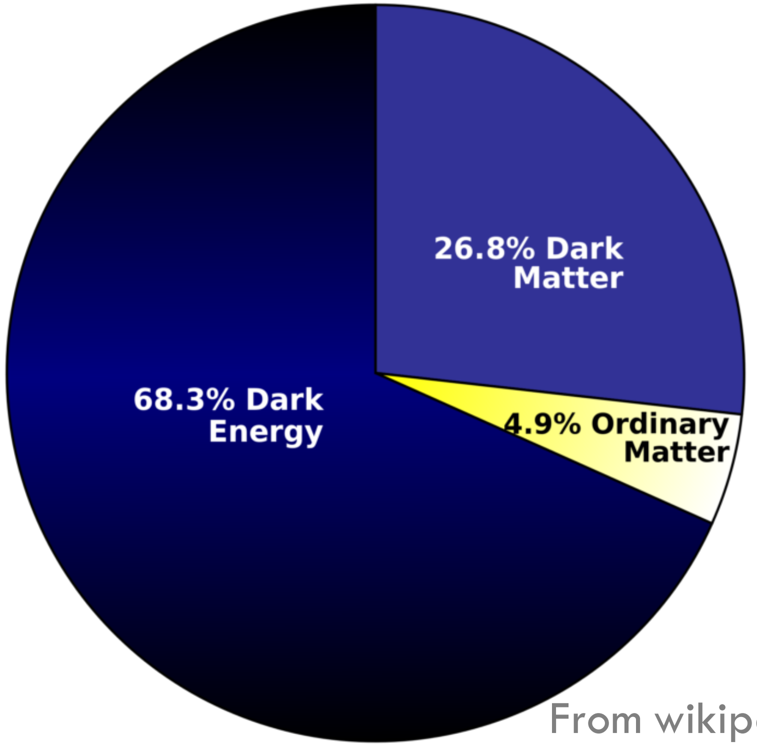
Electroweak Phase Transitions in NMSSM

Yang Zhang（张阳），Monash University

With Peter Athron, Csaba Balazs, Andrew Fowlie, Giancarlo Pozzo and Graham White

Introduction



From wikipedia

To explain the baryon asymmetry of the Universe (BAU)

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10},$$

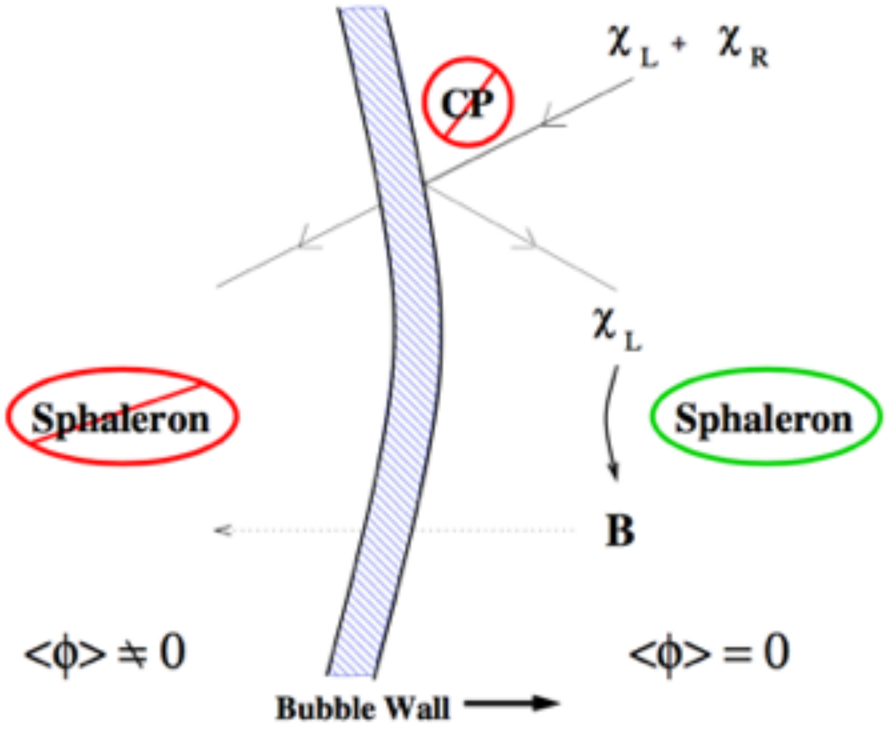
Sakharov Criteria for baryogenesis must be satisfied:

- ➢ Baryon number violation,
- ➢ C-symmetry and CP-symmetry violation,
- ➢ Interactions out of thermal equilibrium.
  - Realized by Electroweak phase transition

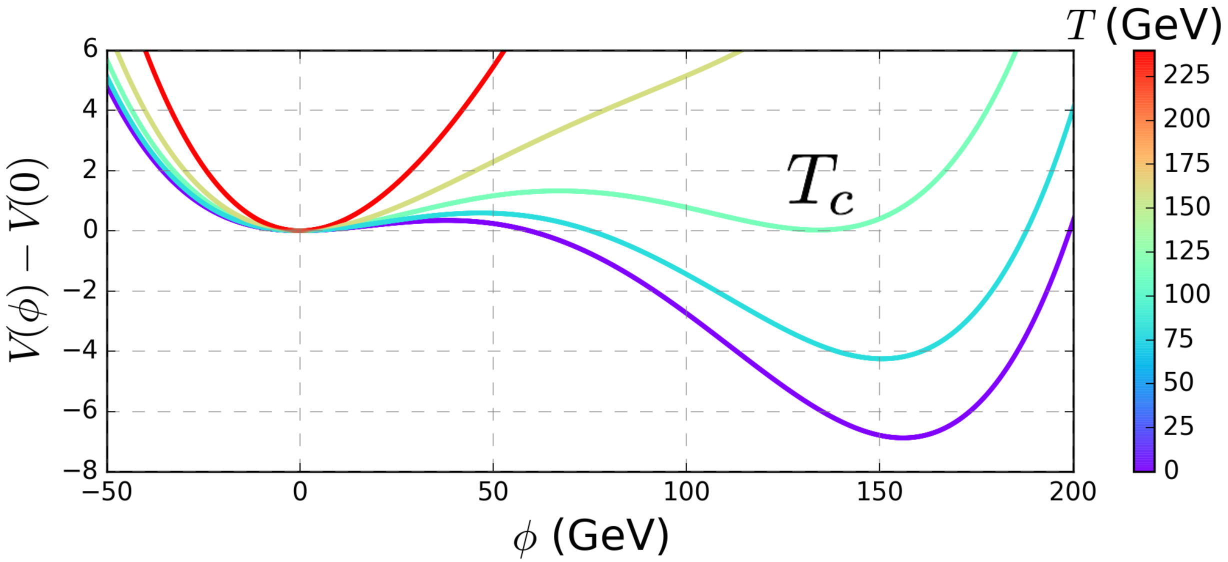
Introduction

In the broken phase, the rate of sphaleron transitions must be strongly suppressed. The bound can be translated into bound on the strength of transition:

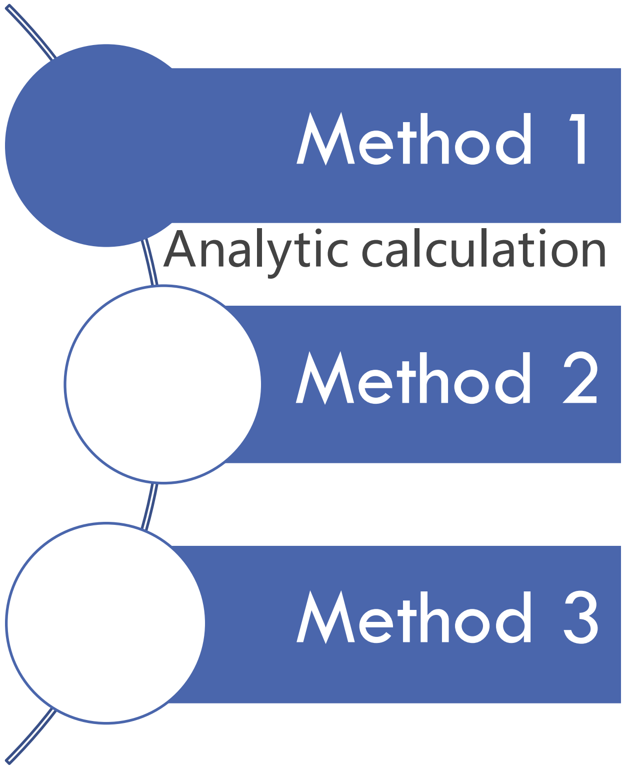
$$\frac{E_{\rm sph}(T_c)}{T_c} > 37 \rightarrow \gamma \equiv \frac{\phi(T_c)}{T_c} \approx \frac{1}{36}\frac{E_{\rm sph}(T_c)}{T_c} > 1.0$$



arXiv:1206.2942



Calculation of transition strength



Strong first order phase transition (SFOFT):

$$\gamma \equiv \frac{\phi(T_c)}{T_c} = \frac{|\phi^{(0)} - \phi^{(1)}|}{T_c} > 1.0$$

$$V(\phi^{(0)}, T_c) = V(\phi^{(1)}, T_c)\ , \quad \left.\frac{\partial V}{\partial \phi}\right|_{\phi^{(0)}, T_C} = \left.\frac{\partial V}{\partial \phi}\right|_{\phi^{(1)}, T_C} = 0$$

- SM + a Z2 symmetric real scalar singlet (arXiv:1611.02073)

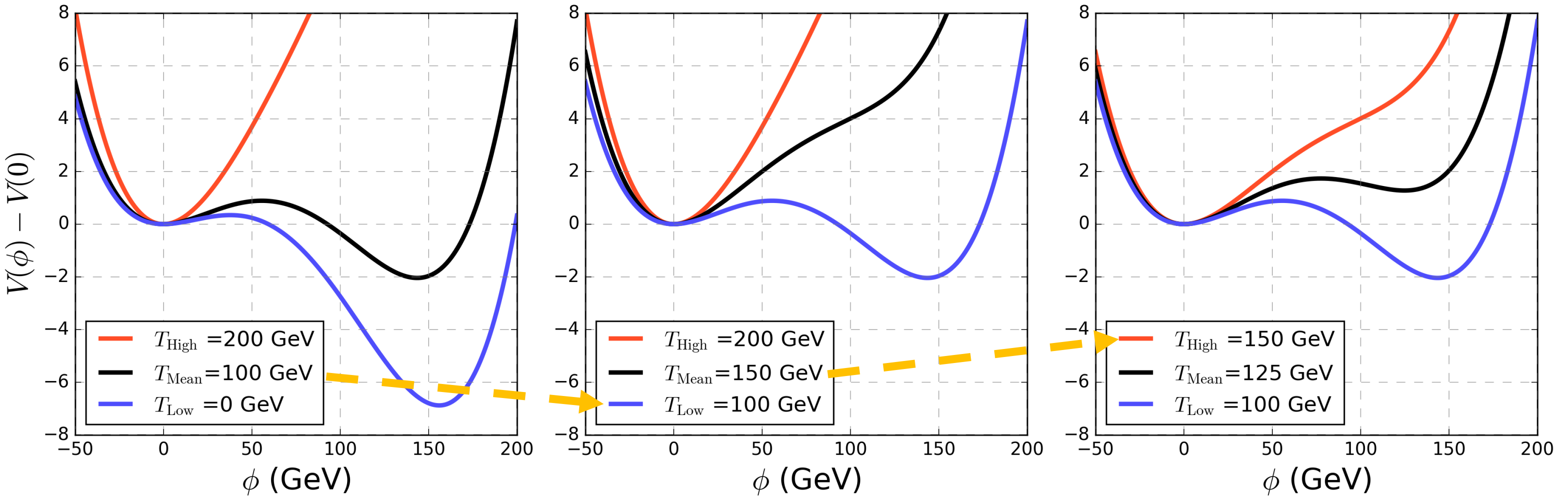
$$V(H,s) = (\mu_h^2 + c_h T^2) H^\dagger H + \lambda_h (H^\dagger H)^2 + \frac{\lambda_{hs}}{2}(H^\dagger H) s^2 + \frac{(\mu_s^2 + c_s T^2)}{2} s^2 + \frac{\lambda_s}{4} s^4$$

$$T_c^2 = \frac{\lambda_s c_h \mu_h^2 - \lambda_h c_s \mu_s^2 - \sqrt{\lambda_h \lambda_s}\,|c_s \mu_h^2 - c_h \mu_s^2|}{\lambda_s c_h^2 - \lambda_h c_s^2}$$

Calculation of transition strength

- Method 1
- Method 2
  - Bisection
- Method 3

Starting with an un-broken phase at high temperature and a broken phase at low temperature, find a temperature that these two phase degenerate using bisection method.

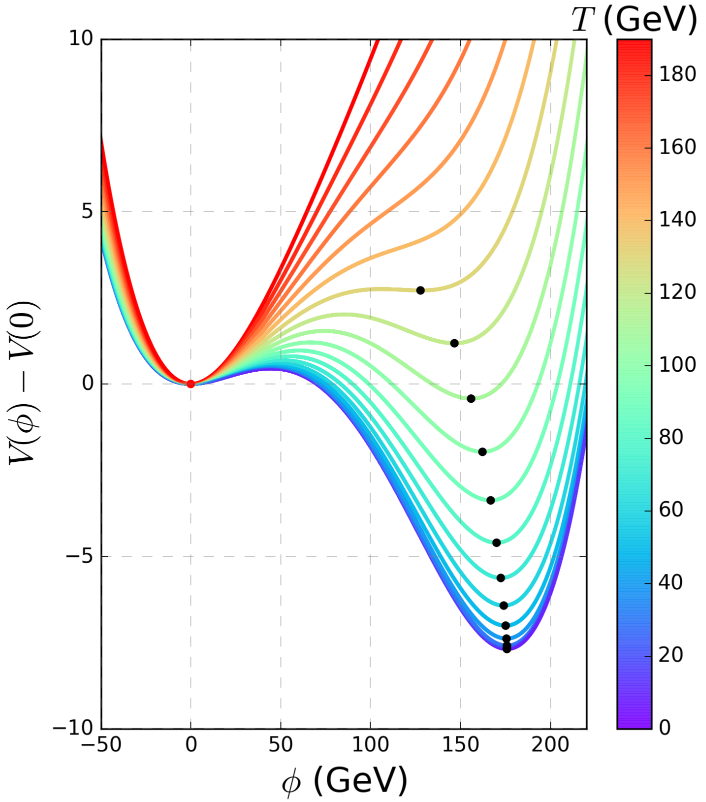


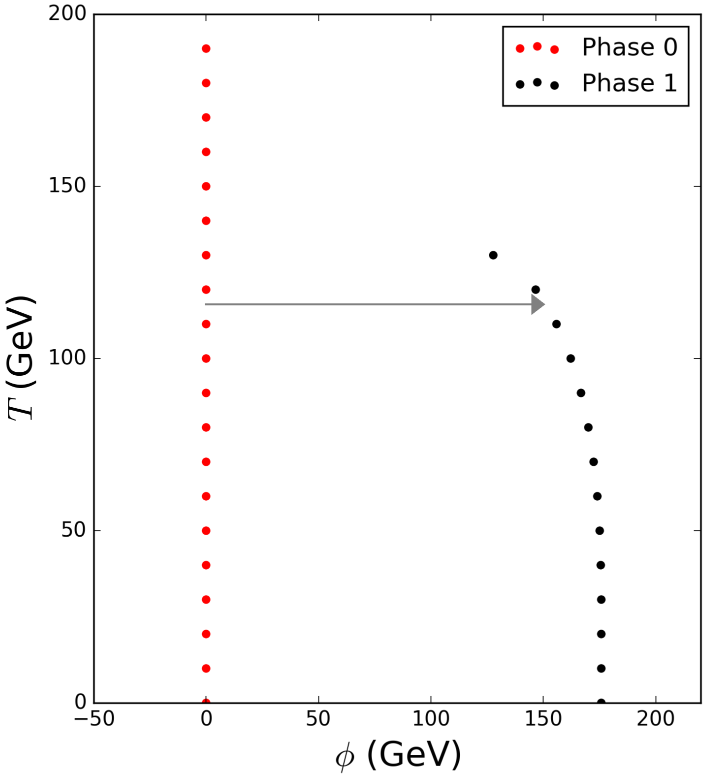
➢ Implemented in in BSMPT (arXiv: 1803.02846)

Calculation of transition strength

- Method 1
- Method 2
- Method 3
  Trace minimum

Starting with a minimum at low/high temperature, trace the location of minimum at different temperatures.





Calculation of transition strength

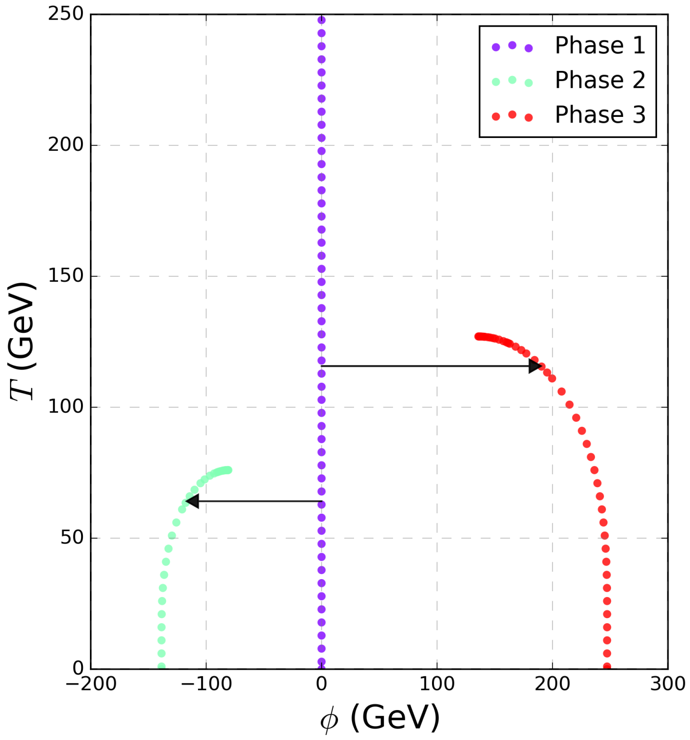
Method 1

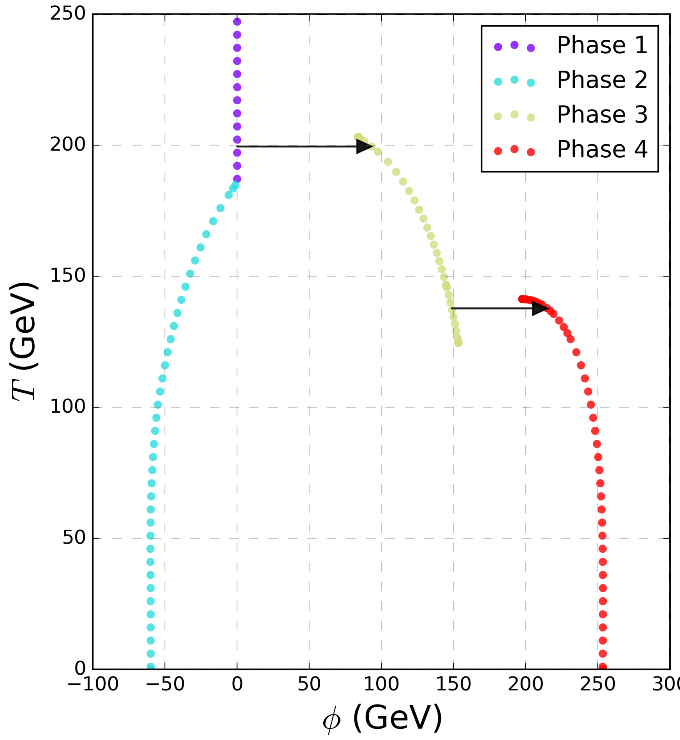
Method 2

Method 3

Trace minimum

Find more than one transition.

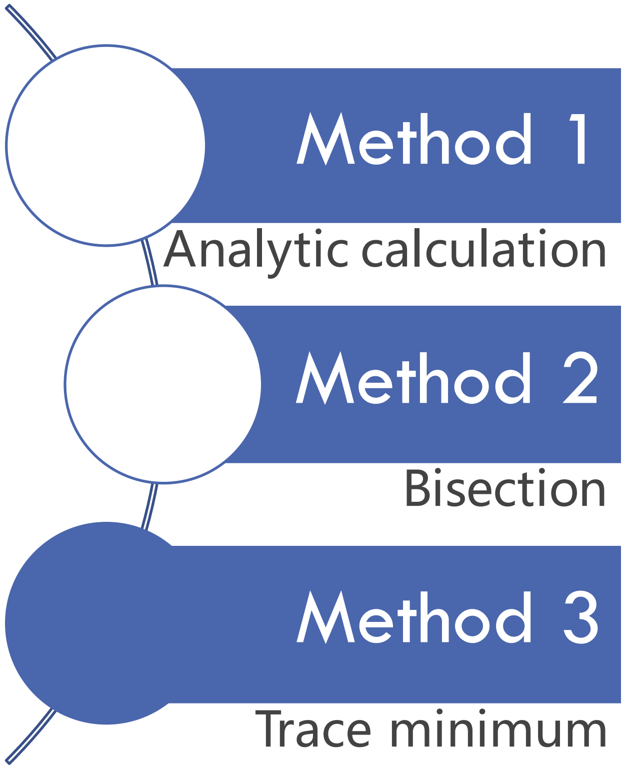




➢ Implemented in in CosmoTransition (arXiv: 1109.4189)

Calculation of transition strength

Fast, Stable, Many assumptions



Slow, Unstable, No assumptions

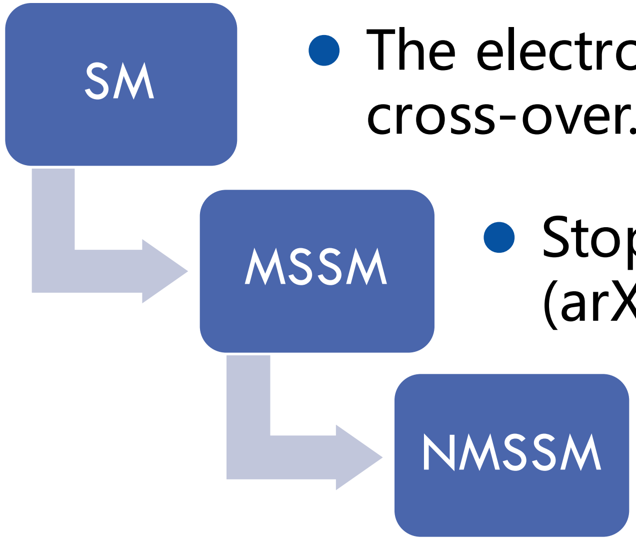
Based on method 3, we develop a program, **PhaseTracer**, to map phase structure and calculate transition strength. Comparing with CosmoTransition（the transition strength calculation part), Phasetracer is optimized for scan:

- Faster

	2D simplified potential	NMSSM
CosmoTrasition	6.55 seconds	8 minutes
PhaseTracer	0.32 second	4 seconds

- Relatively stable for complex potential.
- Automatically classify the phase structure
- … …

EW Phase Transitions in NMSSM



- The electroweak symmetry is smoothly broken via a continuous cross-over.
- Stop mass have to be lighter than 120 GeV to achieve SFOFT (arXiv:0809.3760).
- The added singlet induces tree-level cubic terms in the Higgs potential.

$$
\begin{aligned}
V_F &= |\lambda S|^2 \left(|H_u|^2 + |H_d|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2 , \\
V_D &= \frac{1}{8}(g^2 + g'^2)(|H_u|^2 - |H_d|^2)^2 + \frac{1}{2} g^2 |H_u^\dagger H_d|^2 ,
\end{aligned}
$$

$$
V_{\rm soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\underline{\lambda A_\lambda S H_u \cdot H_d + \kappa A_\kappa S^3} + \text{h.c.}].
$$

Effective potential of NMSSM

To avoid the large logarithms arising from the stops in loop correction, we match the NMSSM to a two Higgs doublet plus singlet model (THDMS) at SUSY scale

$$
\begin{aligned}
V^{\text{tree}}_{\text{THDMS}} = & \frac{1}{2}\lambda_1|H_d|^4 + \frac{1}{2}\lambda_2|H_u|^4 + (\lambda_3+\lambda_4)|H_u|^2|H_d|^2 - \lambda_4|H_u^\dagger H_d|^2 \\
& + \lambda_5|S|^2|H_d|^2 + \lambda_6|S|^2|H_u|^2 + (\lambda_7 S^{*2} H_d\cdot H_u + \text{h.c.}) + \lambda_8|S|^4 \\
& + m_1^2|H_d|^2 + m_2^2|H_u|^2 + m_3^2|S|^2 - (m_4 S H_d\cdot H_u + \text{h.c.}) - \frac{1}{3}(m_5 S^3 + \text{h.c.}),
\end{aligned}
$$

by identifying the tree-level conditions, and include a dominant one-loop threshold correction.

We calculate one-loop finite-temperature corrections including daisy terms using the Arnold-Espinosa method in the ξ = 0 (Landau) gauge, i.e.

$$
V_{\text{eff}} = V^{\text{tree}}_{\text{THDMS}} + \Delta V_{\text{THDMS}} + \Delta V_T + V_{\text{daisy}}.
$$

Parameter scan for NMSSM

SARAH / FlexibleSUSY

Construct model and calculate the effective potential

↓

Lilith

LHC Run I and II measurements of the Higgs boson

↓

PhaseTracer / CosmoTransition

Calculate transition strength and check phase structure

↓

MultiNest

Perform the scan using

$$\chi^2 = \chi^2_{\text{Higgs}} + \chi^2_{\text{SFOPT}} + \chi^2_{\text{LEP}}$$

$$\chi^2_{\text{SFOPT}} \equiv \left(\frac{\log_{10}\gamma_{\text{EW}}}{0.2}\right)^2, \quad \chi^2_{\text{LEP}} \equiv \begin{cases} 0 & \mu \geq 100\,\text{GeV}, \\ \left(\frac{\mu - 100\,\text{GeV}}{5\,\text{GeV}}\right)^2 & \mu < 100\,\text{GeV}. \end{cases}$$

Parameter	Range	Prior
λ	0, 1.5	Flat
κ	0, 1.5	Flat
A_λ	-10 TeV, 10 TeV	Signed_log
A_κ	-10 TeV, 10 TeV	Signed_log
A_t	-10 TeV, 10 TeV	Signed_log
$m_{\tilde{t}_R}$	1 TeV, 10 TeV	Log
$m_{\tilde{t}_L}$	1 TeV, 10 TeV	Log
v_S	10 GeV, 10 TeV	Log
$\tan\beta$	1, 60	Log

$$\chi^2_{\text{Higgs}} - \min\chi^2_{\text{Higgs}} \leq 6.18,\ \mu \geq 100\,\text{GeV and } \gamma_{\text{EW}} \geq 1$$

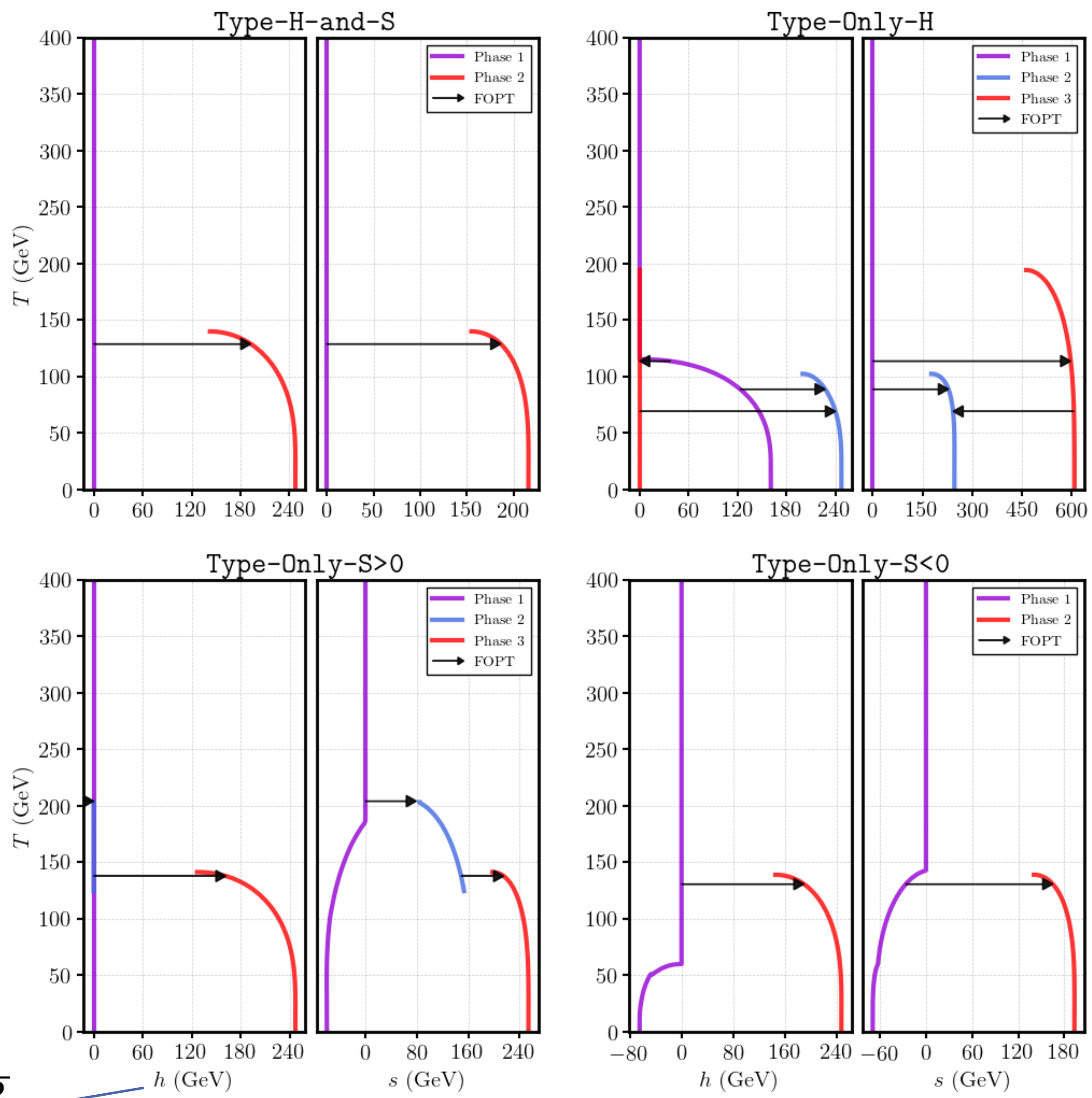
$$\gamma_{\text{EW}} \equiv \sqrt{(h_u^{(0)} - h_u^{(1)})^2 + (h_d^{(0)} - h_d^{(1)})^2}/T_c,$$

where $h_u^{(0)} = h_d^{(0)} = 0$, $s^{(0)}$ and $s^{(1)}$ can be any value.

Classification

We classify points on the nature of the first possible phase transition in the history:

1. **Type-H-and-S**: Higgs field and the singlet field obtain non-vanishing VEVs simultaneously.
2. **Type-Only-H**: Higgs fields obtaining VEVs, but the singlet VEV remains zero.
3. **Type-Only-S>0**: EW symmetry remains unbroken, but the singlet field obtains a VEV, which is positive.
4. **Type-Only-S<0**: EW symmetry remains unbroken, but the singlet field obtains a VEV, which is negative



$$h \equiv \text{sign}(h_u \cdot h_d)\sqrt{h_u^2 + h_d^2}$$

Type-H-and-S

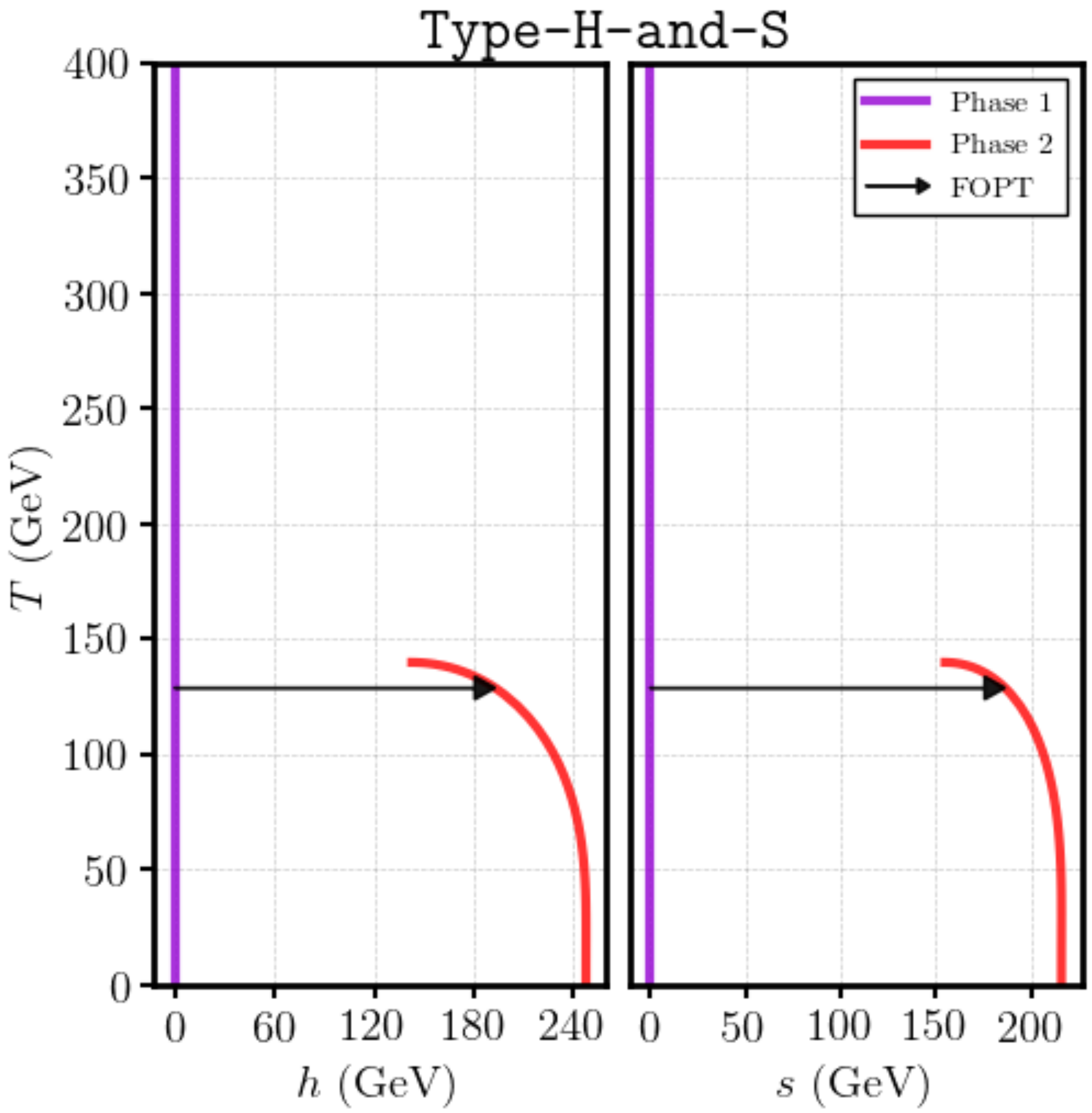
- At high temperature, the symmetry is unbroken,

  $(h_u, h_d, s) = (0, 0, 0)\ \mathrm{GeV}$
- At critical temperature

  $T_c = 128.8\ \mathrm{GeV}$

  $V(0,0,0) = V(139.6, 132.9, 186.2)$
- Nucleation temperature

  $T_n = 103.8\ \mathrm{GeV}$
- EW symmetry is spontaneously broken such that Higgs field and the singlet field obtain non-vanishing VEVs simultaneously.



Type-Only-S>0

- The first possible phase transition

  $T_c = 204.1$ GeV

  $V(0,0,0) = V(0,0,79)$

  $\gamma_{\rm EW} = 0$ and $\gamma = 0.29$

  $T_n = 203.6$ GeV

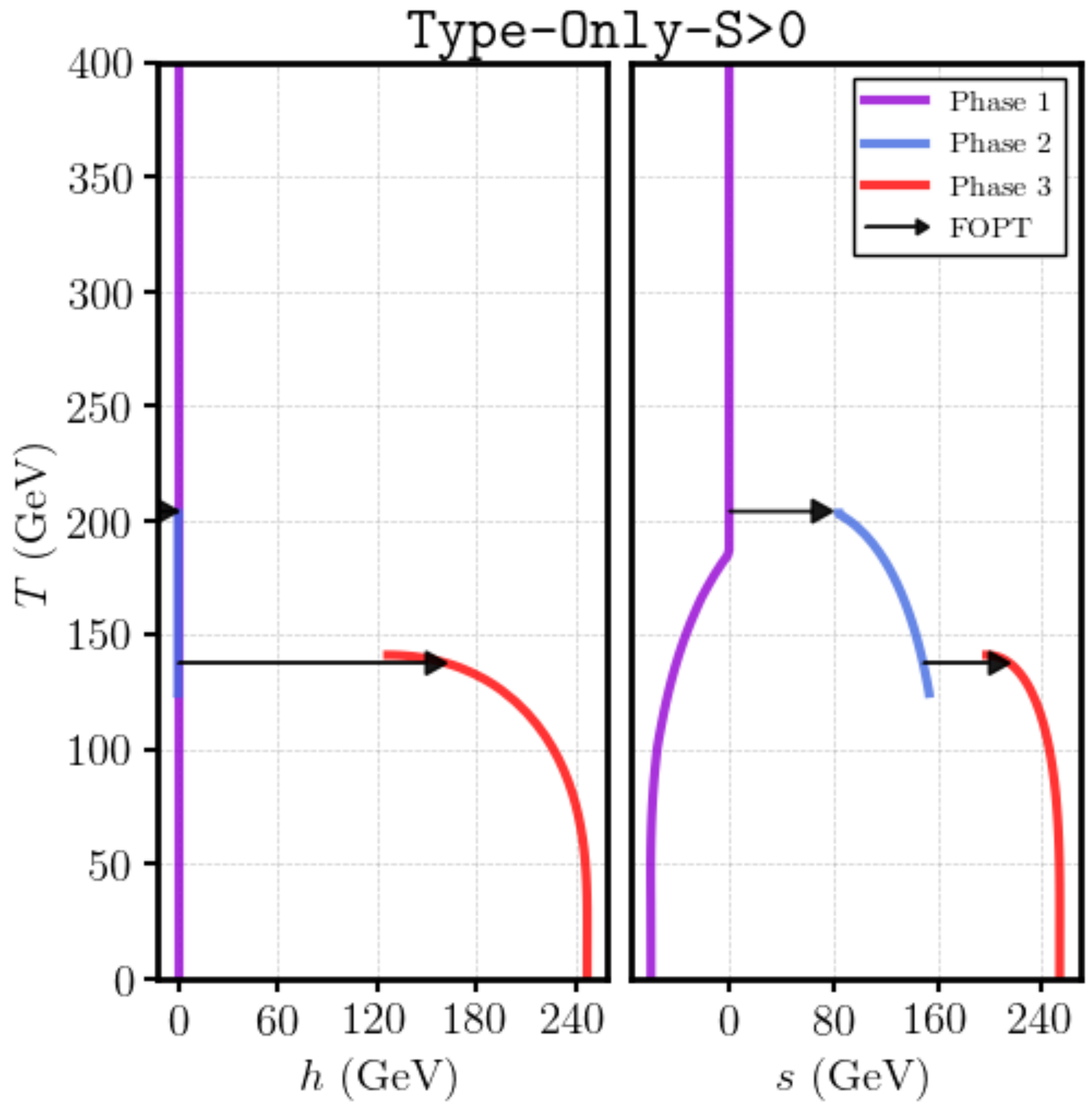
- The second possible phase transition

  $T_c = 137.7$ GeV

  $V(0,0,150) = V(115,129,220)$

  $\gamma_{\rm EW} = 1.2$ and $\gamma = 1.4$

  $T_n = 134.3$ GeV



Type-Only-S<0

- At 142.7 GeV, the singlet field breaks through second order phase transition, while EW symmetry remains unbroken.

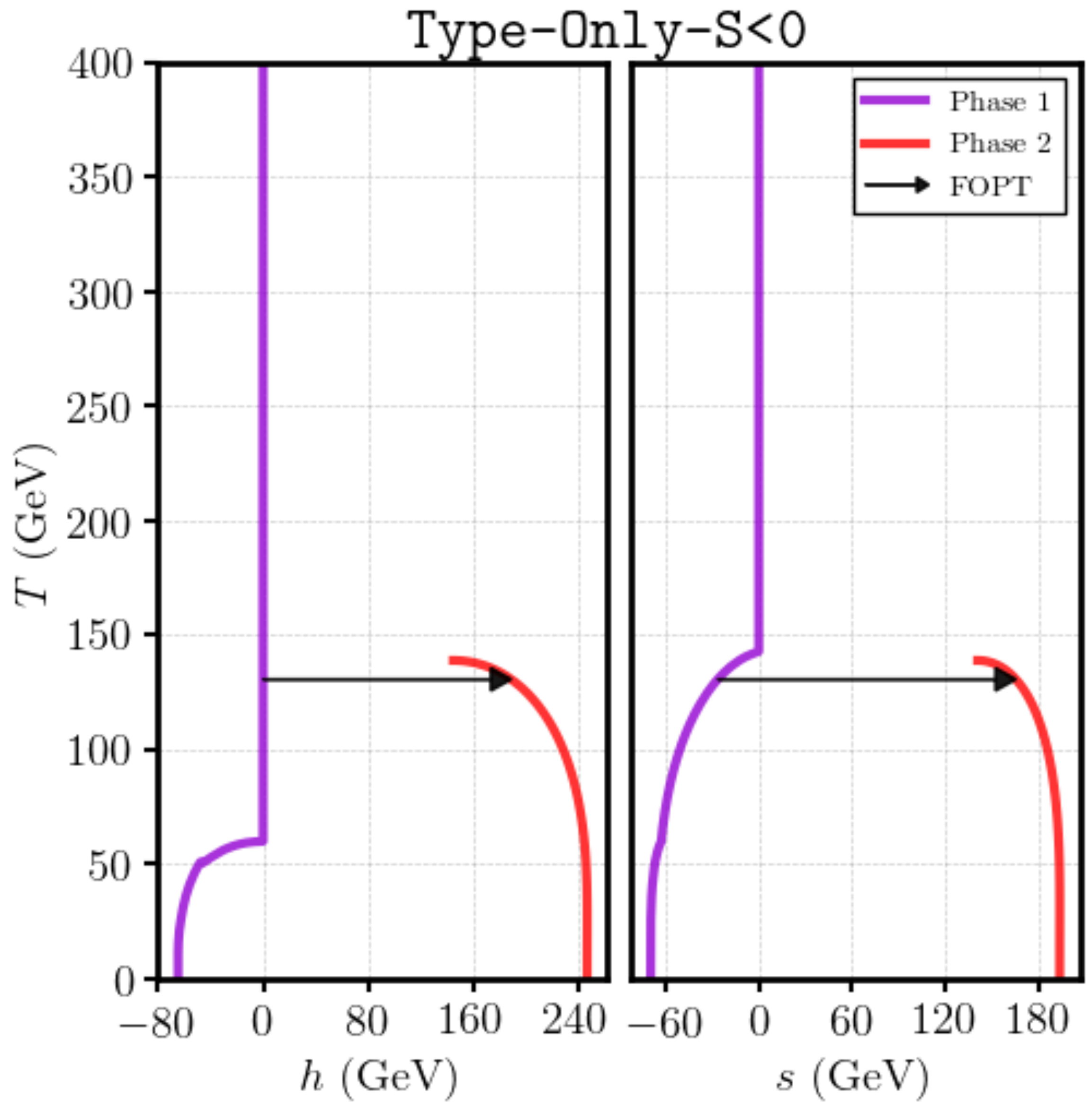
- The second possible phase transition:

$$T_c = 137.7 \text{ GeV}$$

$$V(0, 0, -26.3) = V(120, 147, 165)$$

$$\gamma_{\text{EW}} = 1.45 \text{ and } \gamma = 2.1$$

$$T_n = 107.2 \text{ GeV}$$



Type-Only-H

- At 115.2 GeV, the Higgs field obtains a VEV through second order phase transition, but the singlet VEV remains zero.
- The second possible phase transition

$$T_c = 113.6 \text{ GeV}$$

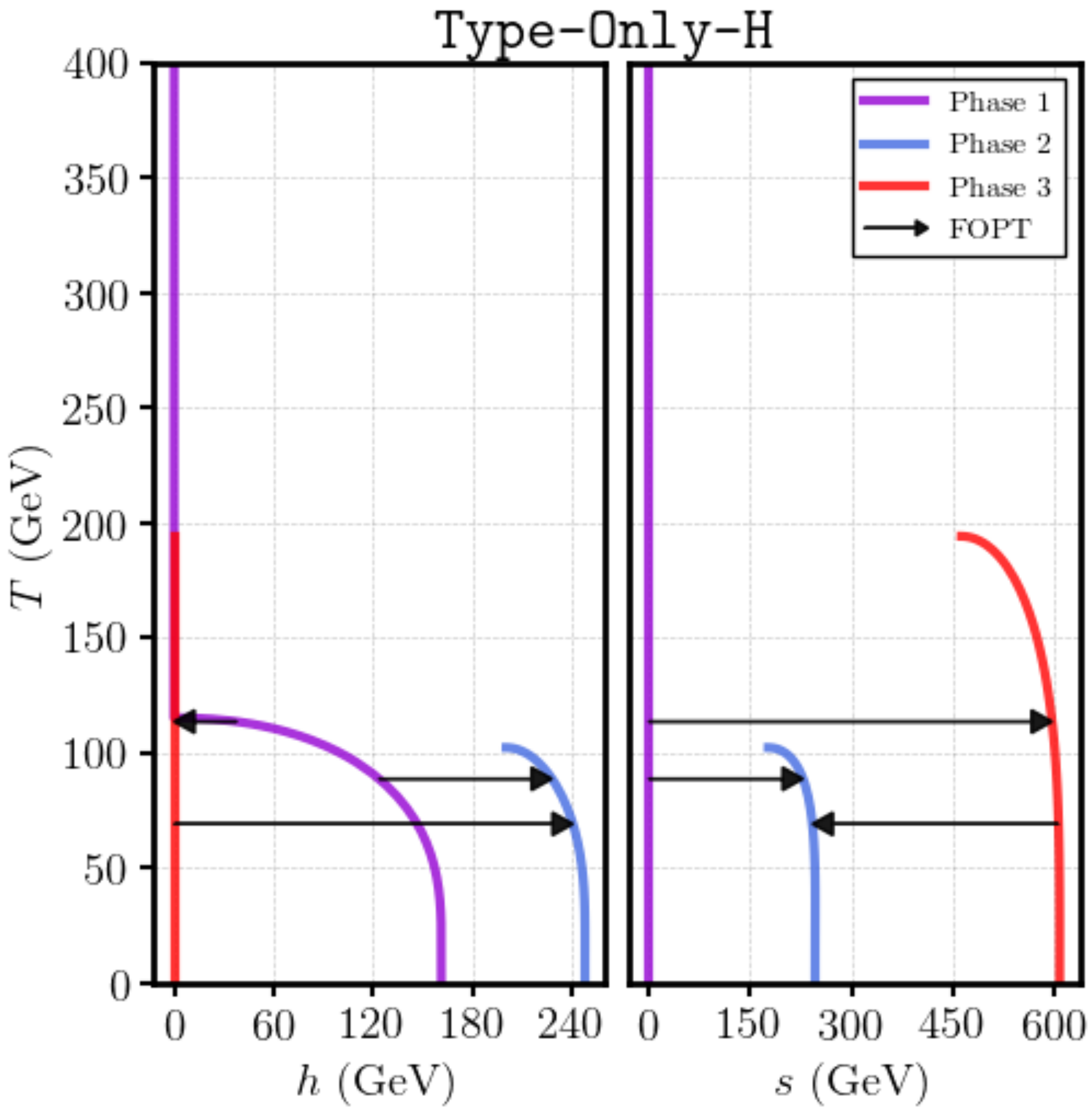
$$V(0,38,0) = V(0,0,597)$$

restores EW symmetry .

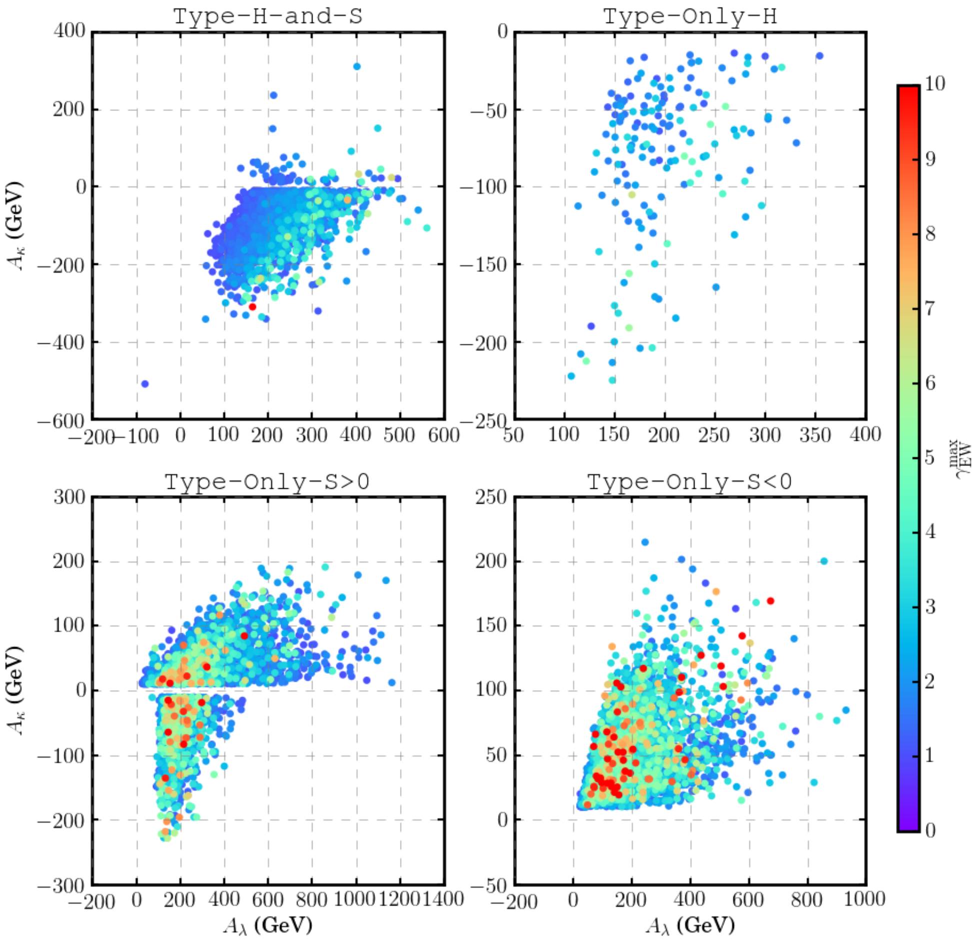
- The third possible phase transition:

$$T_c = 69.1 \text{ GeV}$$

$$V(0,0,607) = V(147,190,242)$$



Parameter space (preliminary)



$$\gamma_{\rm EW} \equiv \sqrt{(h_u^{(0)} - h_u^{(1)})^2 + (h_d^{(0)} - h_d^{(1)})^2}/T_c,$$

where $h_u^{(0)} = h_d^{(0)} = 0$, $s^{(0)}$ and $s^{(1)}$ can be any value.

$h_u^{(1)} > 0$ and $h_d^{(1)} > 0$

$$V_{\rm tree}(h_u, h_d, s) = \frac{1}{32}(g_1^2 + g_2^2)(h_u^2 - h_d^2)^2 + \frac{1}{4}\kappa^2 s^4 - \frac{1}{2}\lambda\kappa s^2 h_u h_d + \frac{1}{4}\lambda^2(h_u^2 h_d^2 + s^2(h_u^2 + h_d^2)) + \frac{\sqrt{2}}{6}\kappa A_\kappa s^3 - \frac{\sqrt{2}}{2}\lambda A_\lambda s h_u h_d + \frac{1}{2}m_d^2 h_d^2 + \frac{1}{2}m_u^2 h_u^2 + \frac{1}{2}m_s^2 s^2$$

Conclusions

PhaseTracer

- Calculate strengths of multistep phase transitions, and check phase structure.
- Relatively fast and stable, suitable for scan.

Electroweak transitions in NMSSM

- Four types of phase structure.
- Some interesting features.

Thanks for your attention!