Electroweak phase transition in the Georgi-Machacek model under constraints of LHC data

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- Intro : why GM model?
- The Georgi-Machacek model
- Constraints
- Simulation
- Electroweak phase transition

Why GM model?

- Keeping electroweak ρ parameter at unity
- Enhancement of Higgs signal strength in VV channels
- Generate tiny majorana mass for neutrinos
- More Higgs for new physics

The GM model

$$\mathcal{L}_{\rm GM} = \mathcal{L}_{\rm kin} + \mathcal{L}_Y + \mathcal{L}_\nu - V_H$$

$$\begin{aligned}V_H = {} & m_1^2 {\rm tr}(\Phi^\dagger\Phi) + m_2^2 {\rm tr}(\Delta^\dagger\Delta) + \lambda_1 {\rm tr}(\Phi^\dagger\Phi)^2 + \lambda_2[{\rm tr}(\Delta^\dagger\Delta)]^2 + \lambda_3 {\rm tr}[(\Delta^\dagger\Delta)^2] \\ & + \lambda_4 {\rm tr}(\Phi^\dagger\Phi){\rm tr}(\Delta^\dagger\Delta) + \lambda_5 {\rm tr}\left(\Phi^\dagger\frac{\tau^a}{2}\Phi\frac{\tau^b}{2}\right){\rm tr}(\Delta^\dagger t^a \Delta t^b) \\ & + \mu_1 {\rm tr}\left(\Phi^\dagger\frac{\tau^a}{2}\Phi\frac{\tau^b}{2}\right)(P^\dagger\Delta P)^{ab} + \mu_2 {\rm tr}\left(\Delta^\dagger t^a \Delta t^b\right)(P^\dagger\Delta P)^{ab},\end{aligned}$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

SU(2)L

SU(2)R

SU(2)L×SU(2)R

↓

Custodial SU(2)V

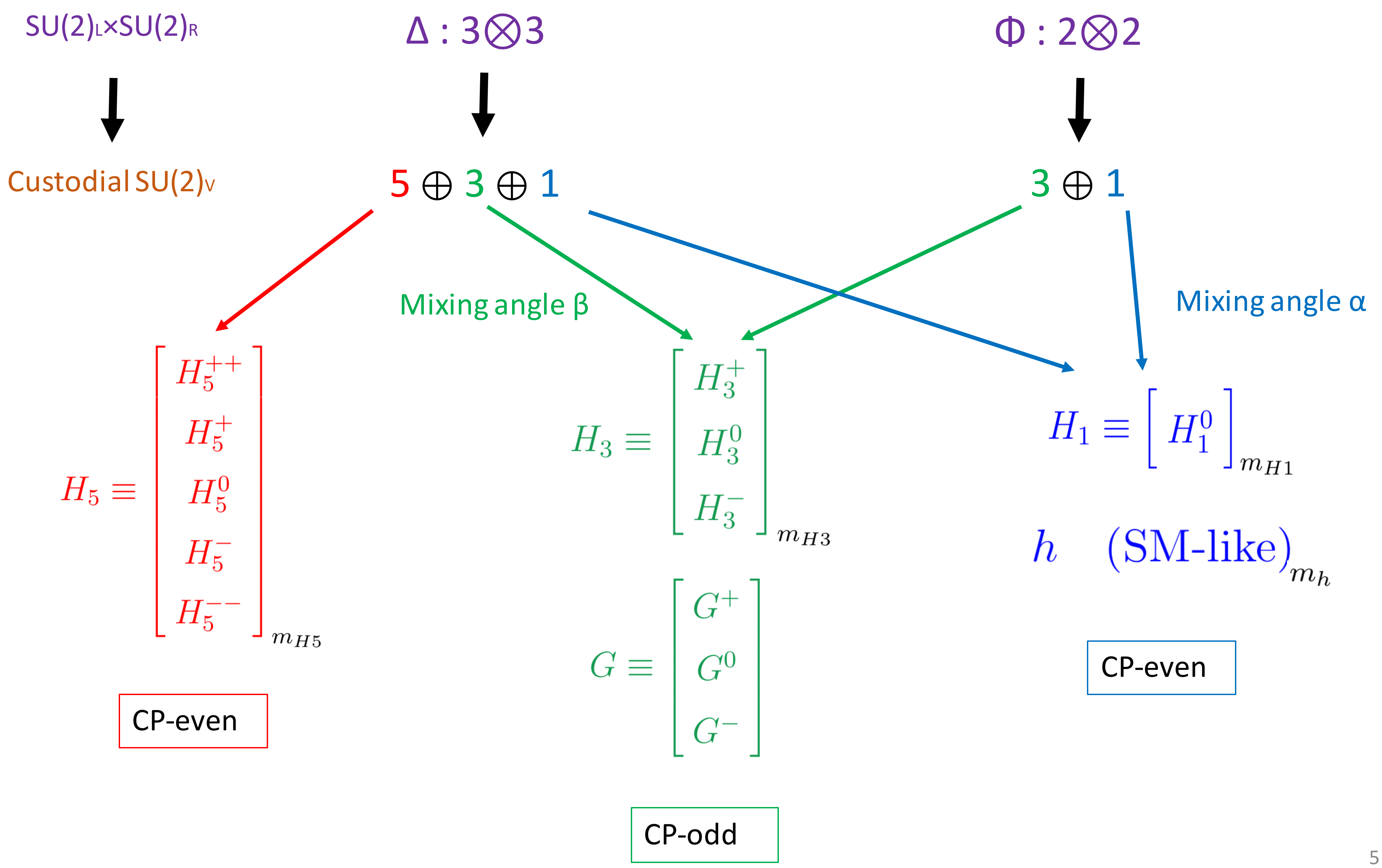
$$\phi^0 = \frac{1}{\sqrt{2}}(h_\phi + i a_\phi),$$

$$\chi^0 = \frac{1}{\sqrt{2}}(h_\chi + i a_\chi),$$

$$\xi^0 = h_\xi,$$

$$\langle h_\phi\rangle = v_\Phi, \quad \langle h_\chi\rangle = \sqrt{2}v_\Delta, \quad \langle h_\xi\rangle = v_\Delta$$

$$v = \sqrt{v_\phi^2 + 8v_\Delta^2}$$



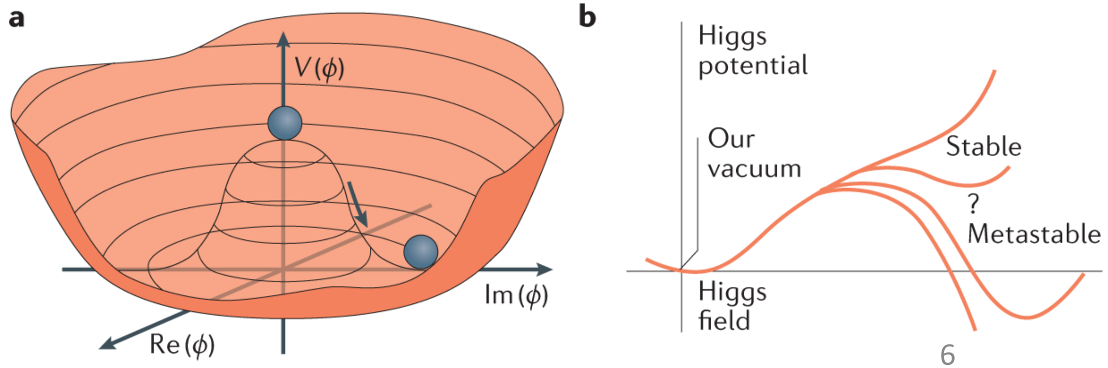
SU(2)L×SU(2)R
Custodial SU(2)V
Δ : 3⊗3
5 ⊕ 3 ⊕ 1
Φ : 2⊗2
3 ⊕ 1
Mixing angle β
Mixing angle α
$H_5 \equiv \begin{bmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{bmatrix}_{m_{H5}}$
CP-even
$H_3 \equiv \begin{bmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{bmatrix}_{m_{H3}}$
$G \equiv \begin{bmatrix} G^{+} \\ G^{0} \\ G^{-} \end{bmatrix}$
CP-odd
$H_1 \equiv \begin{bmatrix} H_1^{0} \end{bmatrix}_{m_{H1}}$
$h \quad (\text{SM-like})_{m_h}$
CP-even

Constraints: theoretical

- Perturbative unitarity conditions
- Bounded from below conditions
- Tadpole conditions:

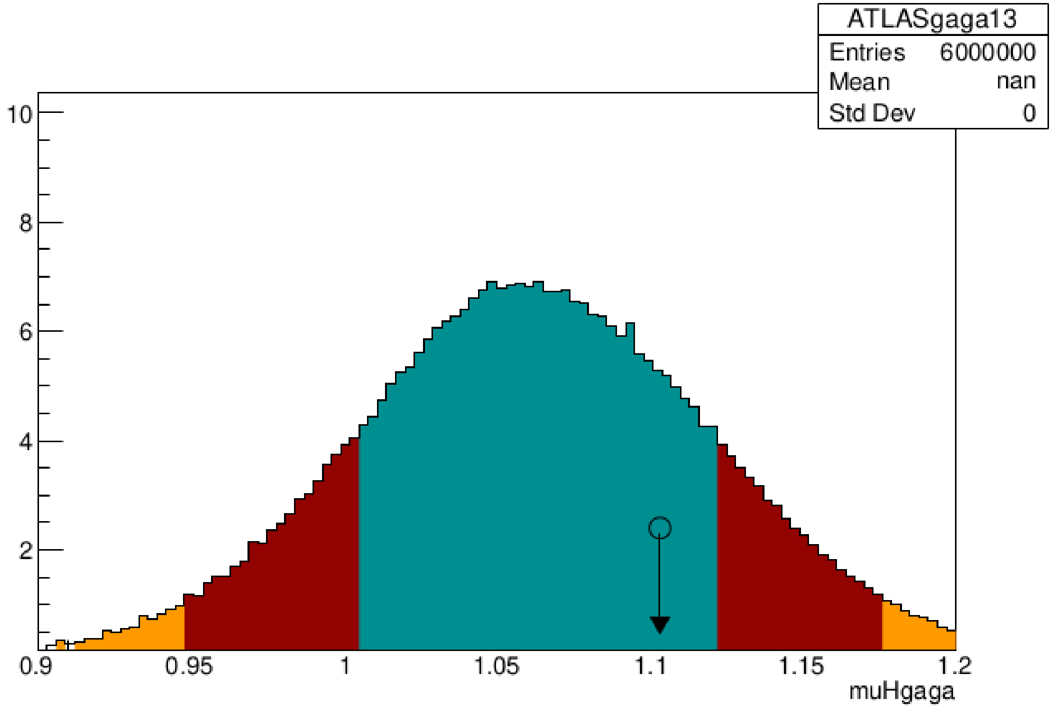
$$\frac{\partial V(\Phi,\Delta)}{\partial h_\phi} = \frac{\partial V(\Phi,\Delta)}{\partial h_\chi} = \frac{\partial V(\Phi,\Delta)}{\partial h_\xi} = 0$$

- Custodial symmetry preservation



Constraints: Higgs signal strength

- ATLAS & CMS
  - Energy threhold: 7, 8, 13 TeV
  - Process: ggF, VBF, Vh, tth
  - Channels: bb, WW, ττ, ZZ, γγ, Zγ, μμ
- CDF & D0
  - Energy threhold: 2 TeV
  - Process: Vh, tth
  - Channels: bb



Constraints: direct searches

Neutral heavy Higgs bosons

- ϕ_0: tt, bb, ττ, γγ, Zγ, WW, VV, $\phi'_0 Z$
- H_1: hh, hZ
- H_3: hZ, $H_1 Z$

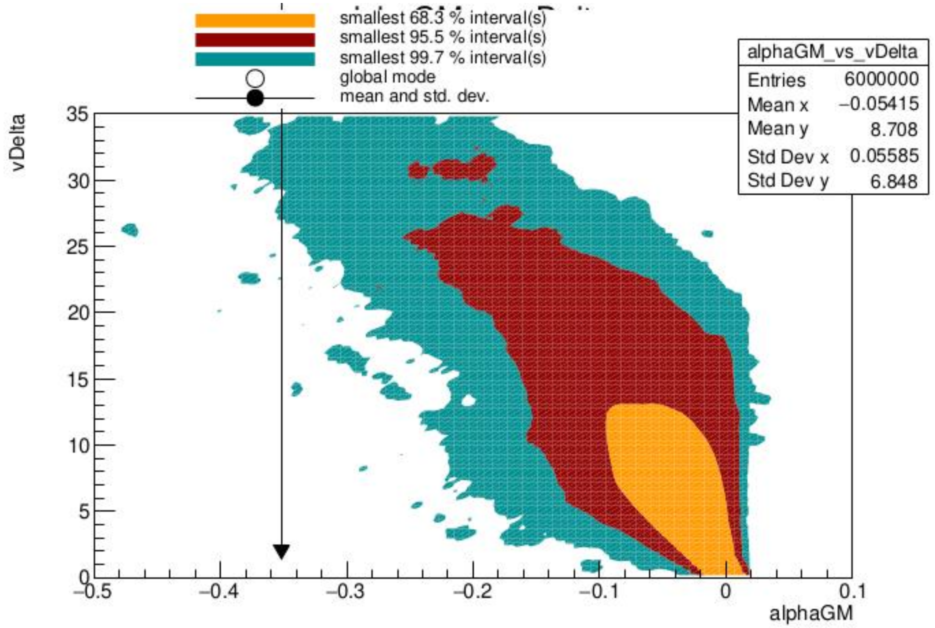
Charged heavy Higgs bosons

- $H_3^{\pm}$: $\tau^{\pm}\nu$, tb
- $H_5^{\pm}$: $W^{\pm}Z^{\pm}$
- $H_5^{\pm\pm}H_5^{\mp\mp}$: $(W^{\pm}W^{\pm})(W^{\mp}W^{\mp})$
- $H_5^{\pm\pm}$: $(W^{\pm}W^{\pm})$

HEPfit

Bayesian MCMC:

$$P(\vec{\mathbf{x}}|D) = \frac{P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})}{\int P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})d\vec{\mathbf{x}}}$$



Parameters	Scale	Shape	Error/Range
Input		Priors	
m_2^2 / GeV^2	log	Gaussian	$(10^{-6}, 10^6)$
λ_2	linear	Uniform	$(-3, 3)$
λ_3	linear	Uniform	$(-3, 3)$
λ_4	linear	Uniform	$(-3, 3)$
λ_5	linear	Uniform	$(-12, 12)$
μ_1 / GeV	linear	Gaussian	$(-10^3, 10^3)$
μ_2 / GeV	linear	Gaussian	$(-10^3, 10^3)$
Output		Posteriors	
$m_{H_{1,3,5}}$/GeV	reals	Flat	$(50, 200)$

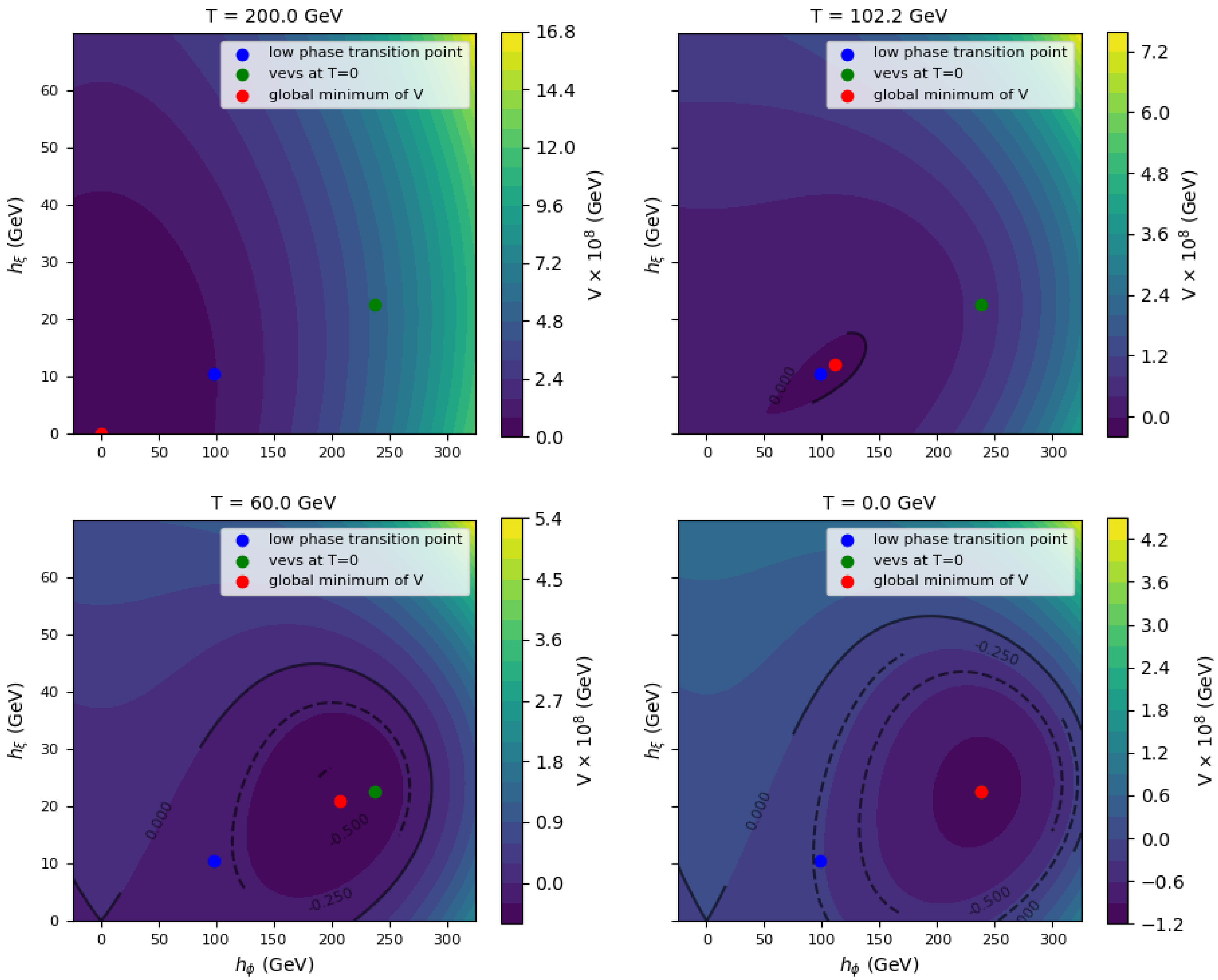
Electroweak phase transition

high-temperature expansion:

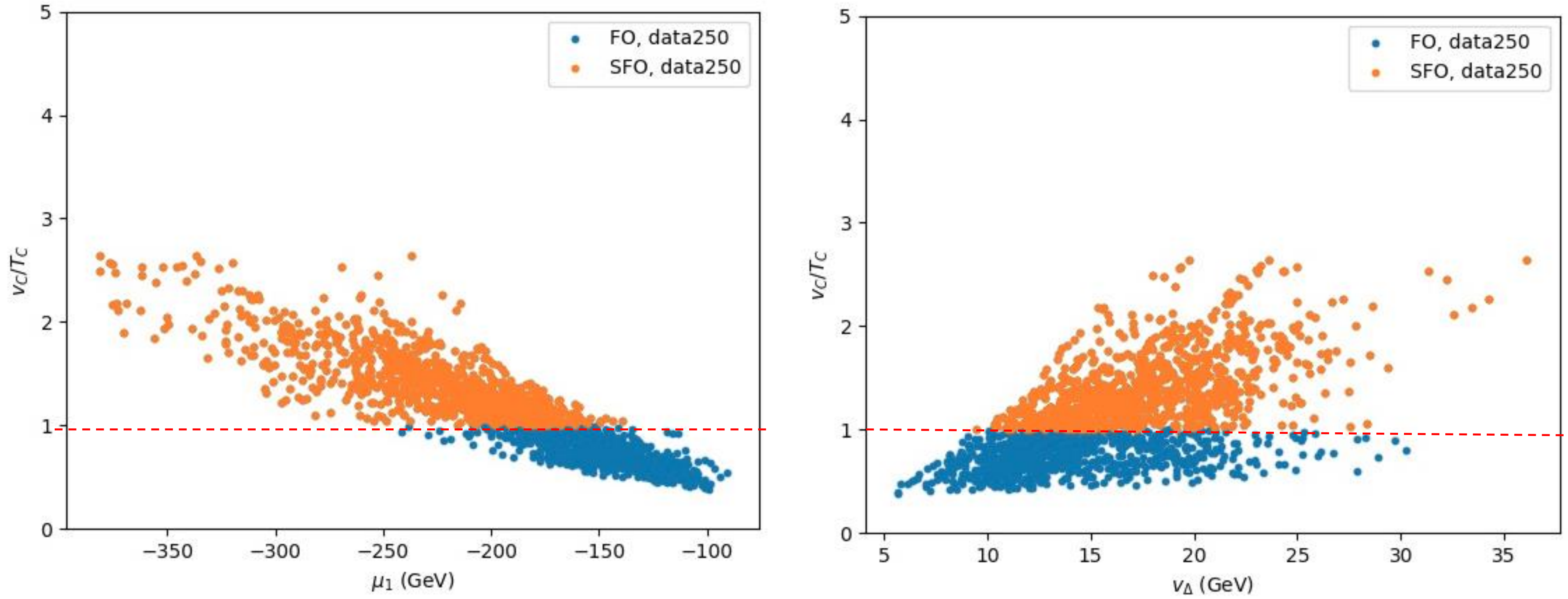
$$V_T = V_0 + \frac{c_\phi T^2}{2} h_\phi^2 + \frac{c_\xi T^2}{2} h_\xi^2 + \frac{c_\chi T^2}{2} h_\chi^2$$

$$c_\phi = \frac{3g^2}{16} + \frac{g'^2}{16} + \lambda_1 + \frac{3\lambda_4}{4} + \frac{1}{4} y_t^2 \csc^2 \beta$$
$$c_\xi = \frac{g^2}{2} + \frac{11\lambda_2}{6} + \frac{7\lambda_3}{6} + \frac{\lambda_4}{3}$$
$$c_\chi = \frac{g^2}{2} + \frac{g'^2}{4} + \frac{11\lambda_2}{6} + \frac{7\lambda_3}{6} + \frac{\lambda_4}{3}$$

$\lambda_1 = 0.03521$
$\lambda_2 = -0.0106$
$\lambda_3 = 0.122212$
$\lambda_4 = 0.176963$
$\lambda_5 = 0.937933$
$\mu_1 = -137.967$ (GeV)
$\mu_2 = -22.5348$ (GeV)
$\alpha = -0.06368$
$v_\Delta = 22.6364$ (GeV)
$m_{H1} = 289.333$ (GeV)
$m_{H3} = 252.872$ (GeV)
$m_{H5} = 115.005$ (GeV)
$T_c = 102.2332$ (GeV)



Finding the strong first-order phase transition



Conclusion

- Within LHC data, the strong first-order phase transition is possible.
- No two-step first-order phase transition was found.

Outlook

- Explore more valid phase space for strong first-order PT.
- Research on determinant/phenomenon for SFOPT.
- Investigate the gravitational wave produced by SFOPT.