV

Results

Type I, impact of demanding $\xi_c > 1$

[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]



$\mu_{F(V)}$ → fermion(gauge boson)-initiated cross section (gluon (vector)-boson fusion and associated production) normalized to SM

$$\mu_{\gamma\gamma} = \mu_F \frac{\text{BR}_{\text{2HDM}}(h_{125} \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H_{\text{SM}} \to \gamma\gamma)}$$

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Conclusion [arXiv:1612.04086]

- investigated the electroweak phase transition in the *CP*-conserving 2HDM
- determined T_c and v_c via the one-loop effective potential at finite T
- renormalization taking into account the position of the global minimum, all physical masses and mixing angles, novel treatment of the Goldstone bosons therein
- detailed phenomenological analysis taking into account most recent bounds and constraints
- findings:

  CP-conserving 2HDM can yield a strong first order PT valid for baryogenesis
  requiring a strong PT has important consequences for collider observables:
  $\rightarrow$ Type I: $m_{A,H^\pm} \approx$ 400-500 GeV favored
  $\rightarrow$ Type I: $\mu_{\gamma\gamma} \lesssim 1.1$
  $\rightarrow$ Type II: $m_A \in [130, 340]$ GeV excluded
  $\rightarrow$ many more in arXiv:1612.04086

Thanks for listening!

Conclusion

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Conclusion [arXiv:1612.04086]

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Thanks for listening!

Backup: Parameter Scans

Settings

- $v = 246.22$ GeV
- $-\pi/2 \leq \alpha \leq \pi/2$

# points	m_h	m_H (in GeV)	m_A	$m_{H\pm}$	m_{12}^2 in GeV^2	$\tan(\beta)$
1 000 000	$m_{h_{125}}$	$130 - 1000$	$30 - 1000$	$65 - 1000$	$0 - 5 \times 10^5$	$1 - 35$
100 000	$30 - 120$	$m_{h_{125}}$	$30 - 1000$	$65 - 1000$	$0 - 5 \times 10^5$	$1 - 35$

Table: Parameter ranges for the scan performed in the 2HDM type I.

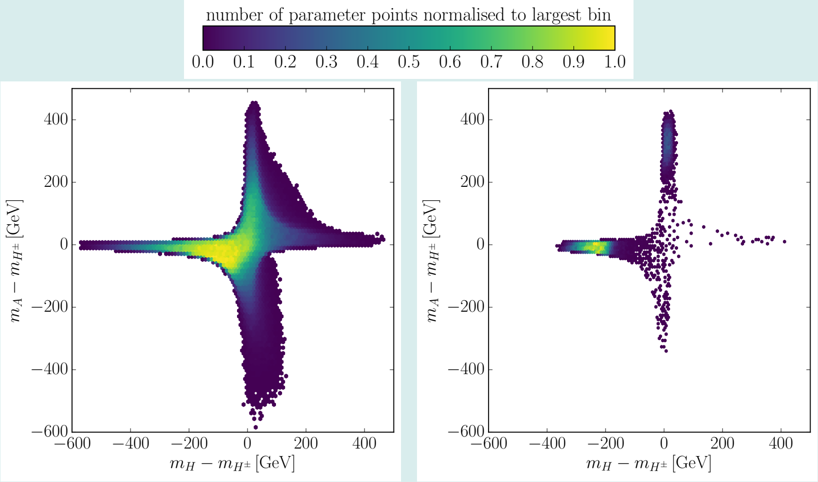
# points	m_h	m_H (in GeV)	m_A	$m_{H\pm}$	m_{12}^2 in GeV^2	$\tan(\beta)$
1 000 000	$m_{h_{125}}$	$130 - 1000$	$30 - 1000$	$480 - 1000$	$0 - 5 \times 10^5$	$0.1 - 35$
100 000	$30 - 120$	$m_{h_{125}}$	$450 - 1000$	$480 - 1000$	$0 - 5 \times 10^5$	$0.1 - 35$

Table: Parameter ranges for the scan in the 2HDM type II.

Backup: Results

Type I, impact of demanding $\xi_c > 1$

[Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka '16]



Backup: Calculation

Effective Potential at Finite Temperature

[excellent review e.g. in Quiros '99]

- Tree-level potential + one-loop corrections at finite temperature
- corresponds to diagrammatic calculation with vanishing external momenta
- one-loop contributions at finite temperature can be split into two parts:

  Coleman-Weinberg potential V_{CW} [Coleman, Weinberg '73]

  Temperature potential V_T
- V_{CW} in the $\overline{\text{MS}}$-scheme: [e.g. Quiros '99]

$$V_{\text{CW}}(\{\omega\}) = \sum_i \frac{n_i}{64\pi^2}(-1)^{2s_i}\, m_i^4(\{\omega\}) \left[\log\left(\frac{m_i^2(\{\omega\})}{\mu^2}\right) - c_i\right]$$

$\{\omega\}$: field configurations of the Higgs fields
$m_i^2(\{\omega\})$: eigenvalue of mass matrix at $\{\omega\}$
s_i: spin of particle i
n_i: degrees of freedom for particle i
$c_i = 5/6$ for vector bosons, $3/2$ otherwise
μ^2: renormalization scale

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \omega_1 + \zeta_1 + i\psi_1 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + i\eta_2 \\ \omega_2 + i\omega_3 + \zeta_2 + i\psi_2 \end{pmatrix}$$

Backup: Calculation

Temperature Potential

[excellent review e.g. in Quiros '99]

- temperature potential V_T is given by

$$V_T = \sum_k n_k \frac{T^4}{2\pi^2} J_{\pm}^{(k)}$$

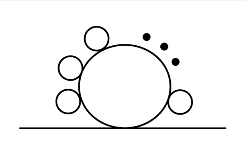
with

$$J_{\pm}\left(\frac{m_k^2}{T^2}\right) = \mp \int_0^\infty \mathrm{d}x\, x^2 \log\left[1 \pm e^{-\sqrt{x^2+m_k^2/T^2}}\right]$$

with $+(-)$ for fermions (bosons)

- problem: breakdown of perturbative expansion for high T [Weinberg '74]

  $\rightarrow$ can be cured by including thermal corrections to the masses of bosons



[Quiros '99]

Temperature Potential

[excellent review e.g. in Quiros '99]

- two different approaches (m ($\overline{m}$) = mass without (with) thermal corrections) :

  Arnold-Espinosa: [Arnold, Espinosa '93]

$$J_{\pm}^{(k)} = \begin{cases} J_{-}\left(\frac{m_k^2}{T^2}\right) - \frac{\pi}{6}\left(\overline{m}_k^3 - m_k^3\right) & k = W_L, Z_L, \gamma_L, \Phi^0, \Phi^{\pm} \\ J_{-}\left(\frac{m_k^2}{T^2}\right) & k = W_T, Z_T \\ J_{+}\left(\frac{m_k^2}{T^2}\right) & k = f \end{cases}$$

  Parwani: [Parwani '92]

$$J_{\pm}^{(k)} = \begin{cases} J_{-}\left(\frac{\overline{m}_k^2}{T^2}\right) & k = W_L, Z_L, \gamma_L, \Phi^0, \Phi^{\pm} \\ J_{-}\left(\frac{m_k^2}{T^2}\right) & k = W_T, Z_T \\ J_{+}\left(\frac{m_k^2}{T^2}\right) & k = f\ . \end{cases}$$

  and also use $\overline{m}$ in V_{CW} where appropriate
- difference formally of higher order, both approaches tested

Backup: Calculation

Renormalization

- recall: set of input parameters

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ \alpha,\ \tan\beta,\ v$$

- use these input parameters for efficient scan of the parameter space
- problem: input parameters $\neq$ one-loop parameters from effective potential

  (input parameters $\hat{=}$ tree-level parameters

  masses and angles from the effective potential at one loop $\hat{=}$ one-loop masses and angles in $\overline{\text{MS}}$-scheme with vanishing external momenta)
- idea: counterterms (CTs) to achieve

$$\text{input parameters} = \text{one-loop parameters from effective potential}$$

- only finite pieces needed
- one CT for each parameter in V_{tree}

Backup: Calculation

Renormalization

- counterterm potential:

$$V_{\text{CT}} = \delta m_{11}^2 \Phi_1^\dagger \Phi_1 + \delta m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[\delta m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right] + \frac{1}{2}\delta\lambda_1 (\Phi_1^\dagger \Phi_1)^2$$
$$+ \frac{1}{2}\delta\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \delta\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \delta\lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \left[\frac{1}{2}\delta\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}\right]$$

- renormalization at $T = 0$ $\Rightarrow$ only V_{tree} and V_{CW} relevant
- position of the minimum $\rightarrow$ first derivative

  masses and mixing angles $\rightarrow$ second derivative (Hesse matrix)
- expressions for derivatives of V_{CW} in gauge basis given in

  [Camargo-Molina, Morais, Pasechnik, Sampaio, Wessen '16]
- Reminder: Higgs fields in gauge basis:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + \mathrm{i}\eta_1 \\ \omega_1 + \zeta_1 + \mathrm{i}\psi_1 \end{pmatrix} \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \mathrm{i}\eta_2 \\ \omega_2 + \mathrm{i}\omega_3 + \zeta_2 + \mathrm{i}\psi_2 \end{pmatrix}$$

Backup: Calculation

Renormalization

- conditions:

$$\partial_{\phi_i} \; V_{\text{CT}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} = -\partial_{\phi_i} \; V_{\text{CW}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}}$$

  and

$$\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CT}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} = -\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CW}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}}$$

  with

$$\phi_i \equiv \{\rho_1, \eta_1, \rho_2, \eta_2, \zeta_1, \psi_1, \zeta_2, \psi_2\}$$

- problem: system over-constrained $\Rightarrow$ no general solution
- idea: approximation $\rightarrow$ take only those elements of the Hesse matrix corresponding to physical particles (h, H, A, H^+, H^-)
- rotate to the tree-level mass basis on both sides
- demand the condition only for the entries for h, H, A, H^+, H^-

$$\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CT}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} \Big|^{H^\pm}_{\text{mass}} = -\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CW}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} \Big|^{H^\pm}_{\text{mass}}$$

  and

$$\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CT}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} \Big|^{h,H,A}_{\text{mass}} = -\partial_{\phi_i}\partial_{\phi_j} \; V_{\text{CW}}(\phi)|_{\phi=\langle\phi^c\rangle_{T=0}} \Big|^{h,H,A}_{\text{mass}}$$

Backup: Calculation

Renormalization

We find:

- eight counterterms to be fixed
- first derivative $\rightarrow$ two independent conditions
- second derivative $\rightarrow$ five independent conditions
- set $\delta\lambda_4 = 0$ (only appears in the sum with $\delta\lambda_3$)

Result:

- minimum of the full effective potential at one-loop remains at $v \pm 2$ GeV
- masses and mixing angles preserved up to numerical fluctuations

Backup: Calculation

Renormalization

- problem: IR divergence in the second derivative of V_{CW} for the Goldstone bosons (we work in Landau gauge $\rightarrow m_{G^0,G^\pm} = 0$)

  [see e.g. Martin '14 and Elias-Miro, Espinosa, Konstandin '14 and references therein]

- solution: this IR divergence is spurious and can be dropped

  [Casas, Espinosa, Quiros, Riotto '94][Elias-Miro, Espinosa, Konstandin '14]

  [Camargo-Molina, Morais, Pasechnik, Sampaio, Wessen '16]

- full self-energy is given by

$$\Sigma(p^2) = \partial^2 V_{\text{eff}} + \Sigma(p^2) - \Sigma(0)$$

  split everything into IR finite and divergent pieces and observe a relation between the divergent pieces

  $\Rightarrow$ find that the divergent piece cancels

- was checked explicitly using the calculation of

  [Krause, Lorenz, Mühlleitner, Santos, Ziesche '16]