HHH, the Higgs Potential, and Baryogenesis

Osama Karkout

Working with
Jorinde van de Vis, Andreas Papaefstathiou, Gilberto Tetlalmatzi, Tristan du Pree, Marieke Postma, Carlo Pandini

The Higgs sector: why?

For massive particles + gauge symmetry:

$$\mathscr{L} \in |D_\mu \phi|^2$$

$$D_\mu = \partial_\mu + ieA_\mu$$

Gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

$$\phi(x) \rightarrow e^{i\alpha(x)}\phi(x)$$

→

$$\Delta\mathscr{L} = 0$$

Gauge sym.

$$< \phi(x) > = v$$

vacuum expectation value
vev

→

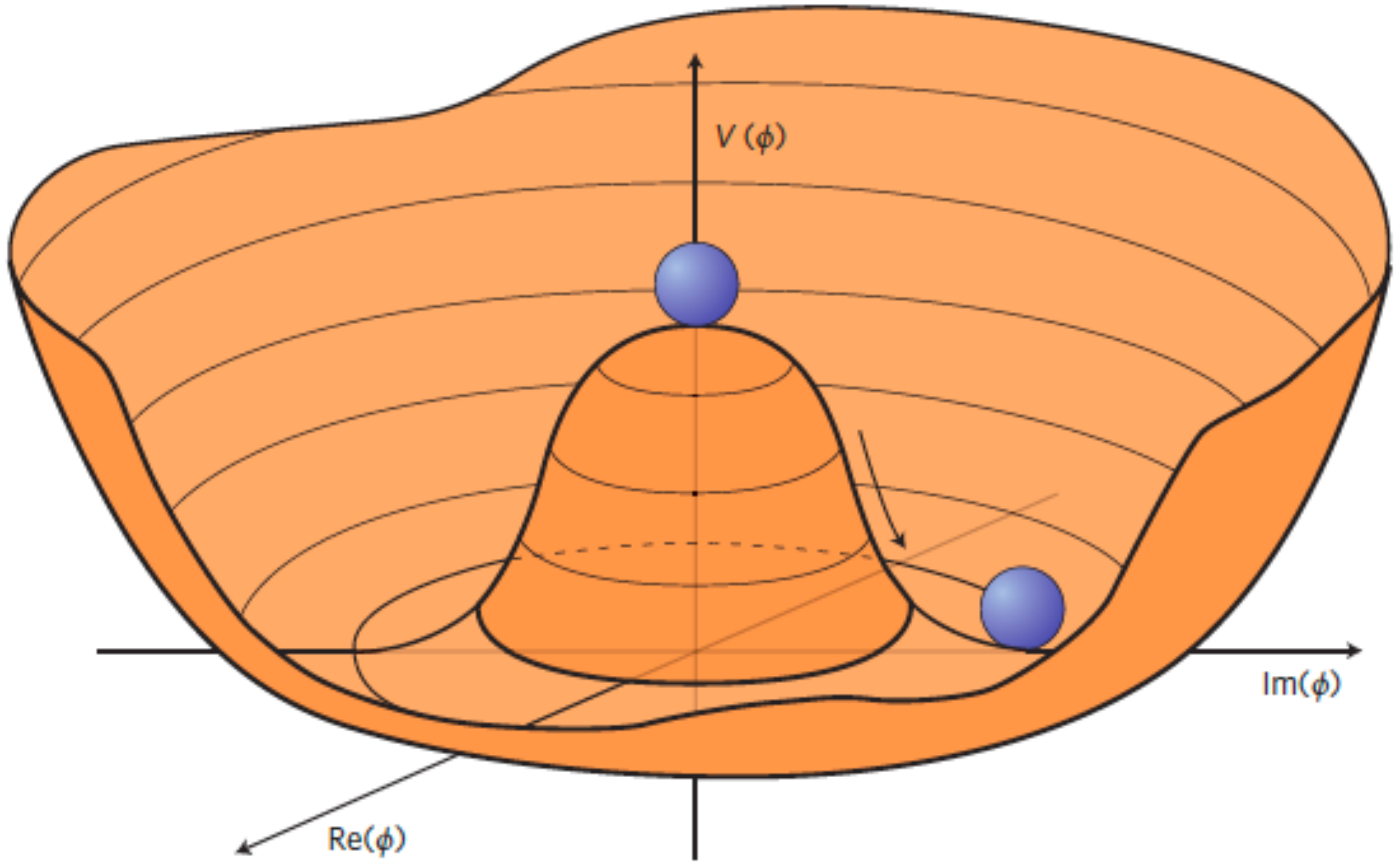
$$|D_\mu \phi|^2 = e^2 v^2 A_\mu A^\mu + \ldots$$

Mass term for gauge boson!

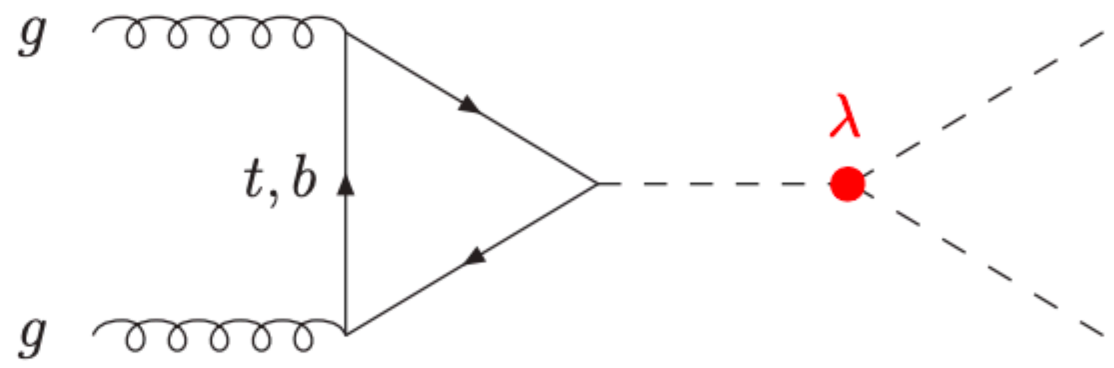
The Higgs sector: why?

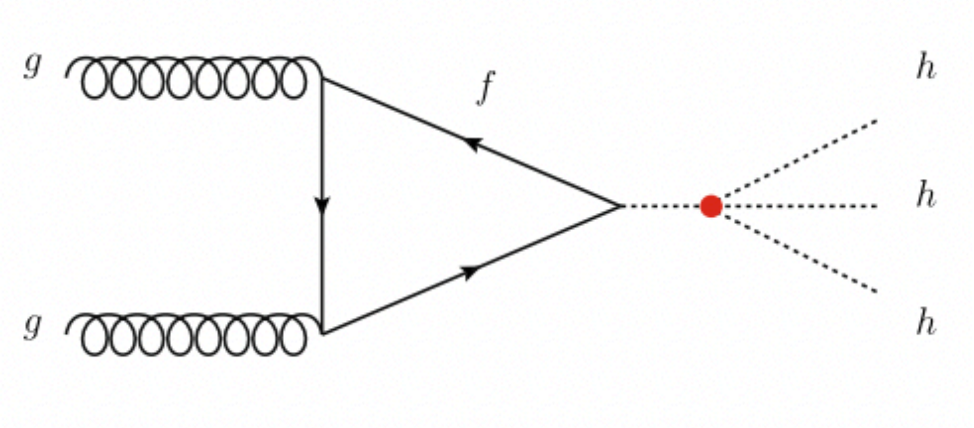
Notice: **no Higgs potential mentioned!**
Unsatisfied with a non-zero vev? Introduce a Higgs sector.
Minimal needed: scalar field with renormalizable potential leading to a vev:

$$\mathscr{L}_\phi = |D_\mu \phi|^2 - V(\phi^\dagger \phi)$$
$$V(\phi^\dagger\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$



$$\phi(x) = \frac{1}{\sqrt{2}}[0, \ v + h(x)]$$
$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$





The Higgs sector: why?

Peskin and Schroeder:

However, there are many other quantum field theories that break $SU(2)$ spontaneously while leaving another global $SU(2)$ symmetry unbroken.

The question of the nature of the Higgs sector and the explicit mechanism of $SU(2) \times U(1)$ breaking is probably the most pressing open problem in the theory of elementary particles.

Since then, one scalar d.o.f found
Still much more to know!

$$V(h, ?) = \frac{1}{2} m_h^2 h^2 + \ldots ?$$

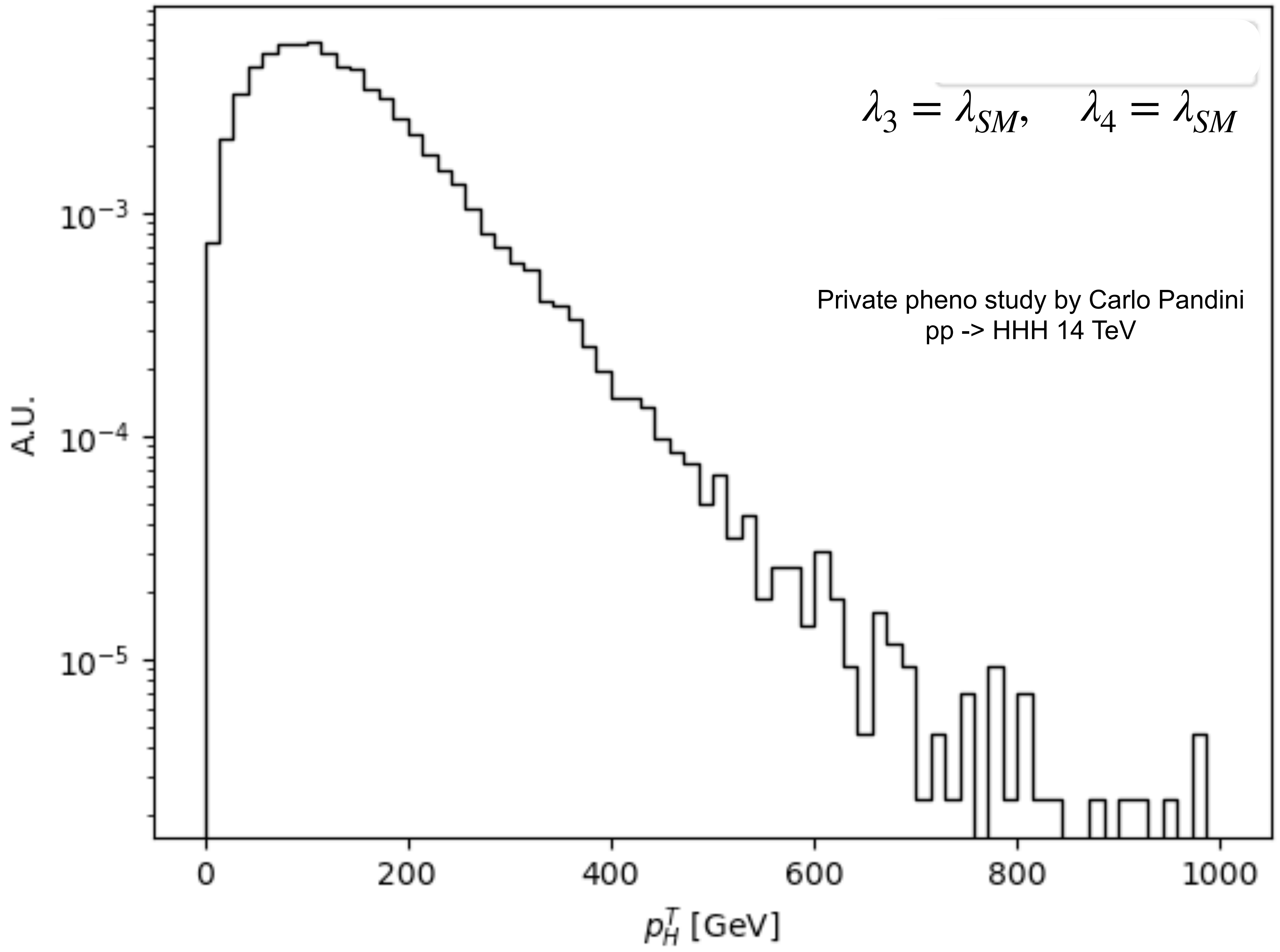
Many possible Higgs sectors (composite Higgs, susy, Higgs portal extensions, etc)
Why? Many reasons (naturalness, hierarchy, my favourite: why not)
My second favourite: **baryogenesis**.

The Higgs sector: how?

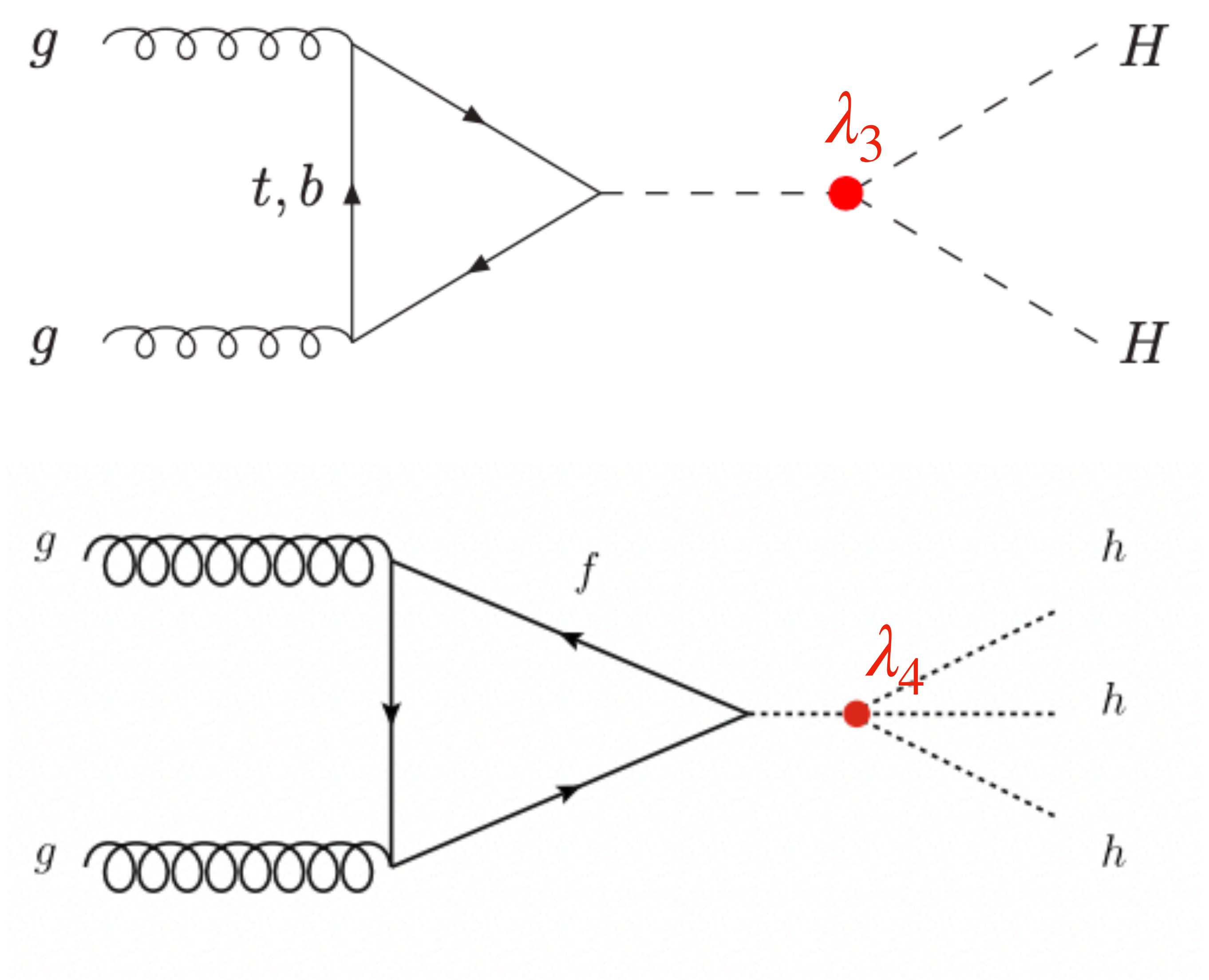
$$V(h,?) = \frac{1}{2}m_h^2h^2 + \ldots ?$$

$$-\mathscr{L}_{SMEFT} \in \frac{1}{2}m_h^2h^2 + \boxed{\lambda_3 v h^3} + \boxed{\frac{1}{4}\lambda_4 h^4}$$

HH HHH



SM predicts HH and HHH production



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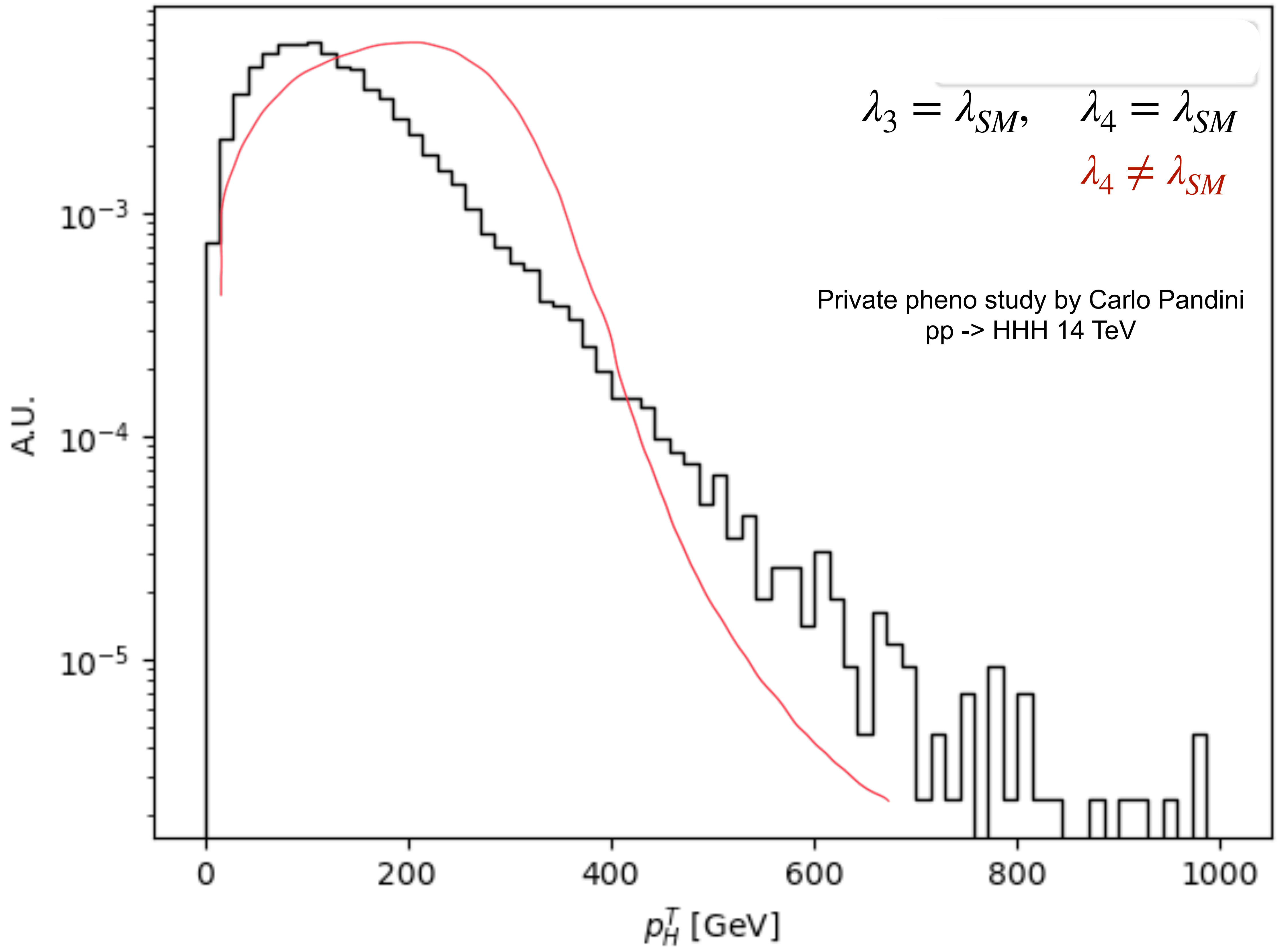
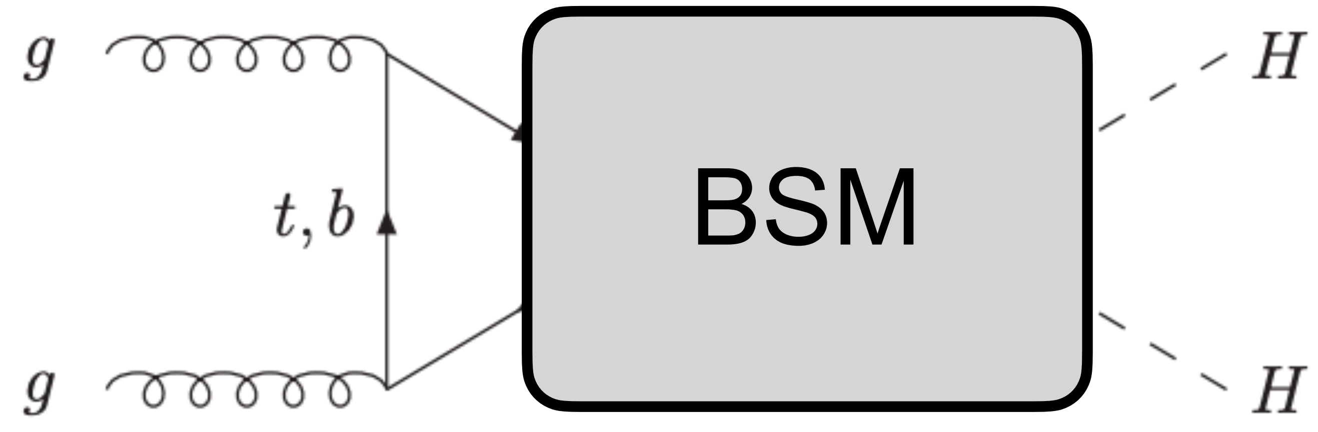
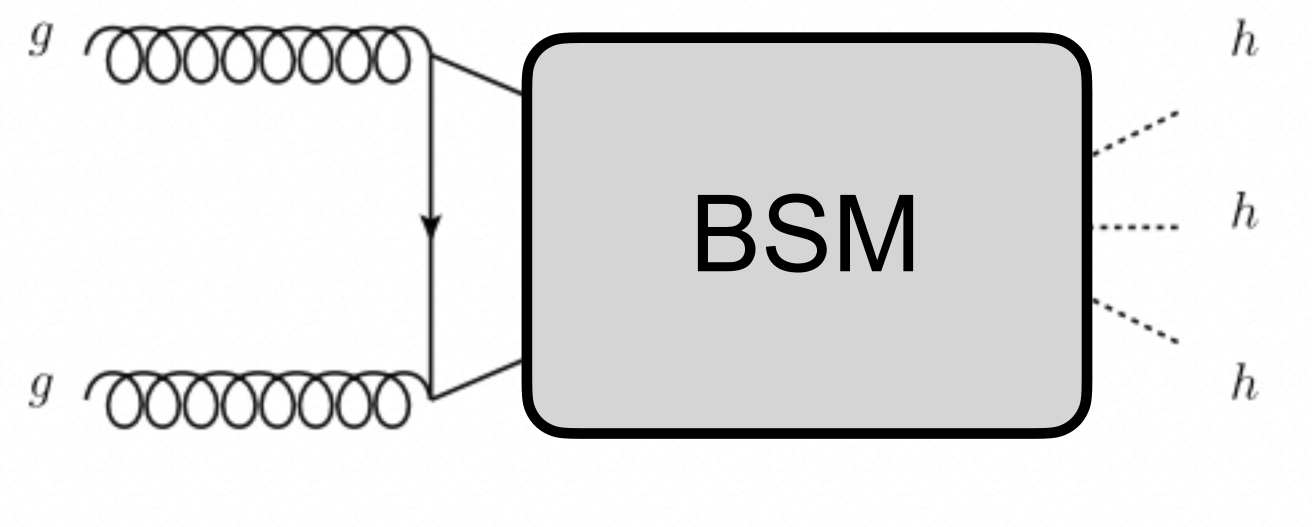


BSM can appear in HH and HHH production

As modification of λ_3 and λ_4





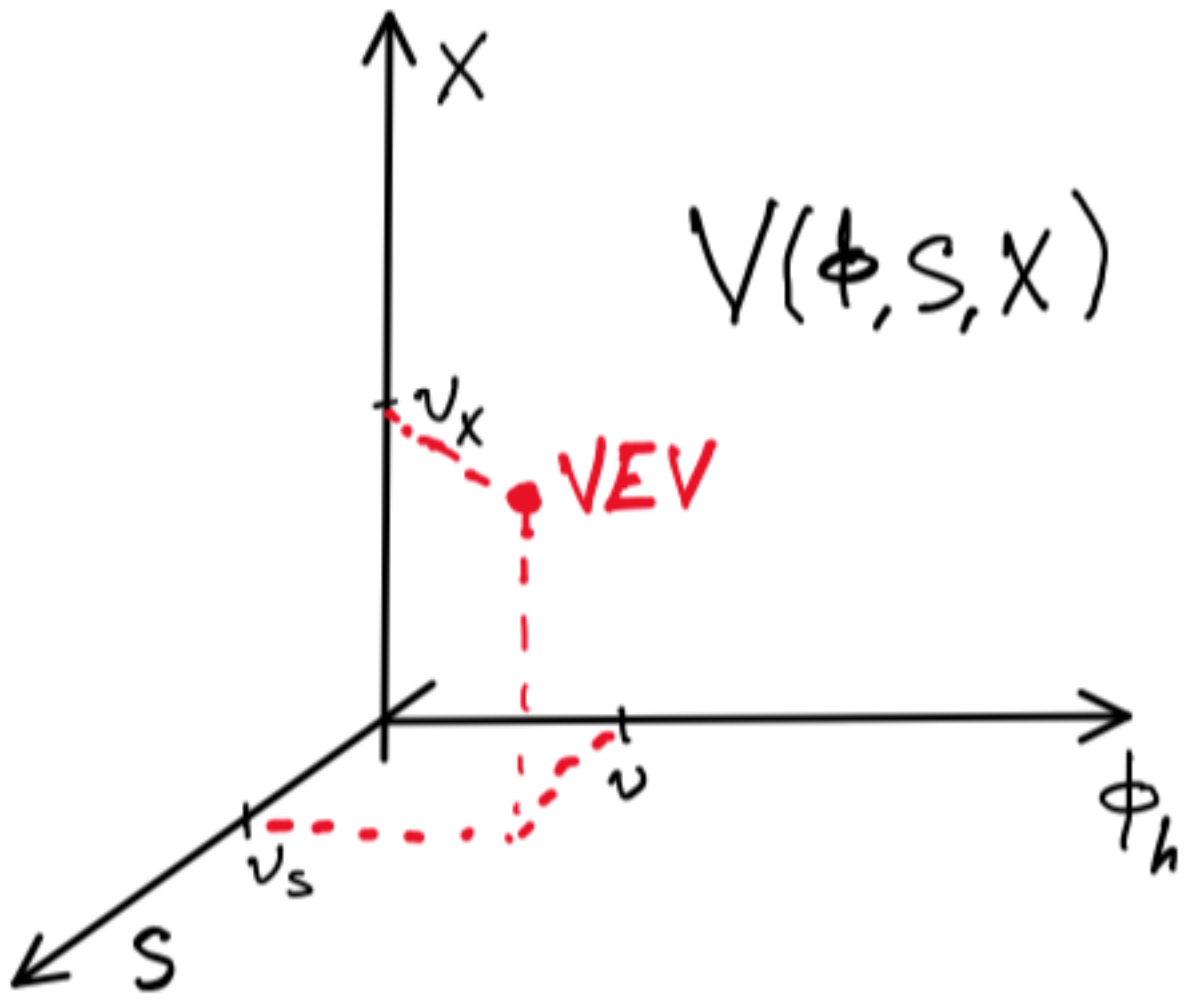
The Higgs sector through HHH

$$V(h,?) = \frac{1}{2}m_h^2 h^2 + \ldots ?$$

BSM model predicting large HHH: TRSM.

SM + two singlets coupling to the Higgs doublet.

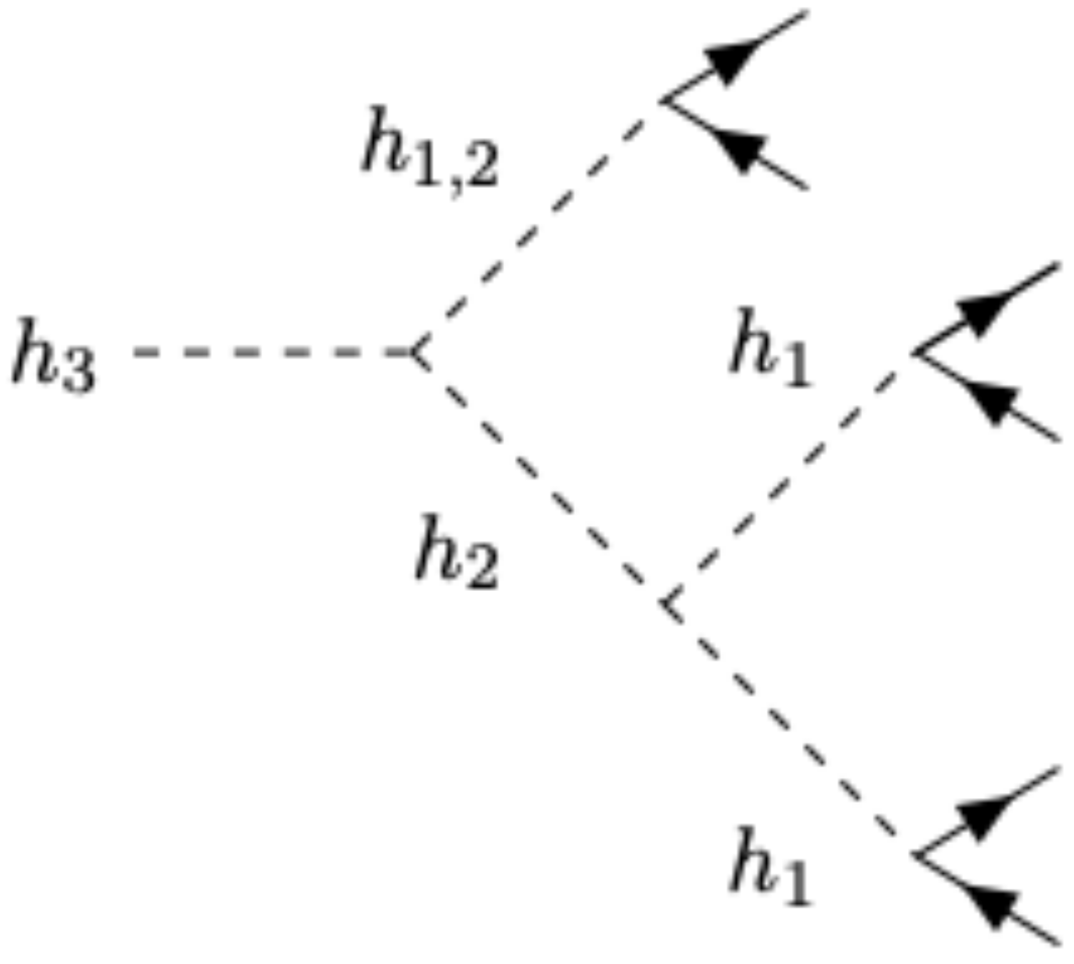
$$V = \mu_\Phi^2 \Phi^\dagger\Phi + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S}\Phi^\dagger\Phi S^2 + \lambda_{\Phi X}\Phi^\dagger\Phi X^2 + \lambda_{SX} S^2 X^2 \,.$$



Mixing:

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{\phi_S + v_S}{\sqrt{2}}, \quad X = \frac{\phi_X + v_X}{\sqrt{2}}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix}$$



h1 can be our scalar particle of 125 GeV

Tania Robens,[1,*] Tim Stefaniak,[2,†] and Jonas Wittbrodt[2,‡]

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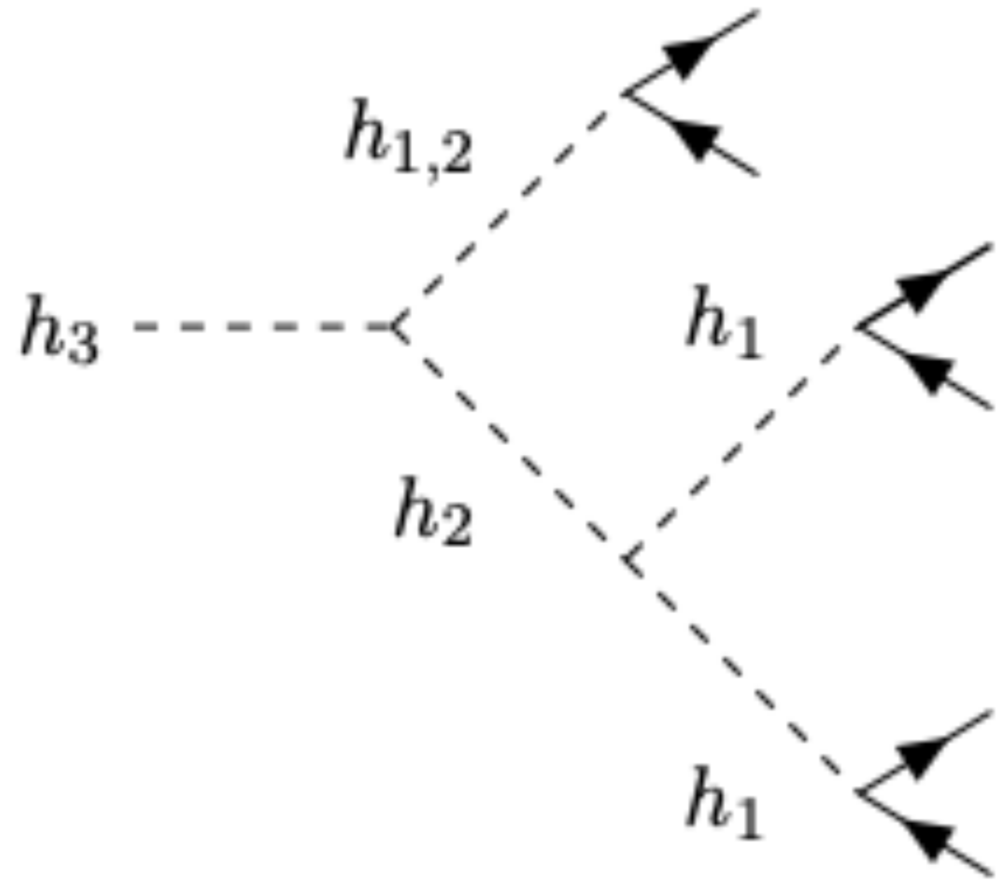
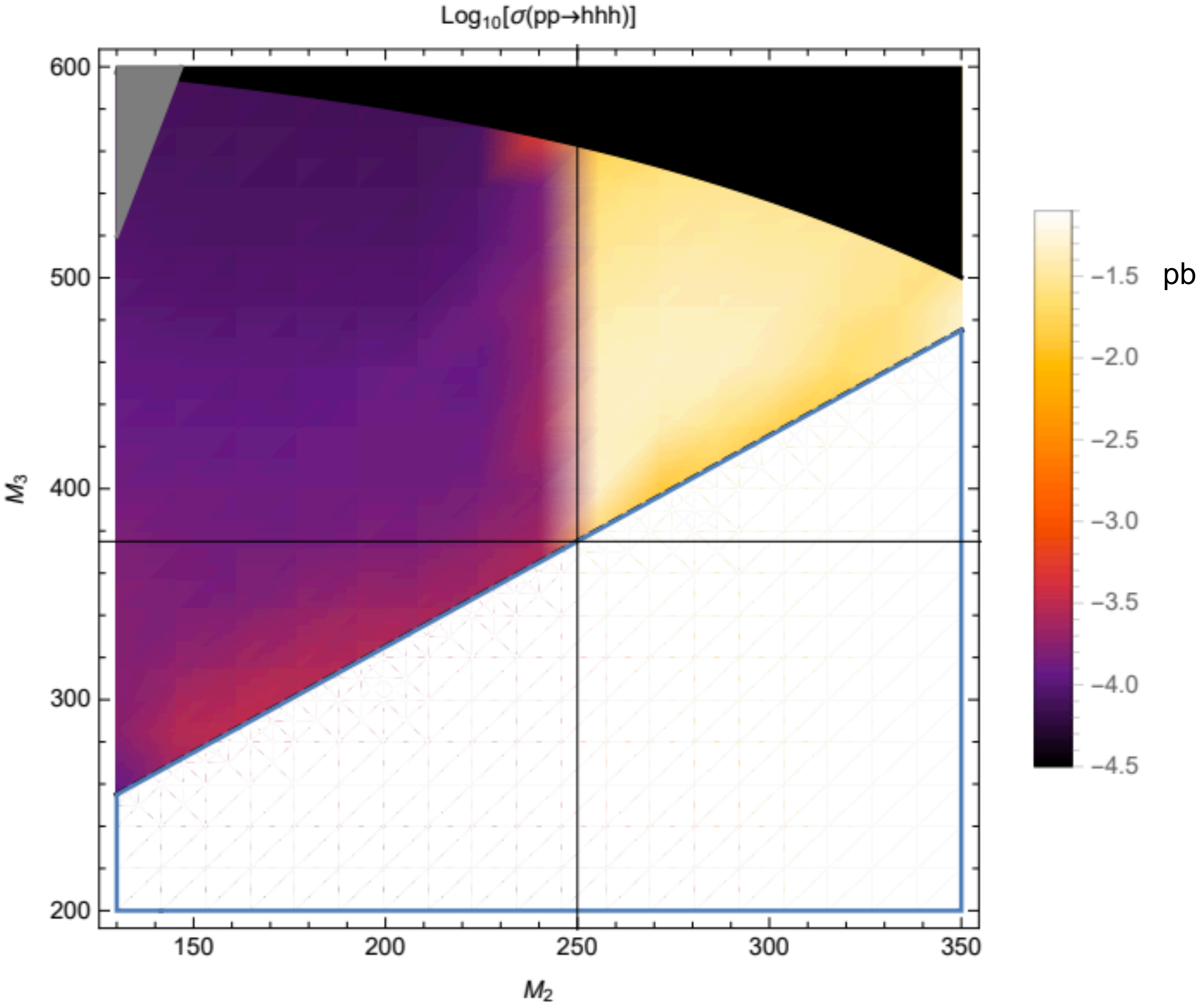
xsec ~ 50 fb (similar to HH production in SM)
=> constrained via HHH



h1 can be our scalar particle of 125 GeV

Andreas Papaefstathiou,[a,b] **Tania Robens,**[c] **Gilberto Tetlalmatzi-Xolocotzi,**[d]

TRSM BP3 @14TeV:



Baryogenesis

Problem: we exist :(

=> need for dynamical mechanism to generate matter-antimatter asymmetry.

Sakharov conditions:

1. Baryon number violation
2. Break C and CP symmetries
3. Out of thermal equilibrium

https://arxiv.org/pdf/hep-ph/0609145.pdf
https://arxiv.org/pdf/2301.05197.pdf
http://www.laine.itp.unibe.ch/cosmology/lec09.pdf

BARYOGENESIS

James M. Cline

Baryogenesis

Sakharov conditions:

1. Baryon number violation

$$\Delta B = \Delta L = \pm 3 \qquad (2.2)$$

In SM: left handed B+L violated!

$$E_{sph} \sim \frac{8\pi v}{g_w}$$

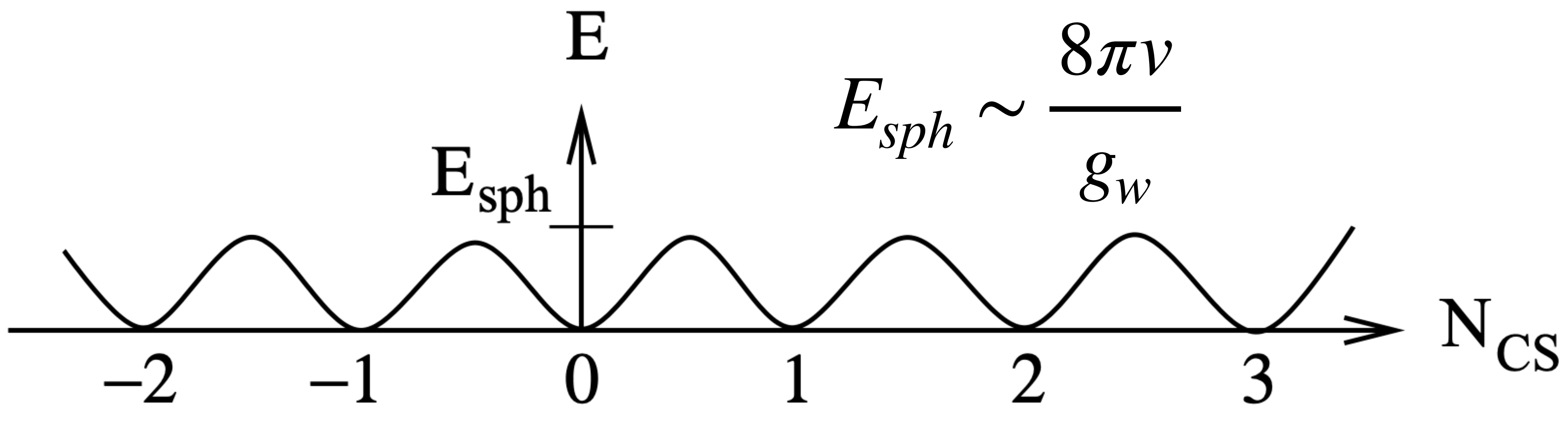


Fig. 8. Energy of gauge field configurations as a function of Chern-Simons number.

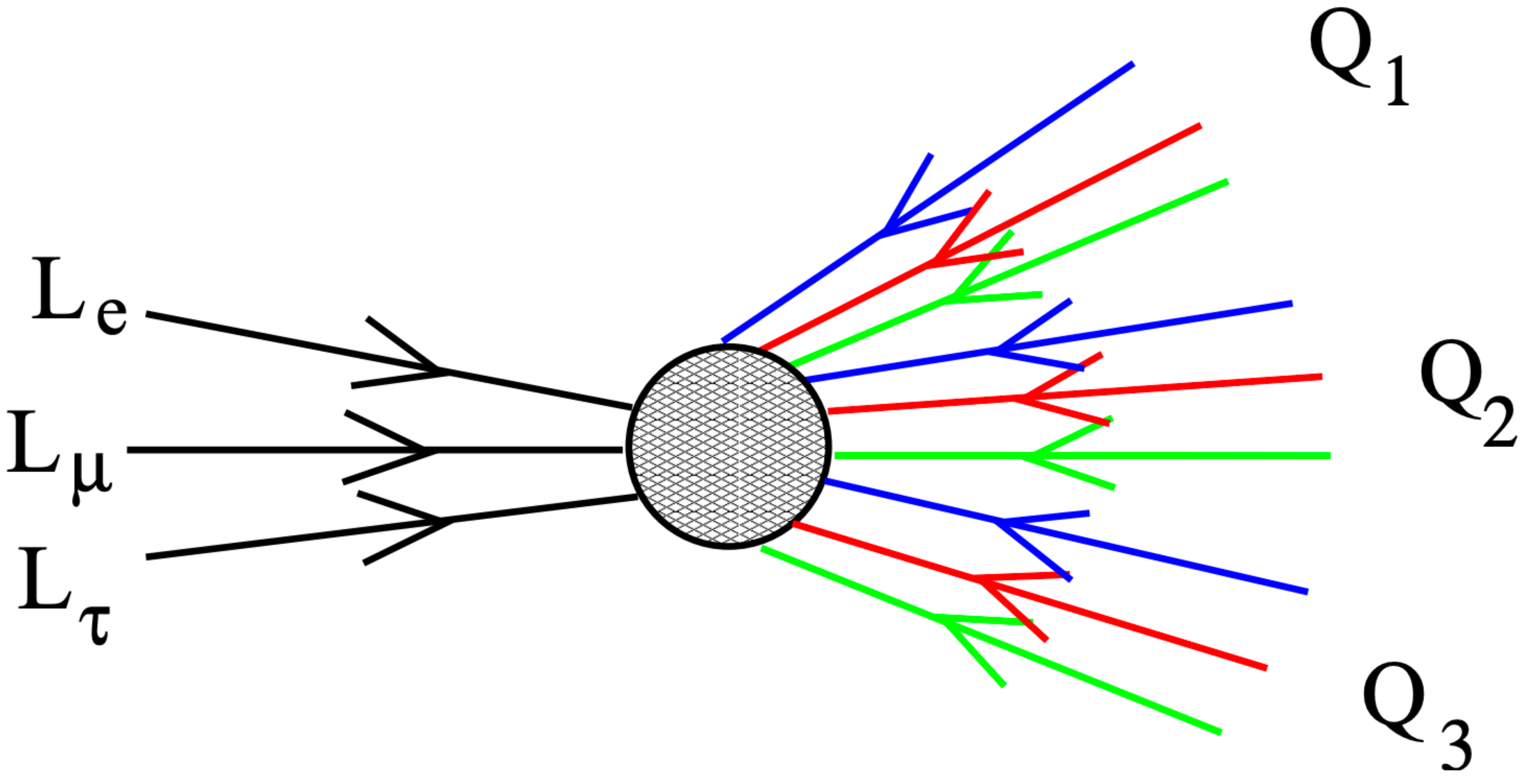


Fig. 4. The sphaleron.

Thermal tunnelling to another vacuum:

$$\Gamma_{sph}(T) \sim e^{-E_{sph}/T} \sim e^{-v/T}$$

Baryogenesis

Sakharov conditions:

1. Baryon number violation
2. Break C and CP symmetries

$$\begin{aligned} C: &\quad q_L \to \bar{q}_L \\ CP: &\quad q_L \to \bar{q}_R \end{aligned}$$

In SM: CP violation in CKM matrix. Possibly not enough though! BSM CP violation is more than welcomed.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_2 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

Baryogenesis

Sakharov conditions:
1. Baryon number violation
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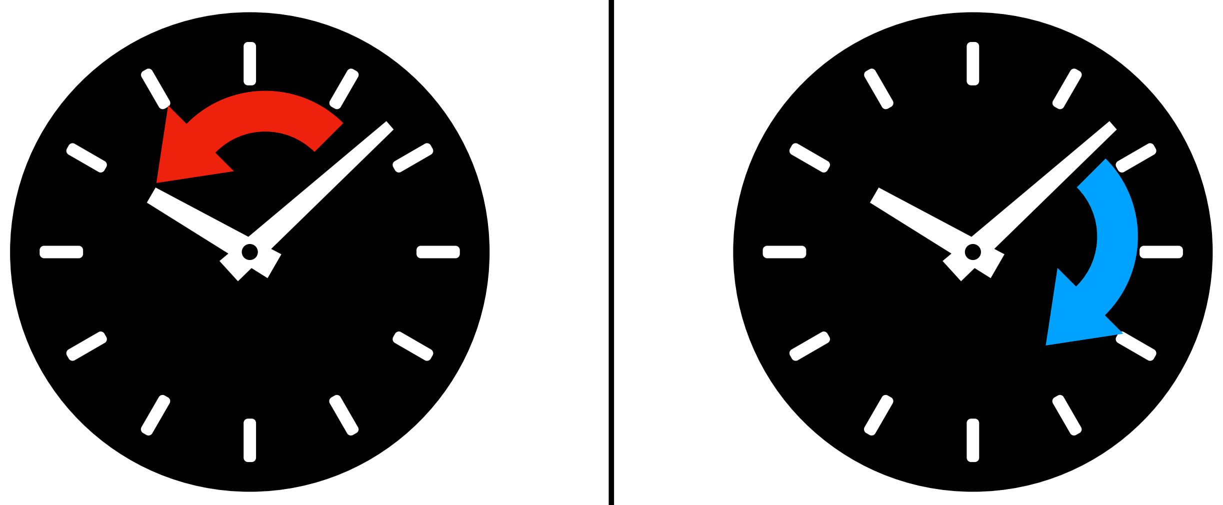


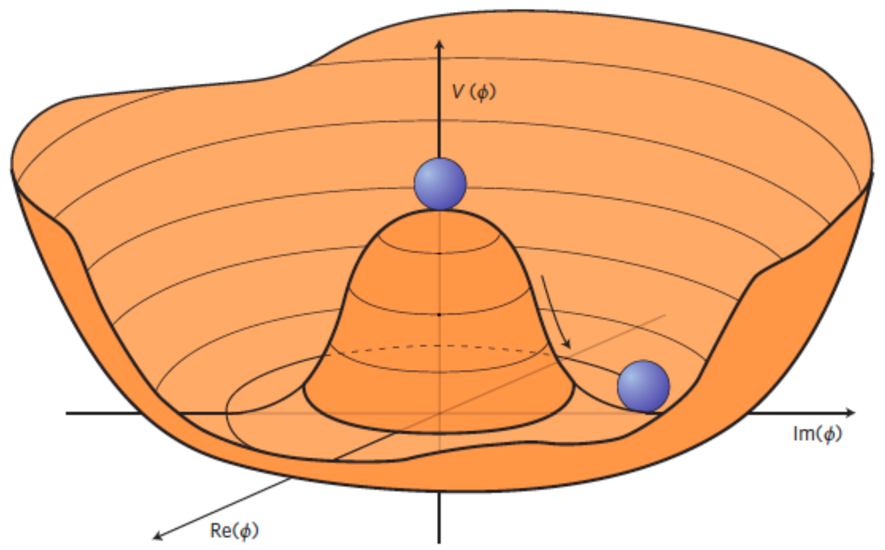
	X	$\leftrightarrow$ $Y + B$
Energy:	m_X	T

Out of thermal equilibrium when $T < m_X$

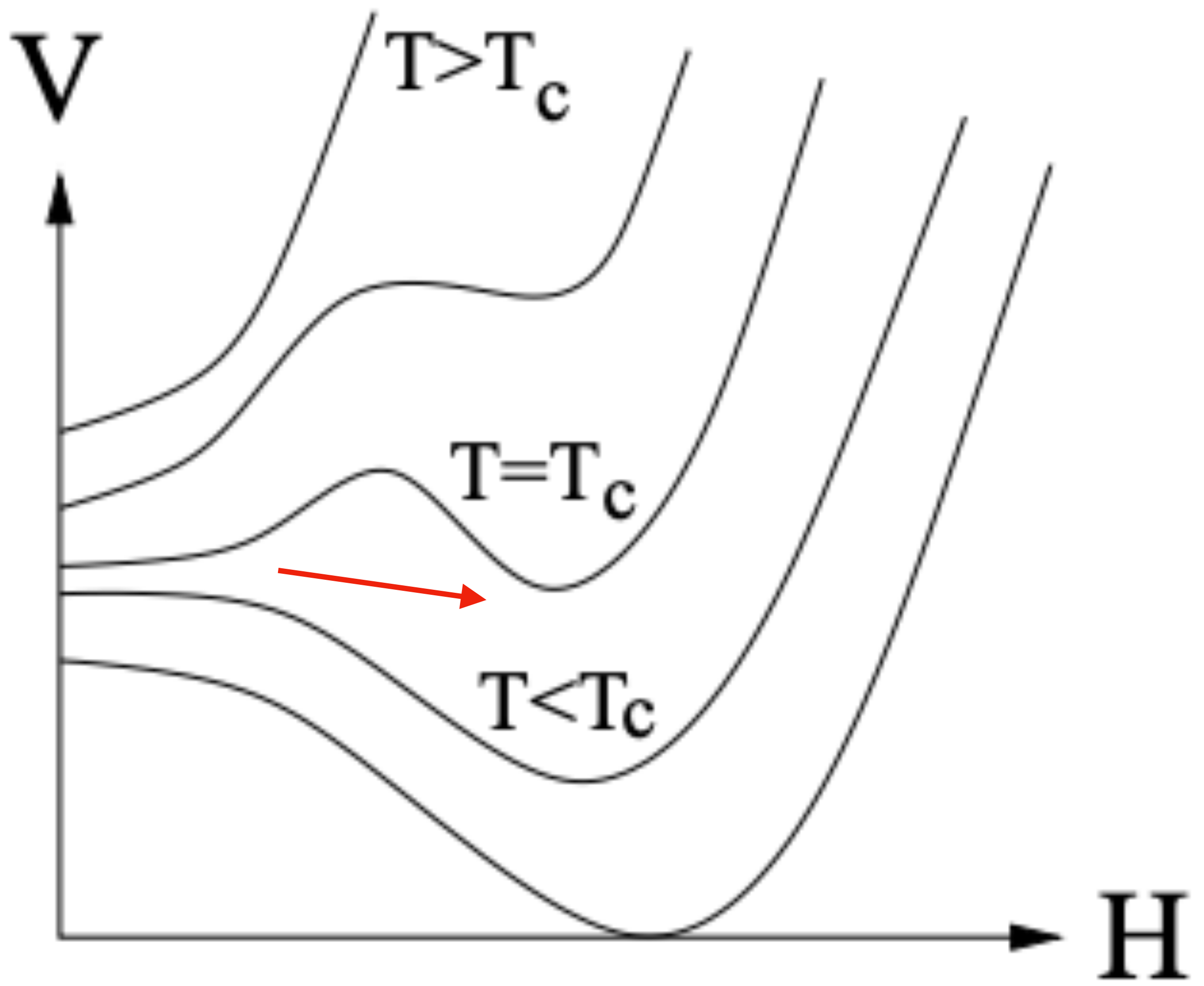
$Y + B \rightarrow X$ surpassed by $e^{-m_X/T}$

Electroweak symmetry breaking (EWSB) is a phase transition!

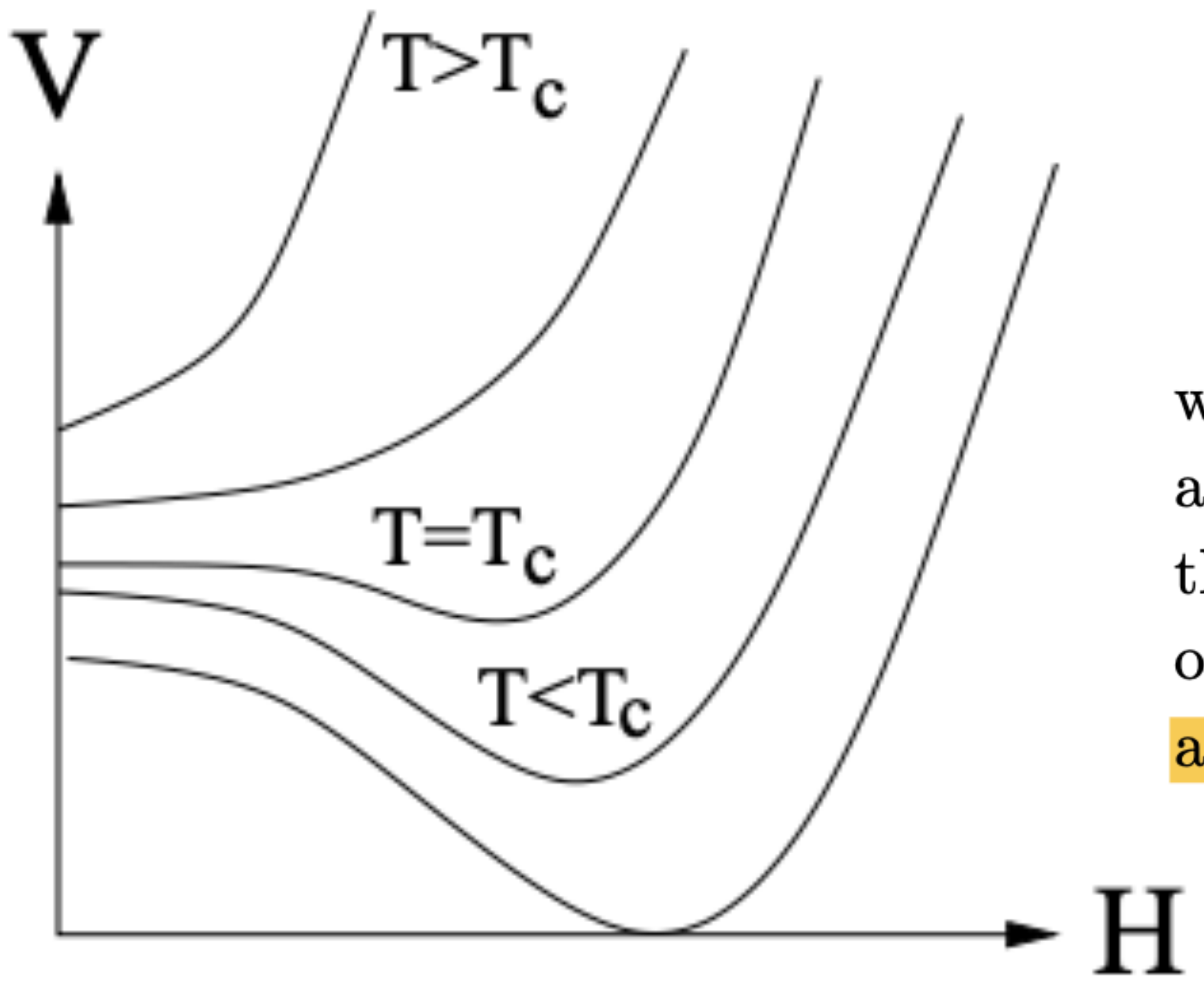
It can cause loss of thermal equilibrium if it is a First Order Phase Transition (FOPT)



Electroweak Phase Transition



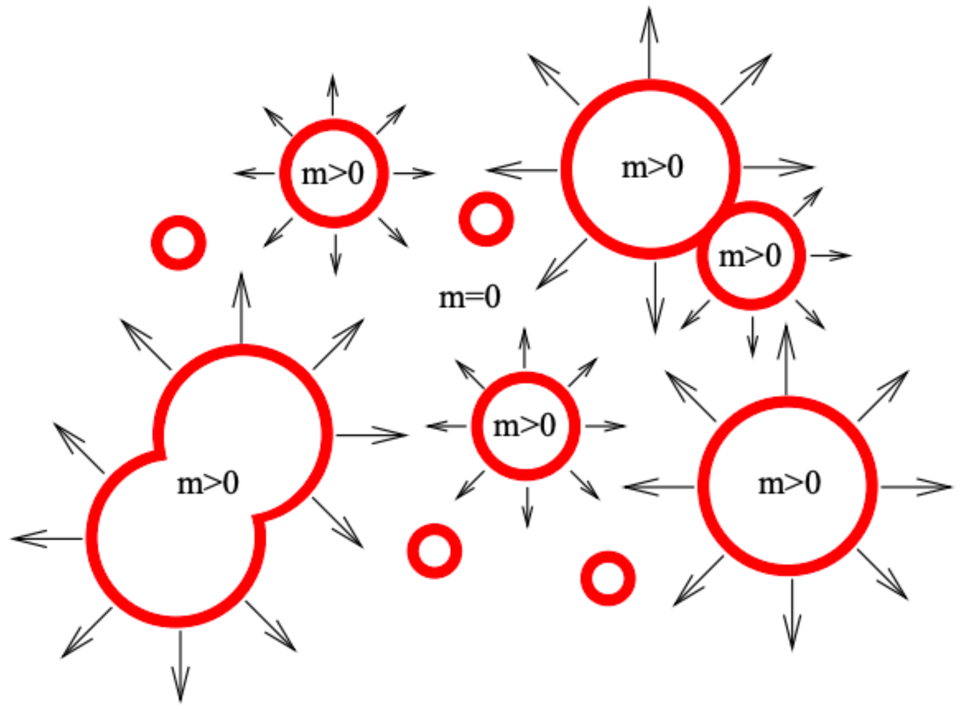
first order phase transition
FOPT

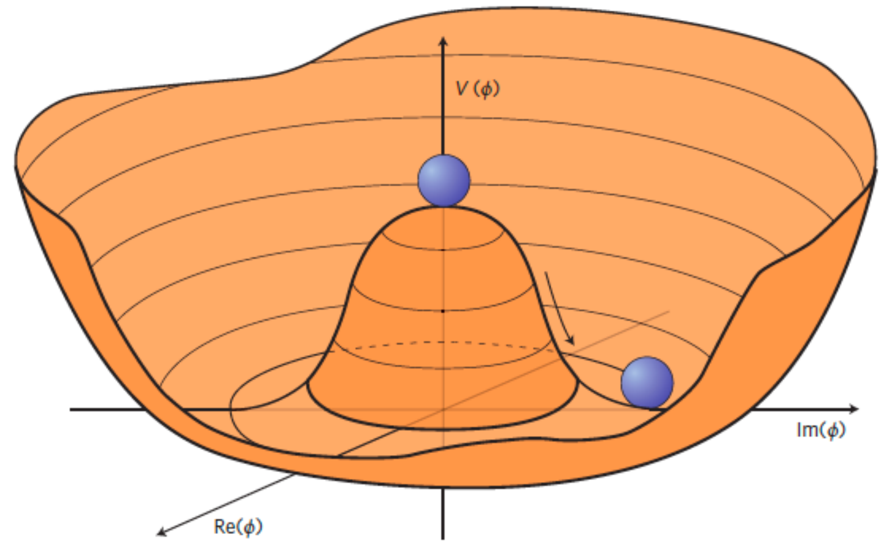


second order phase transition
SOPT
(or crossover)

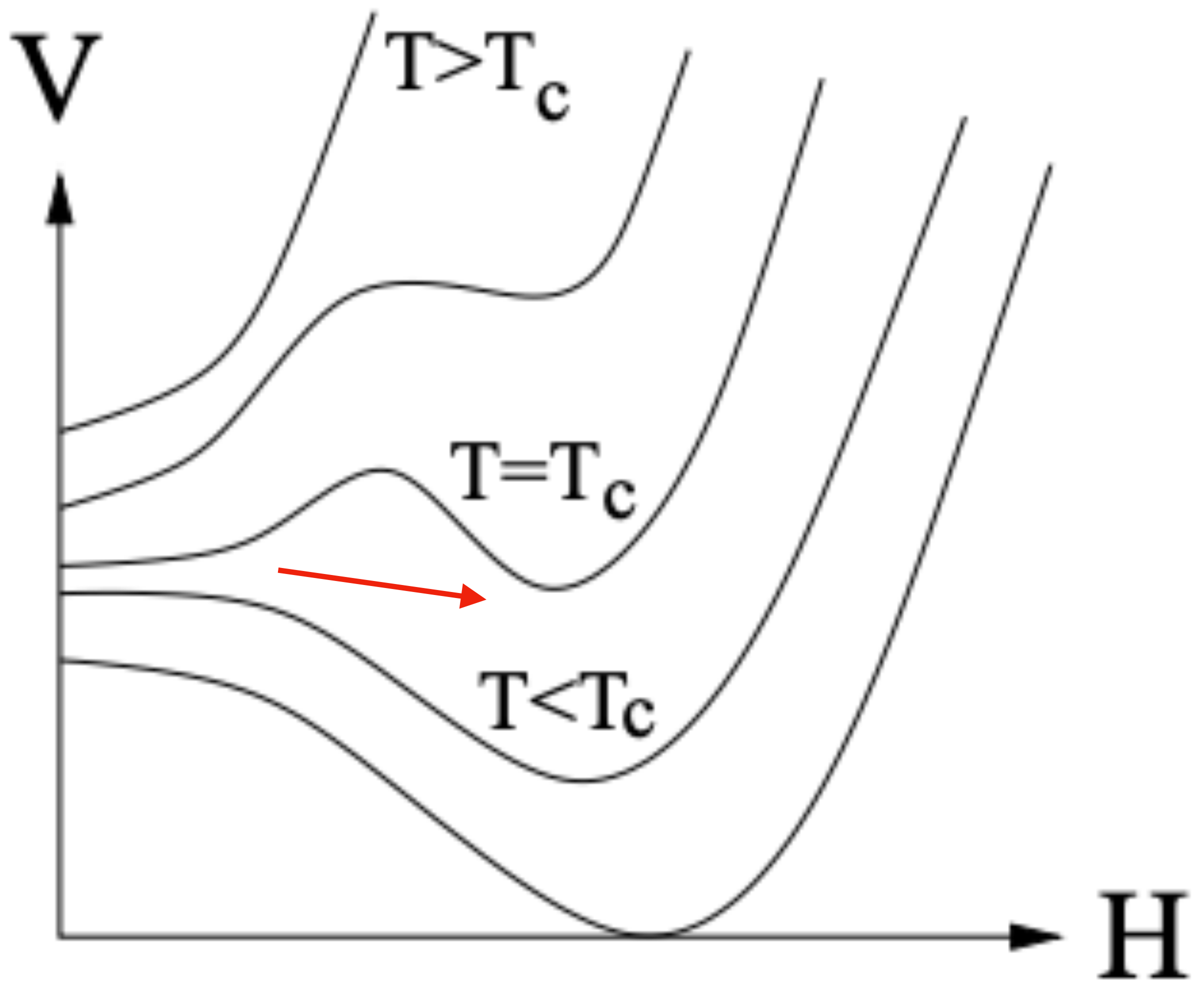
which therefore should be included in the analysis. In a general model-independent EFT approach there is then no, a priori, reason to not consider other dimension-eight operators that can contribute to the generation of the baryon asymmetry. The starting assumption of the SM-EFT approach is thus explicitly violated, and it is not possible to study EWBG and the related phenomenology in a fully model-independent way.

Jordy de Vries,[a] Marieke Postma,[a] Jorinde van de Vis[a] and Graham White[b,c]





Electroweak Phase Transition



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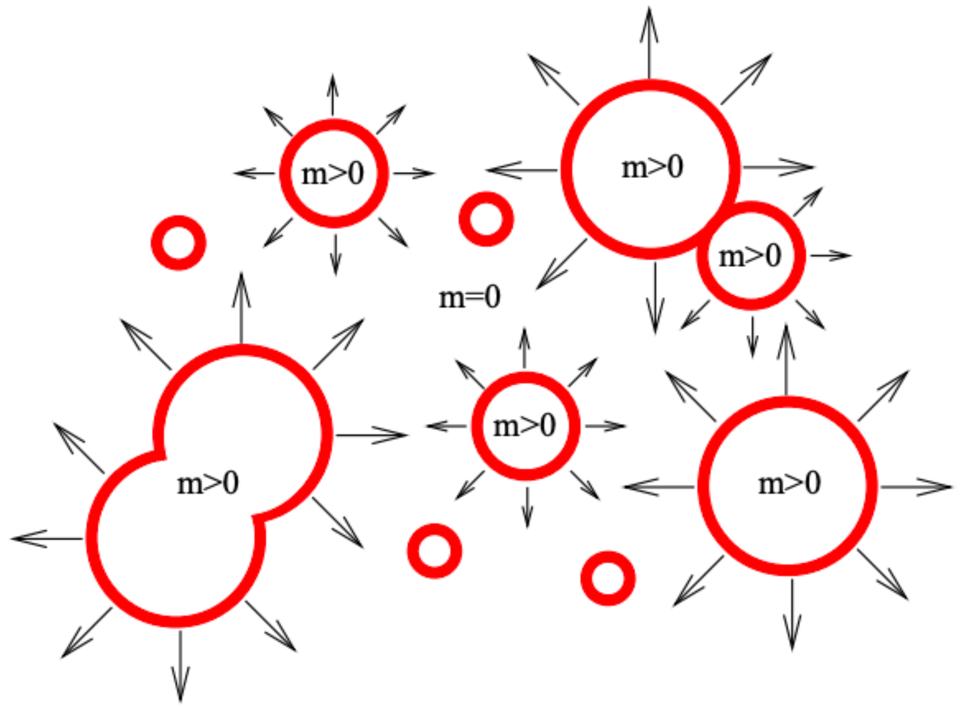

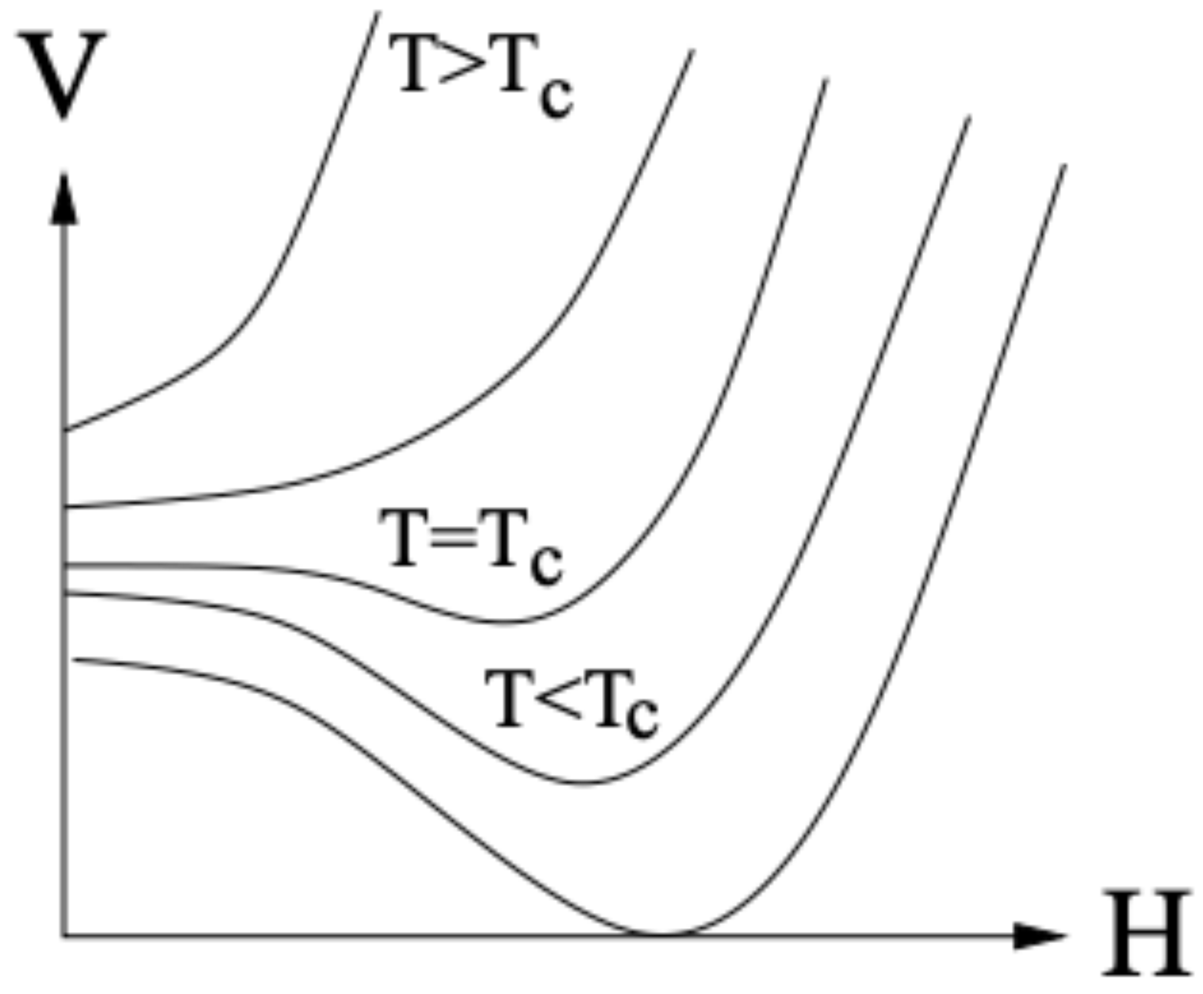

second order phase transition
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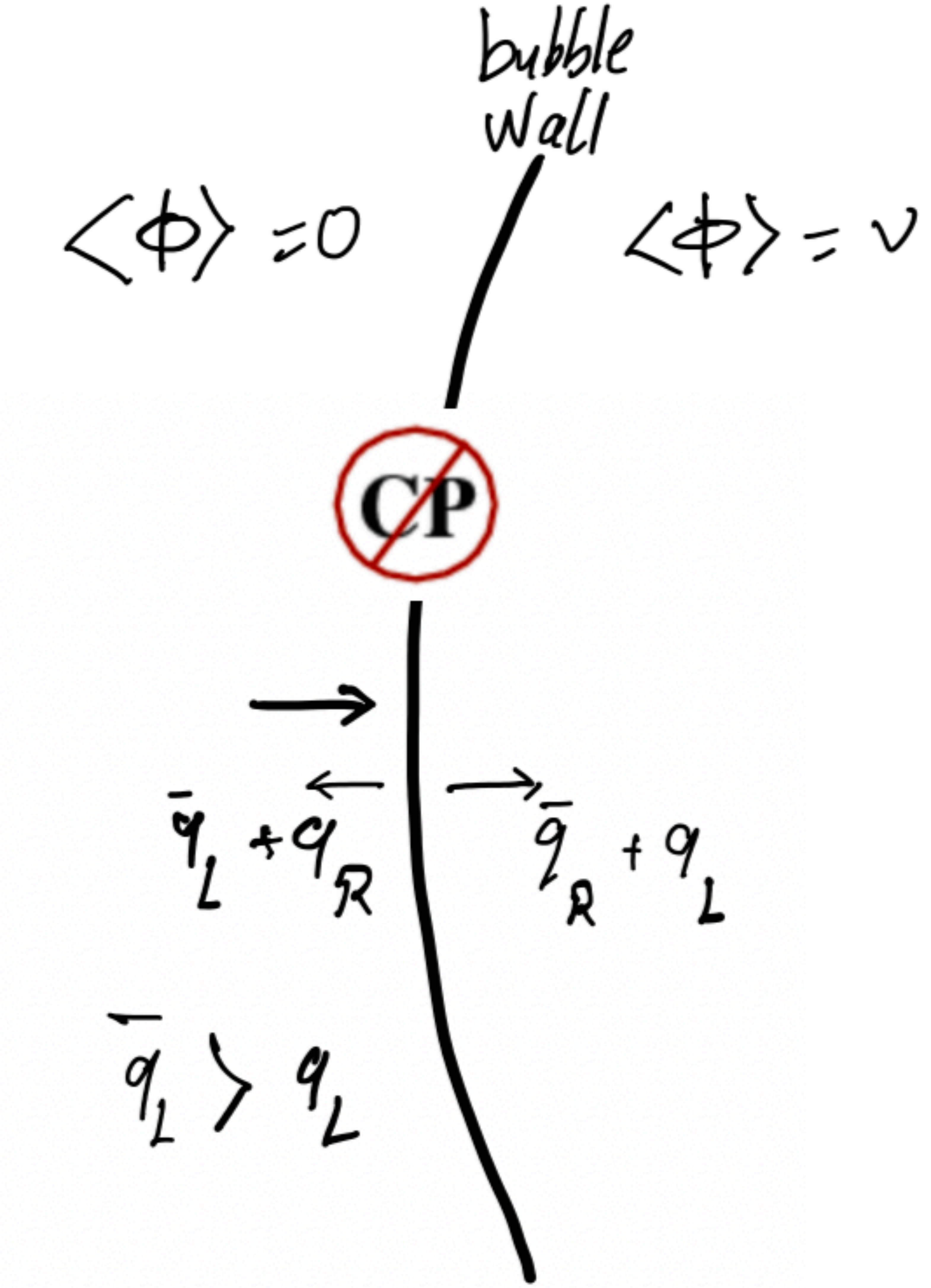
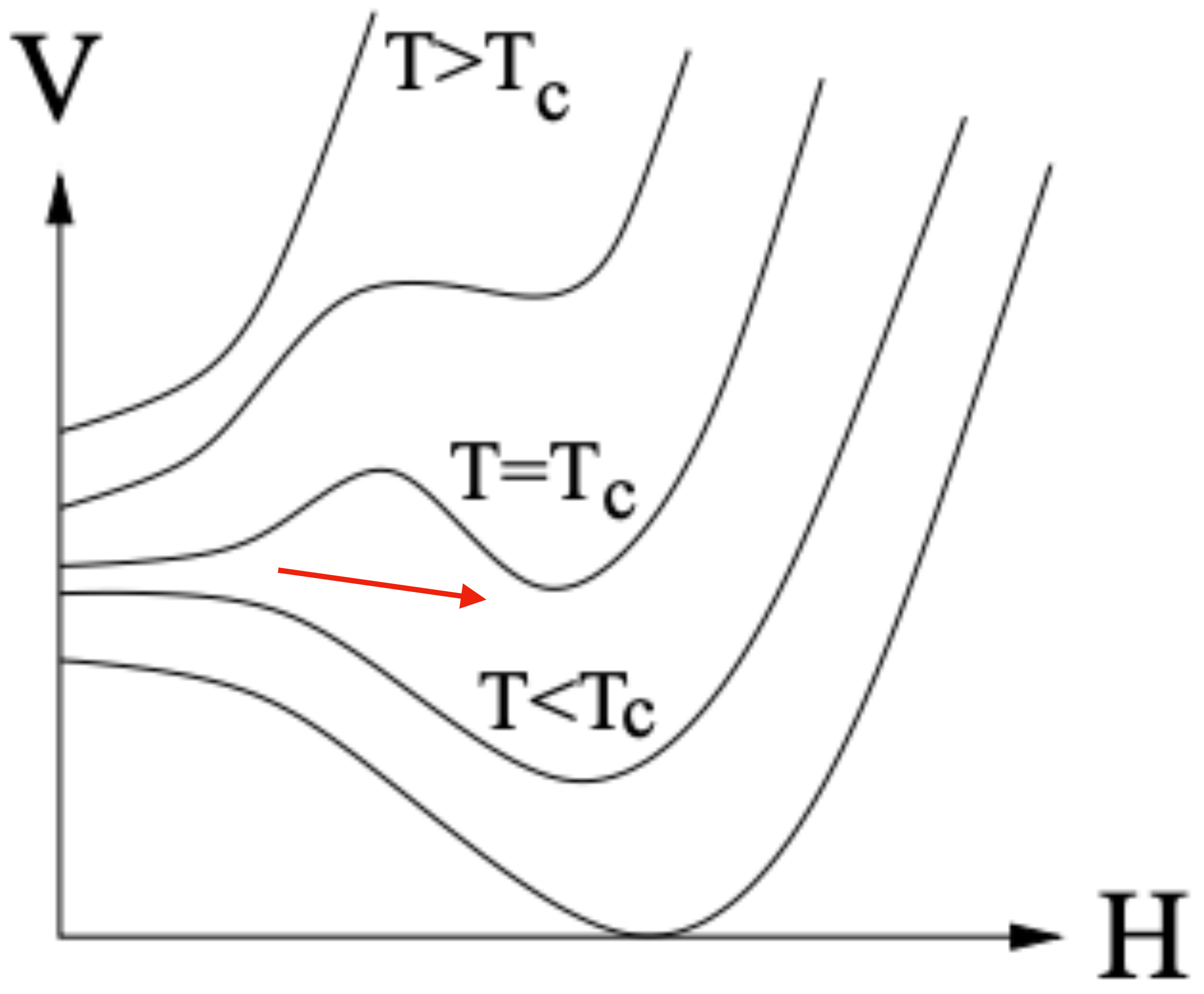


Electroweak Phase Transition



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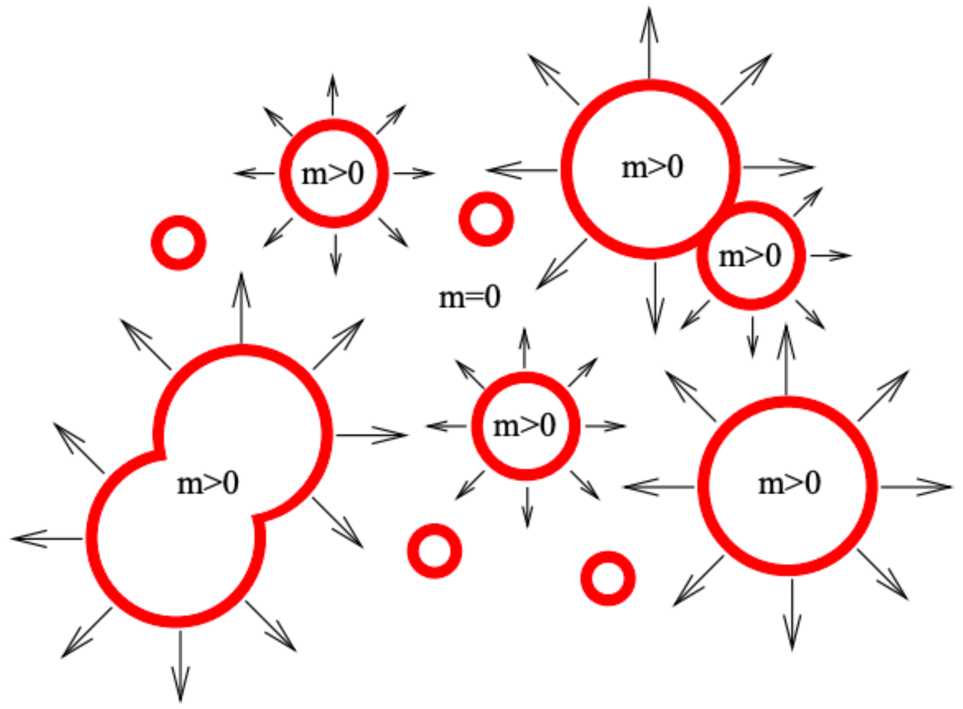

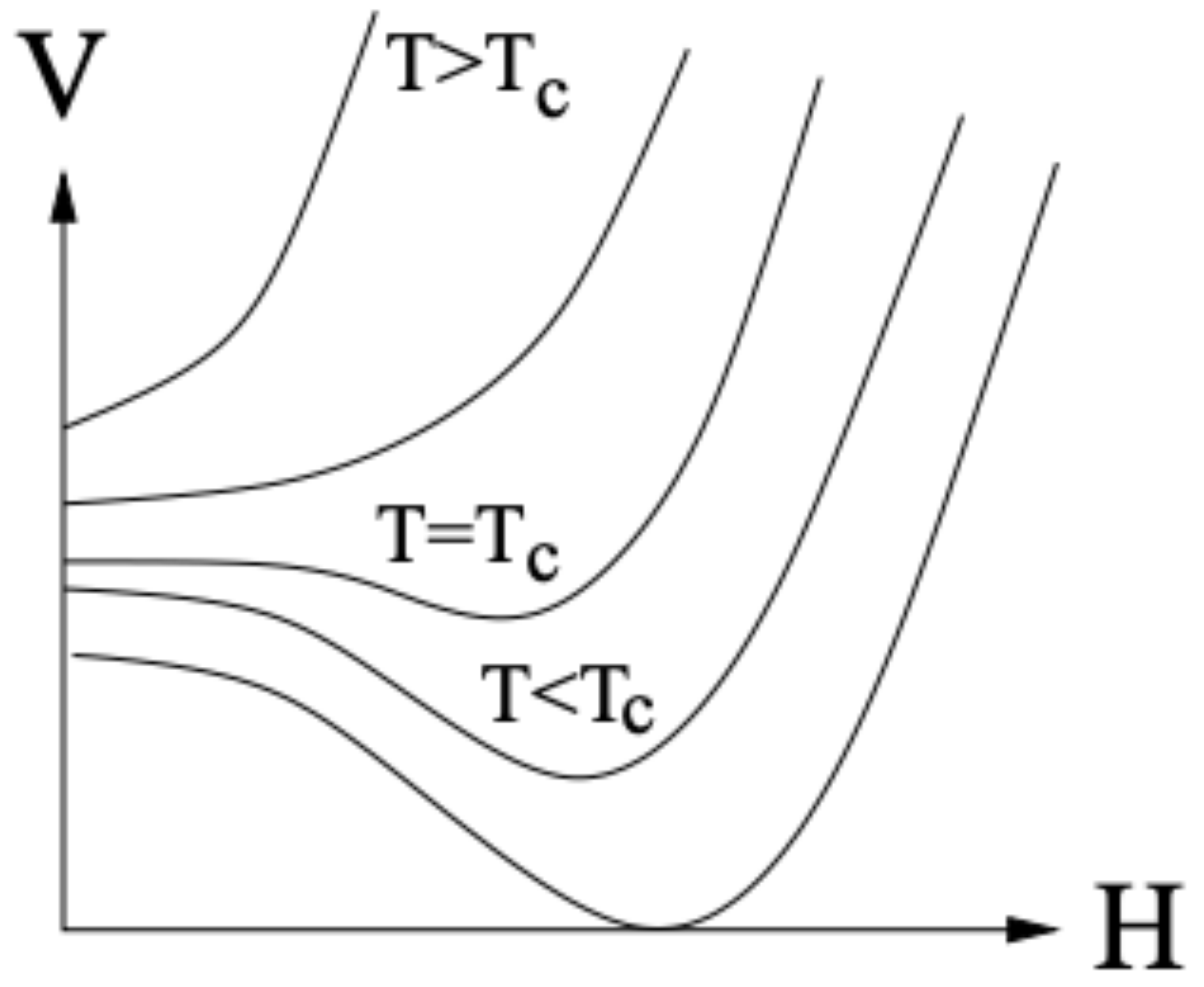

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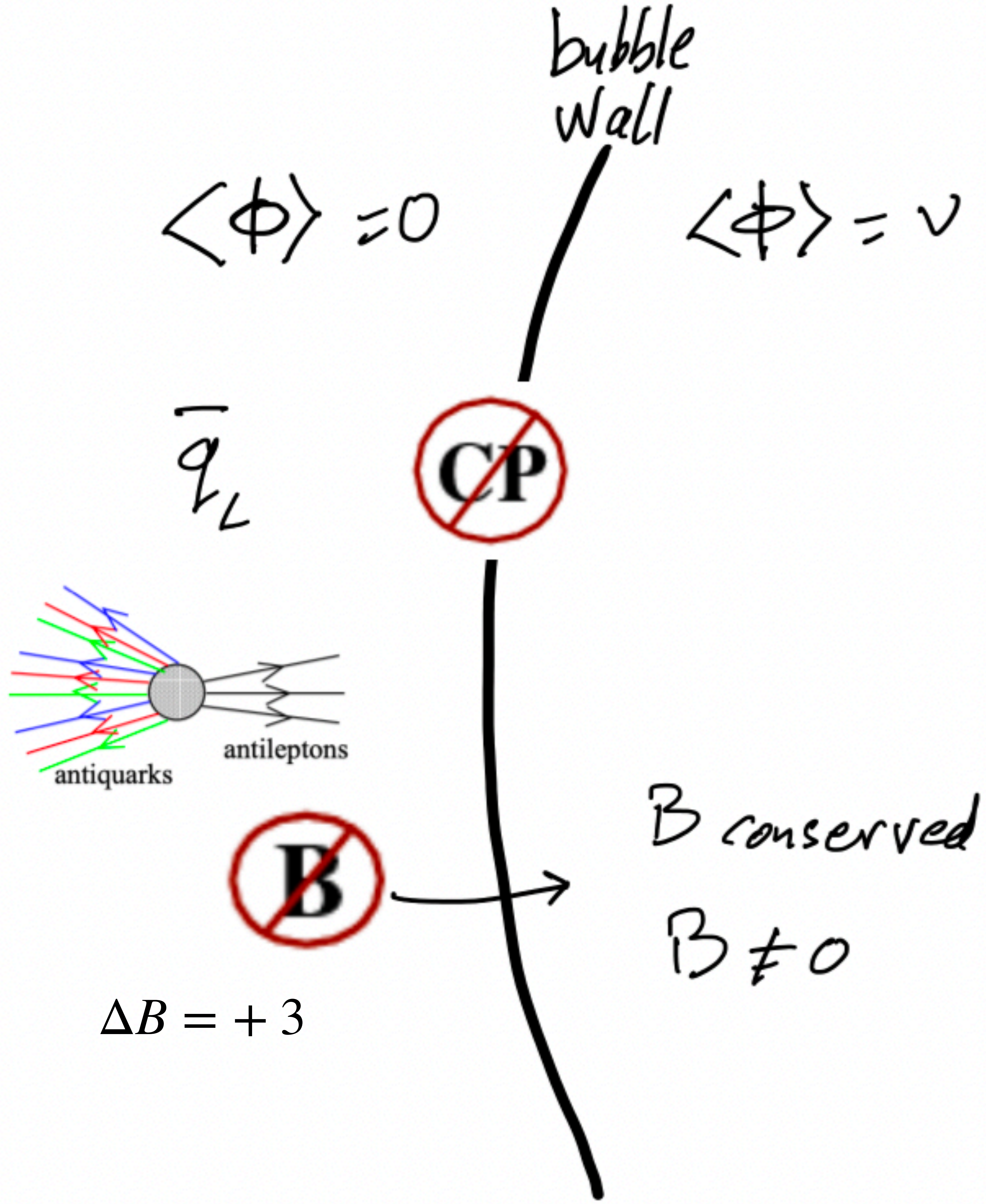
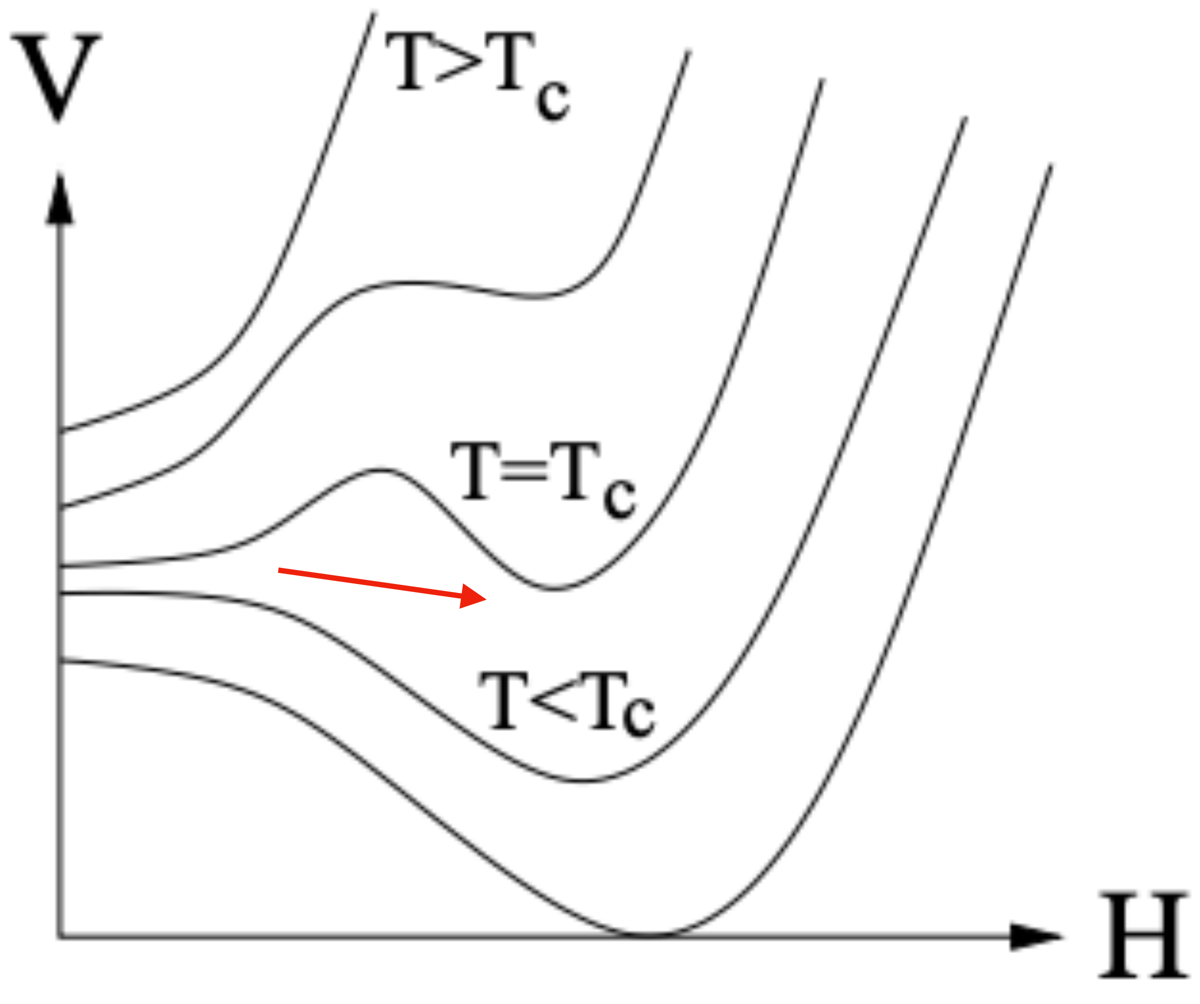


Electroweak Phase Transition: SM



first order phase transition
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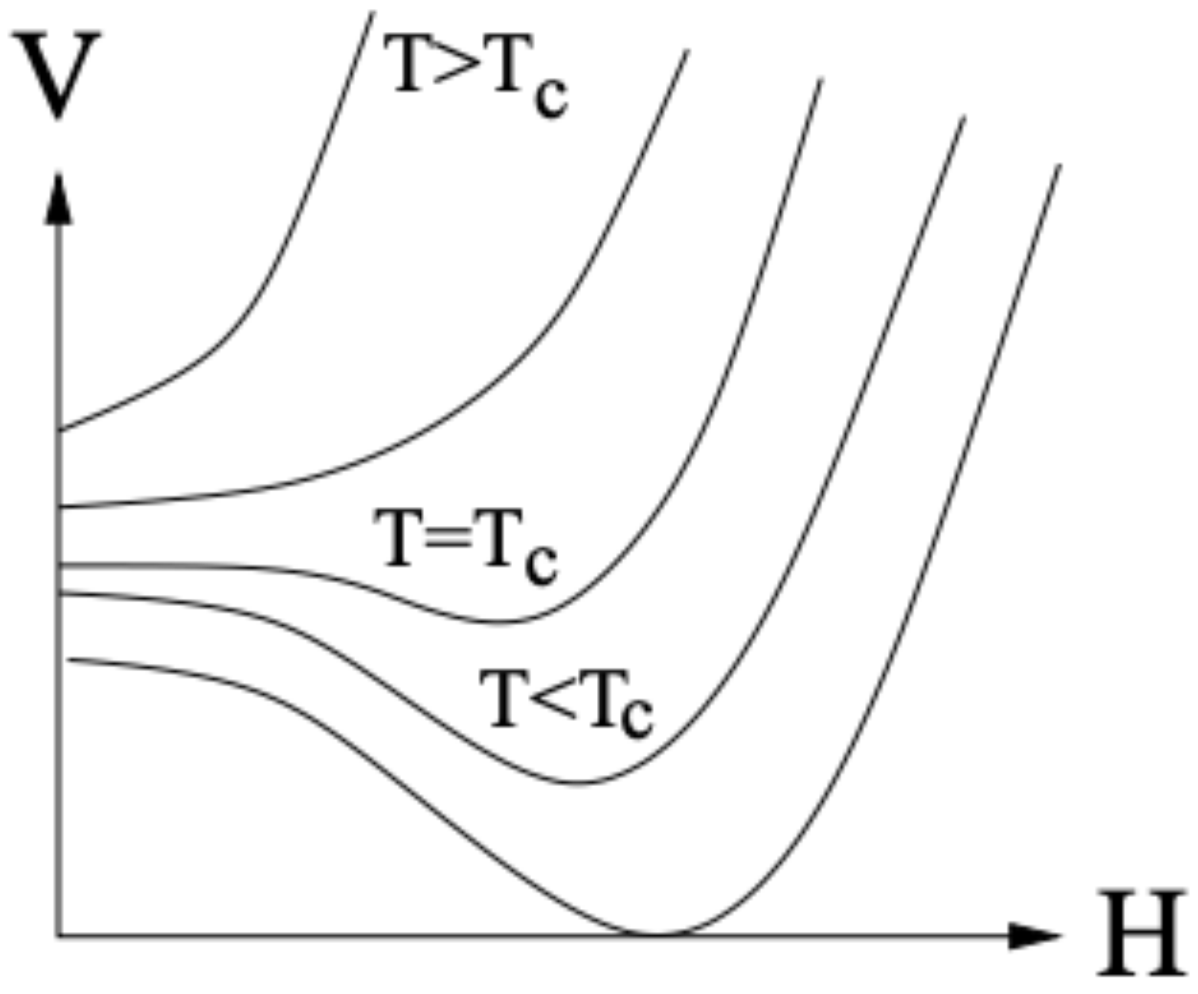

second order phase transition
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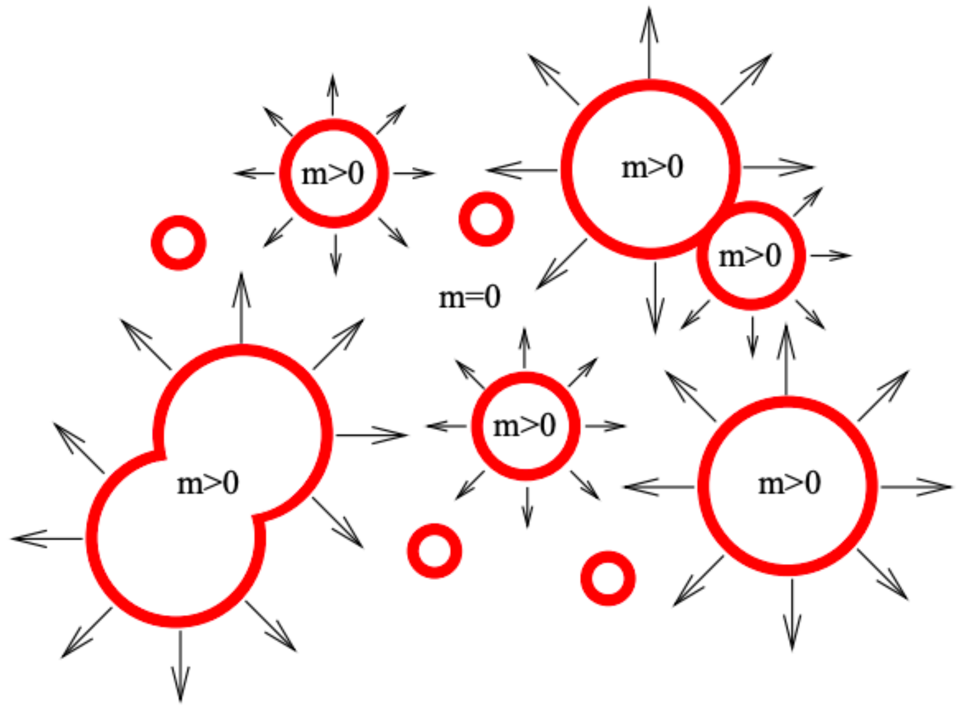


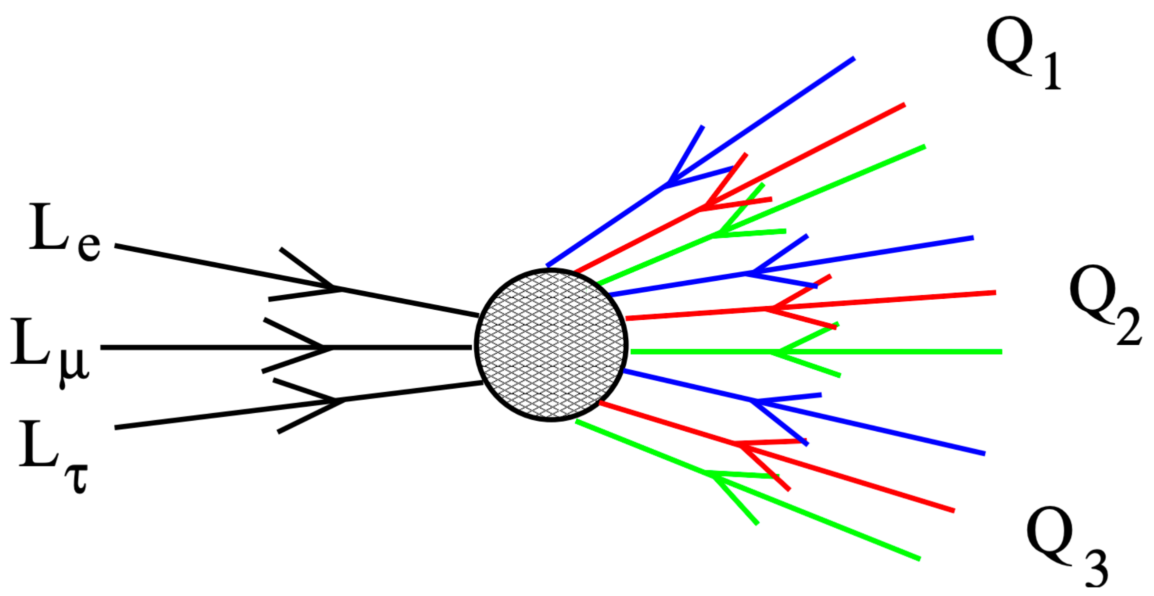
We use the finite T effective potential of H

$$V_{eff}(H,T) = \bigcirc + \{\bigcirc\!\bigcirc + \ominus\} + \ldots$$
$$\sim \frac{1}{2}(-m^2 + \alpha T^2)H^2 - \beta T H^3 + \frac{1}{4}\lambda H^4$$

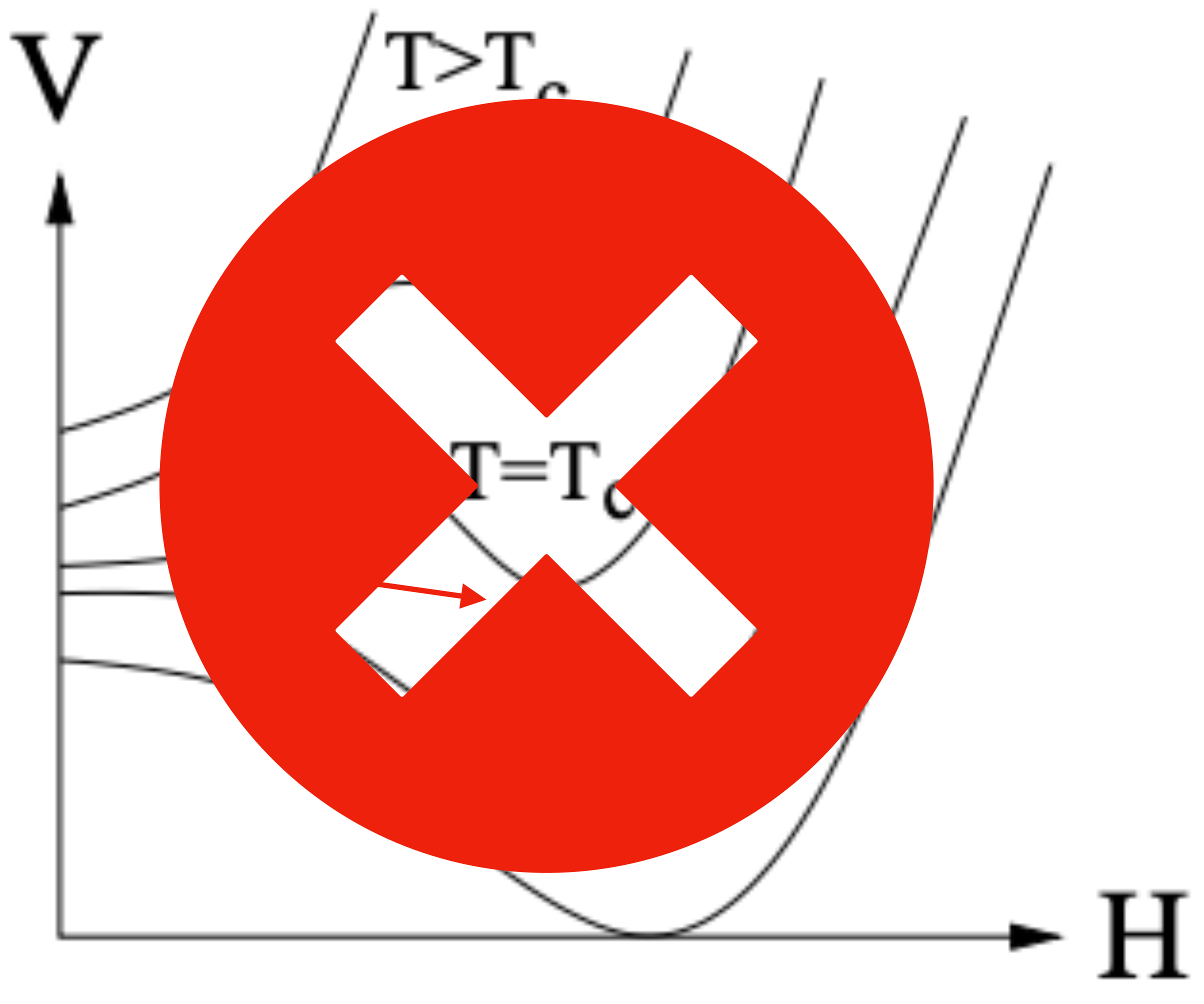
Find the critical T at phase transition, and the vev.

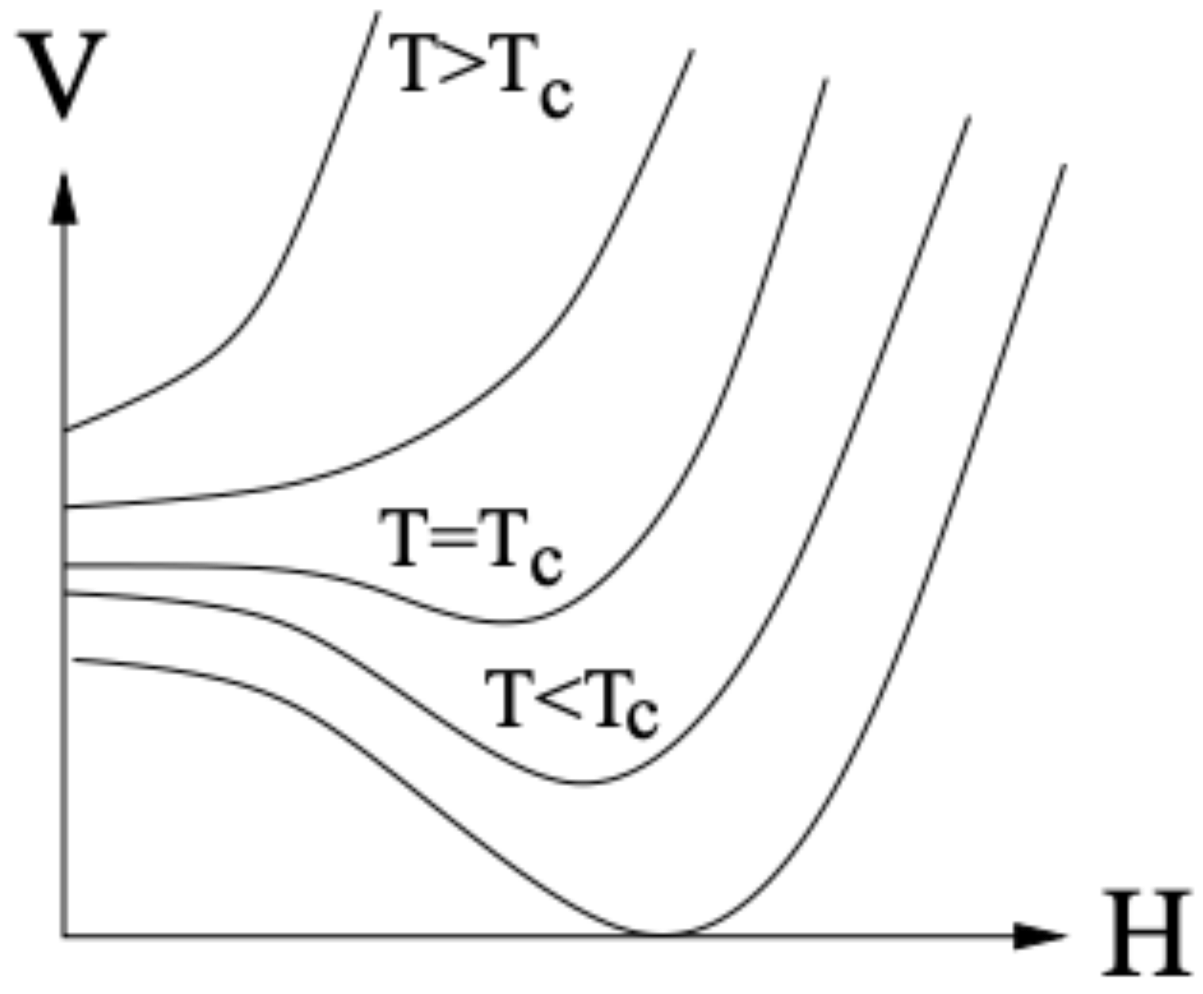
We need: v_c/T_c to be large

$$\Gamma_{sph}(T_c) \sim e^{-E_{sph}/T_c} \sim e^{-v_c/T_c}$$



Electroweak Phase Transition: SM





second order phase transition
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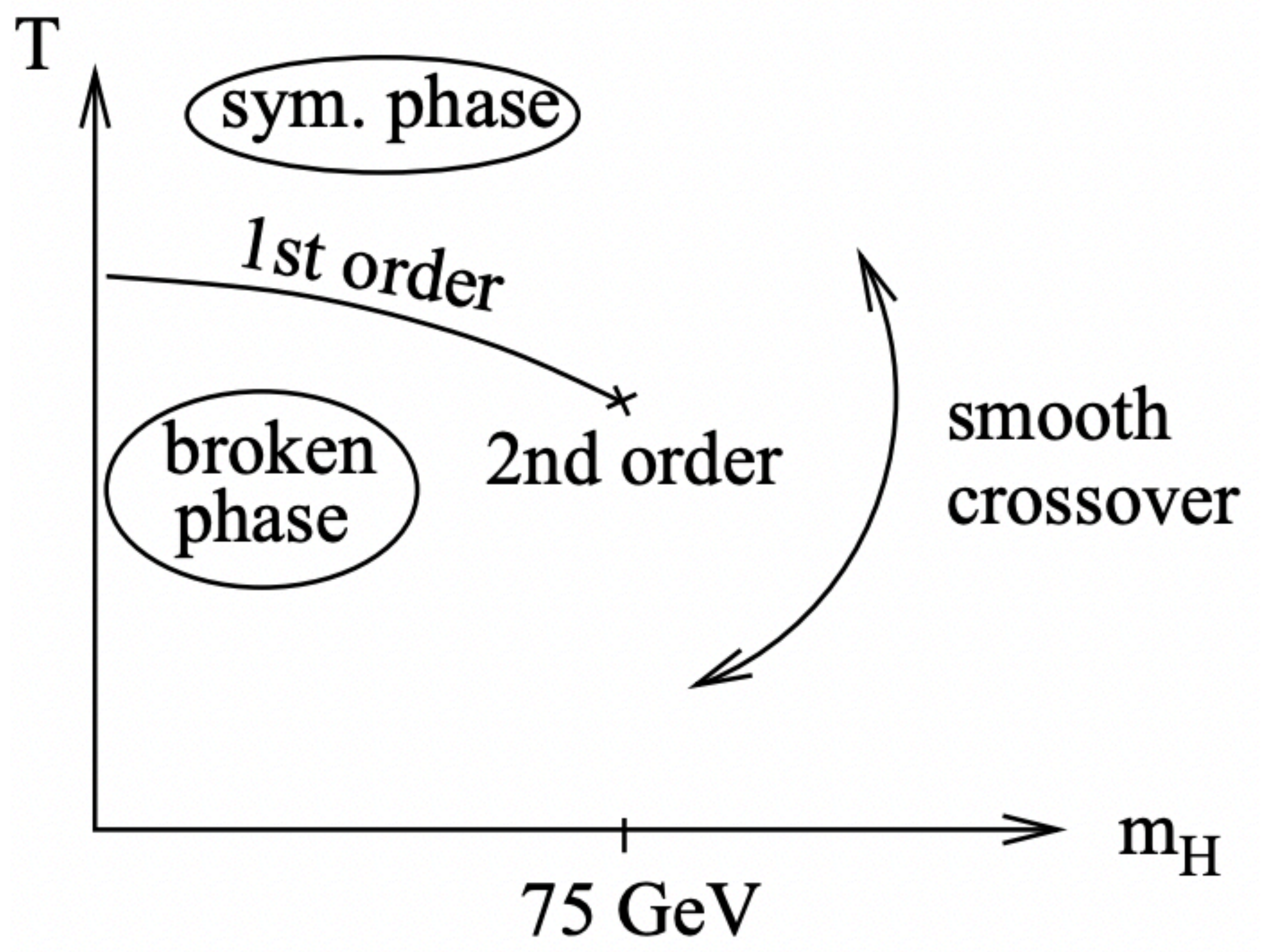


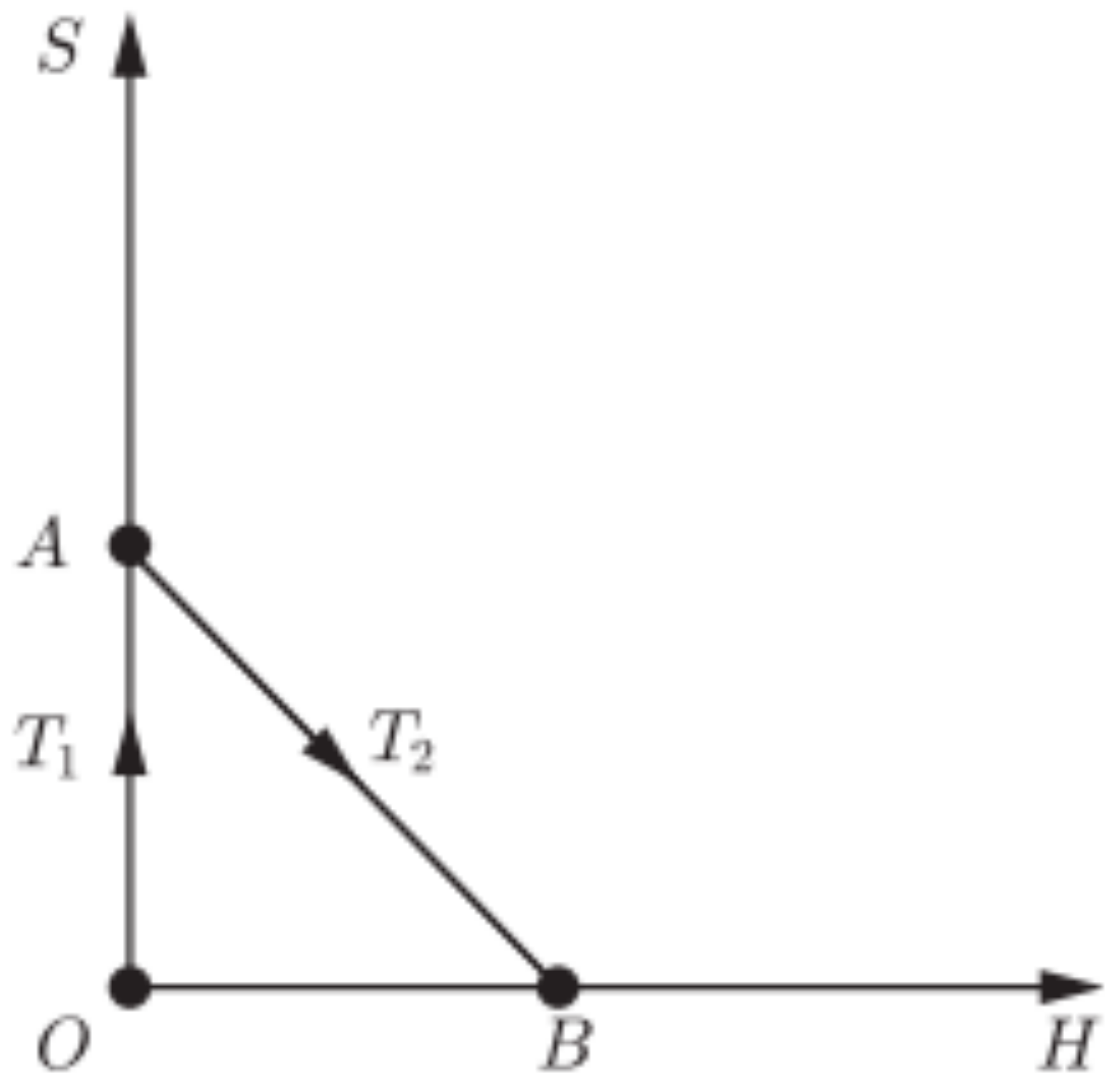
No first order phase transition in SM

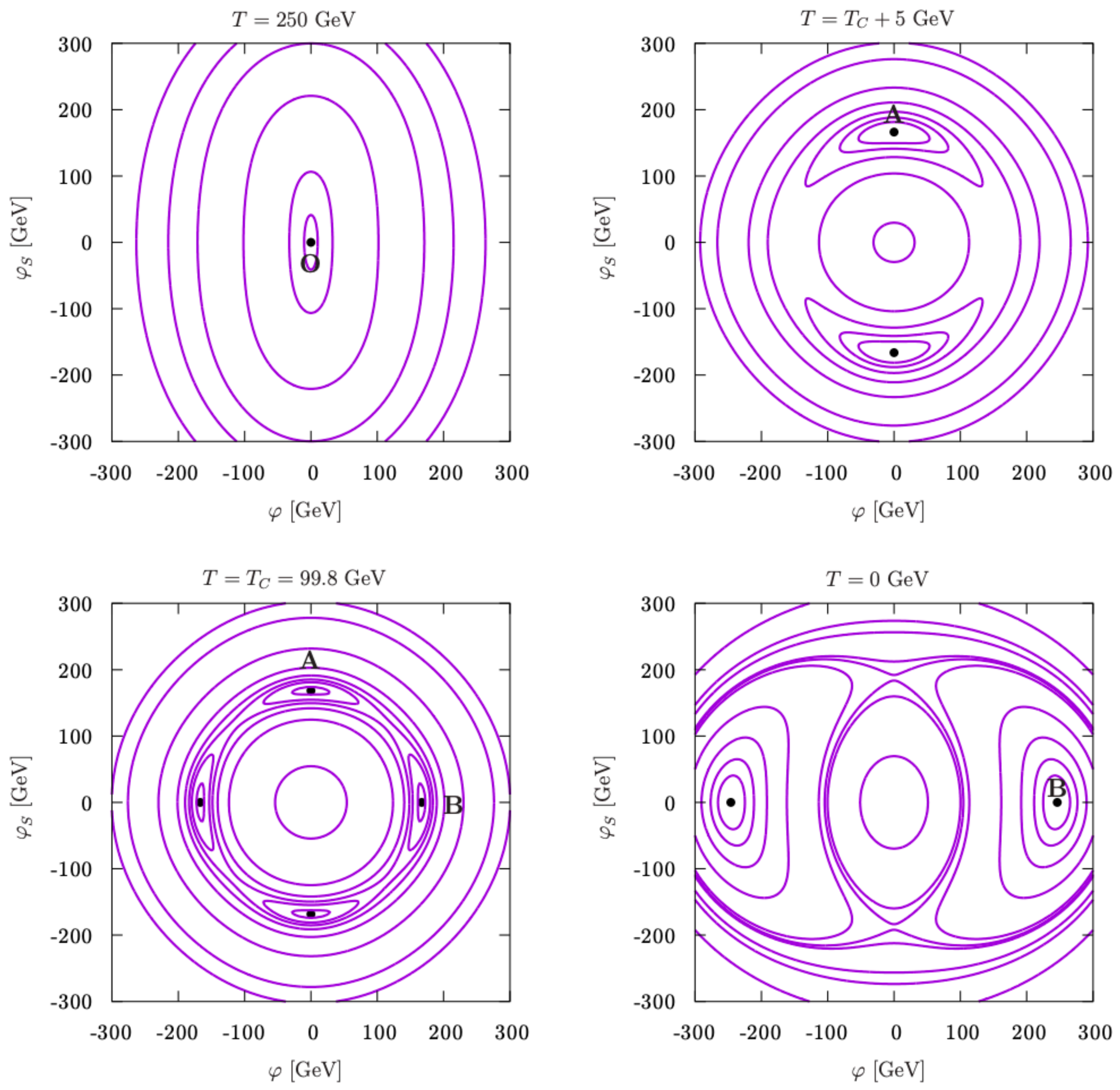
Electroweak Phase Transition: BSM

Adding a scalar field can make a two-step FOPT!

$$V = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\mu_m s h^2 + \frac{1}{4}\lambda_m s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

$$V^{\text{high-}T}(\varphi, \varphi_S; T) = V_0(\varphi, \varphi_S) + \frac{1}{2}(\Sigma_H \varphi^2 + \frac{1}{2}\Sigma_S \varphi_S^2) T^2$$





Cheng-Wei Chiang,[1,2,3,4,*] Michael J. Ramsey-Musolf,[5,6,†] and Eibun Senaha[1,7,‡]

Electroweak Phase Transition: TRSM

Adding two scalar fields?

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2 .$$

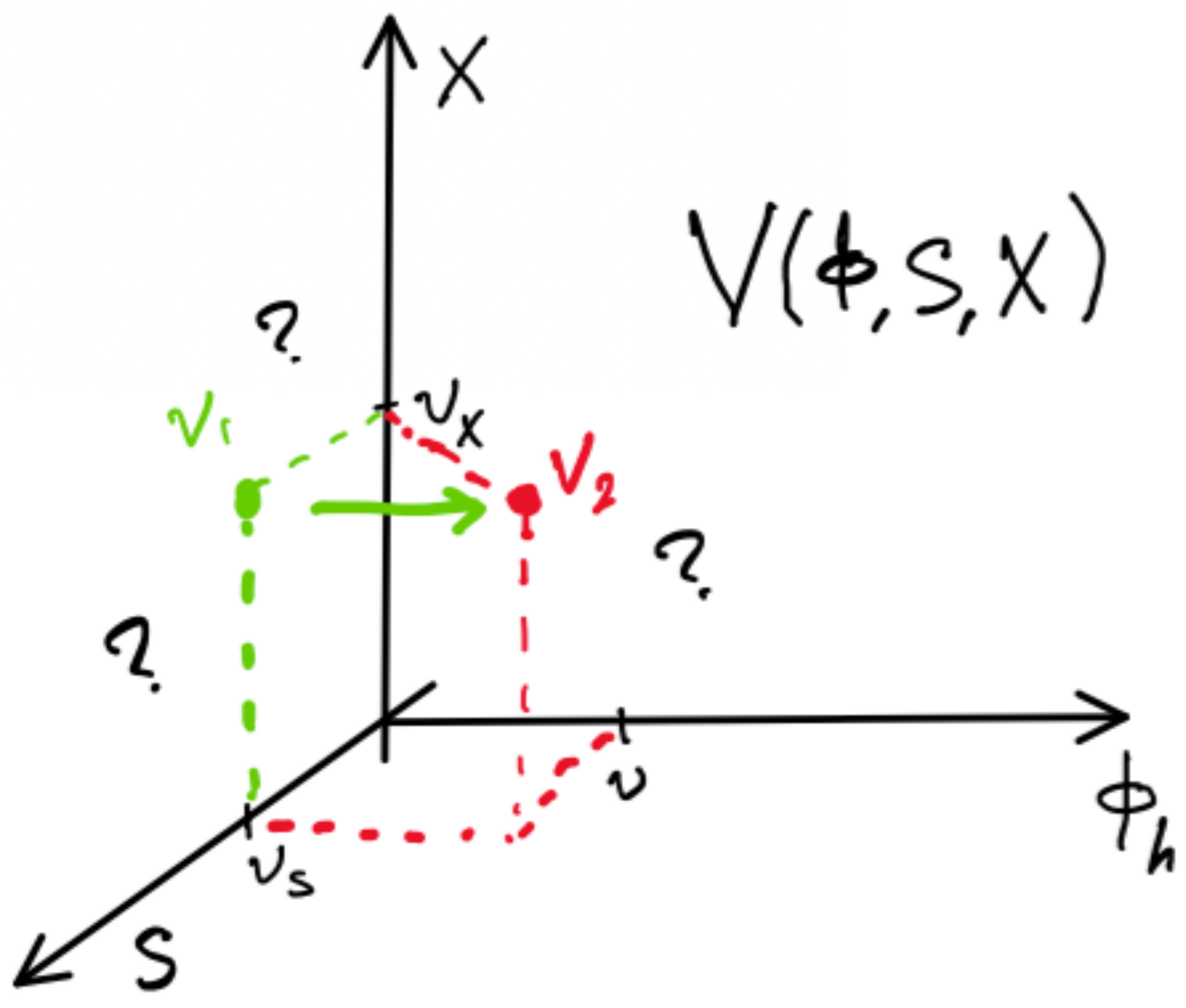
Mixing:

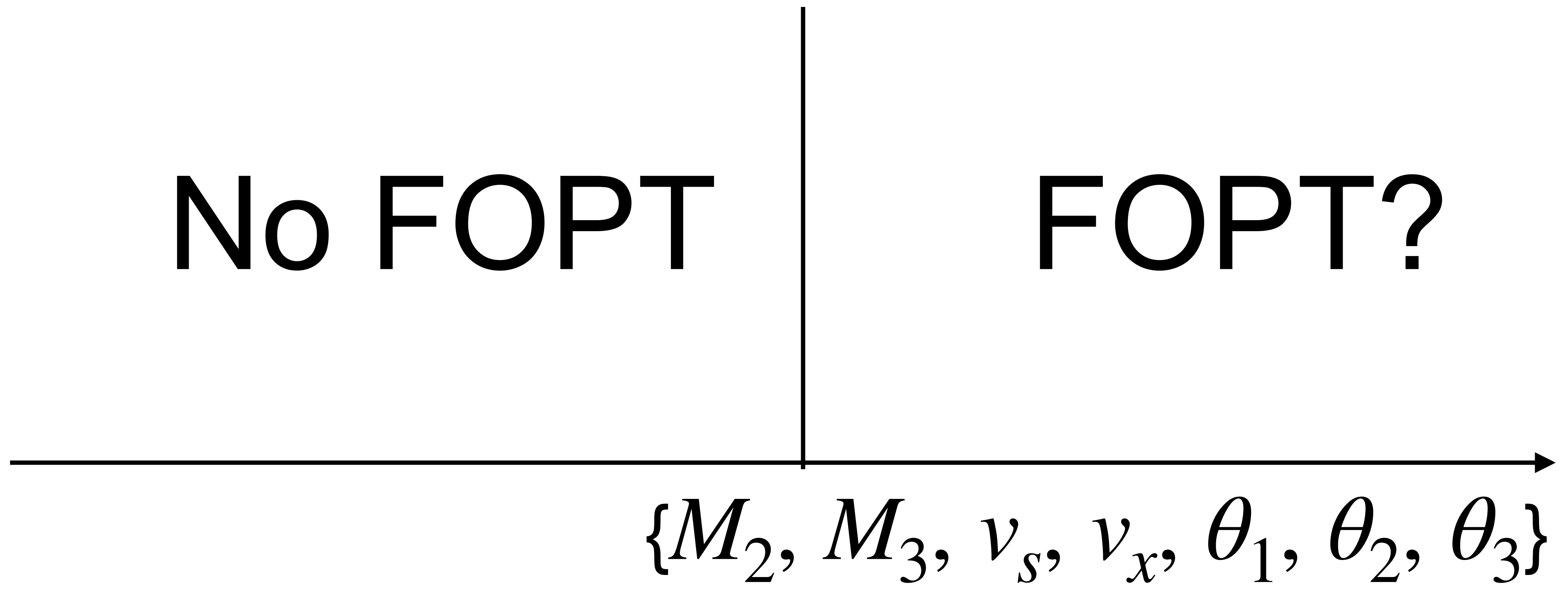
$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{\phi_S + v_S}{\sqrt{2}}, \quad X = \frac{\phi_X + v_X}{\sqrt{2}} \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix}$$

Physical parameter space:

$$\{M_2, M_3, v_s, v_x, \theta_1, \theta_2, \theta_3\}$$

$M_1 = 125\ GeV, v = 246\ GeV$





TRSM: HHH and EWPT

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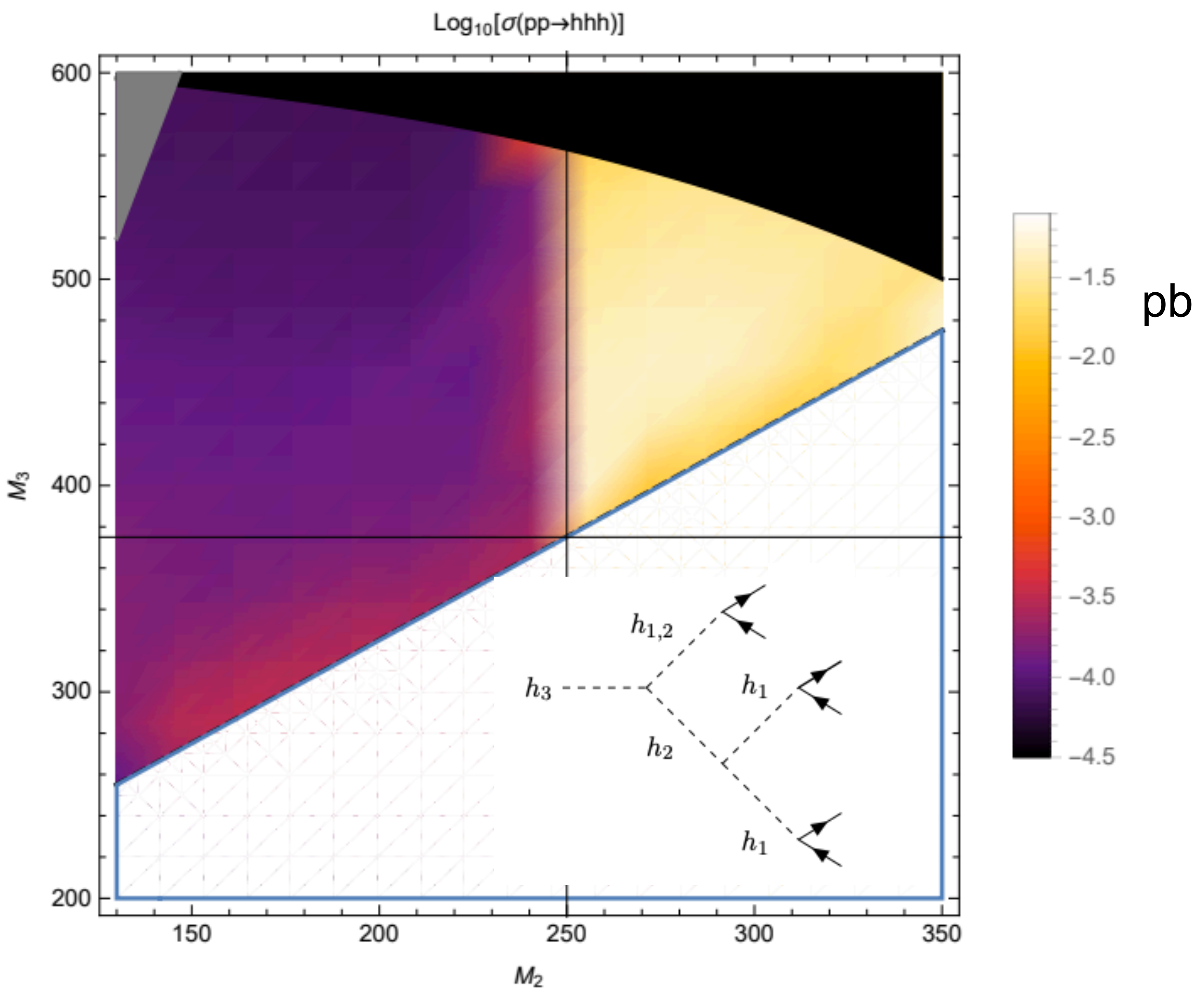
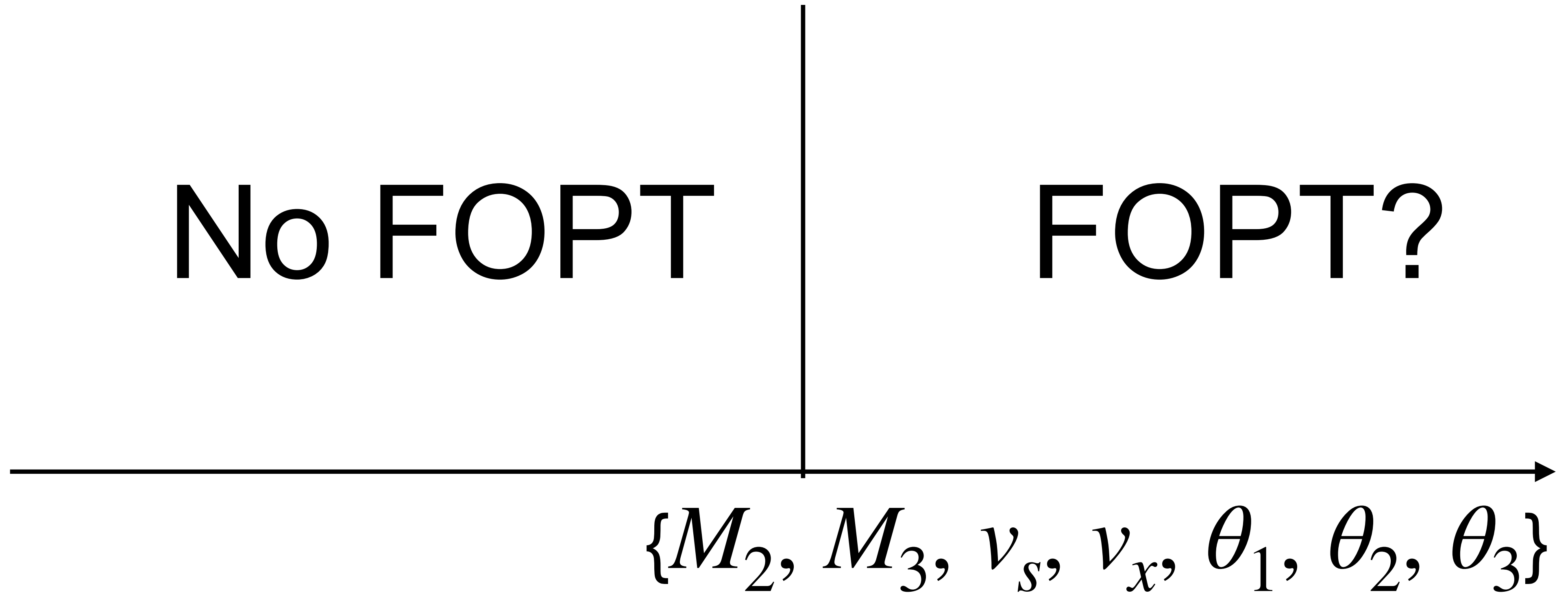
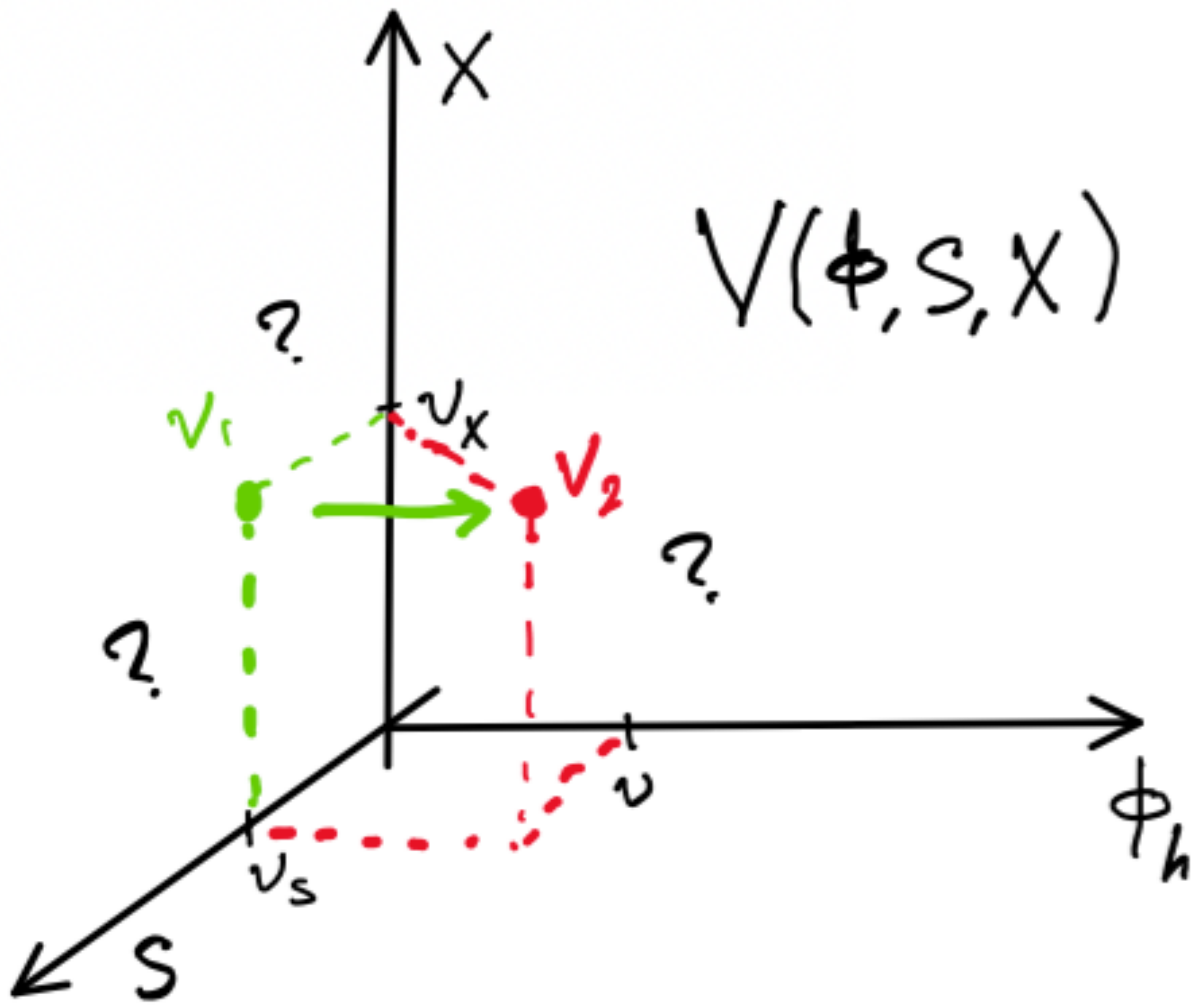
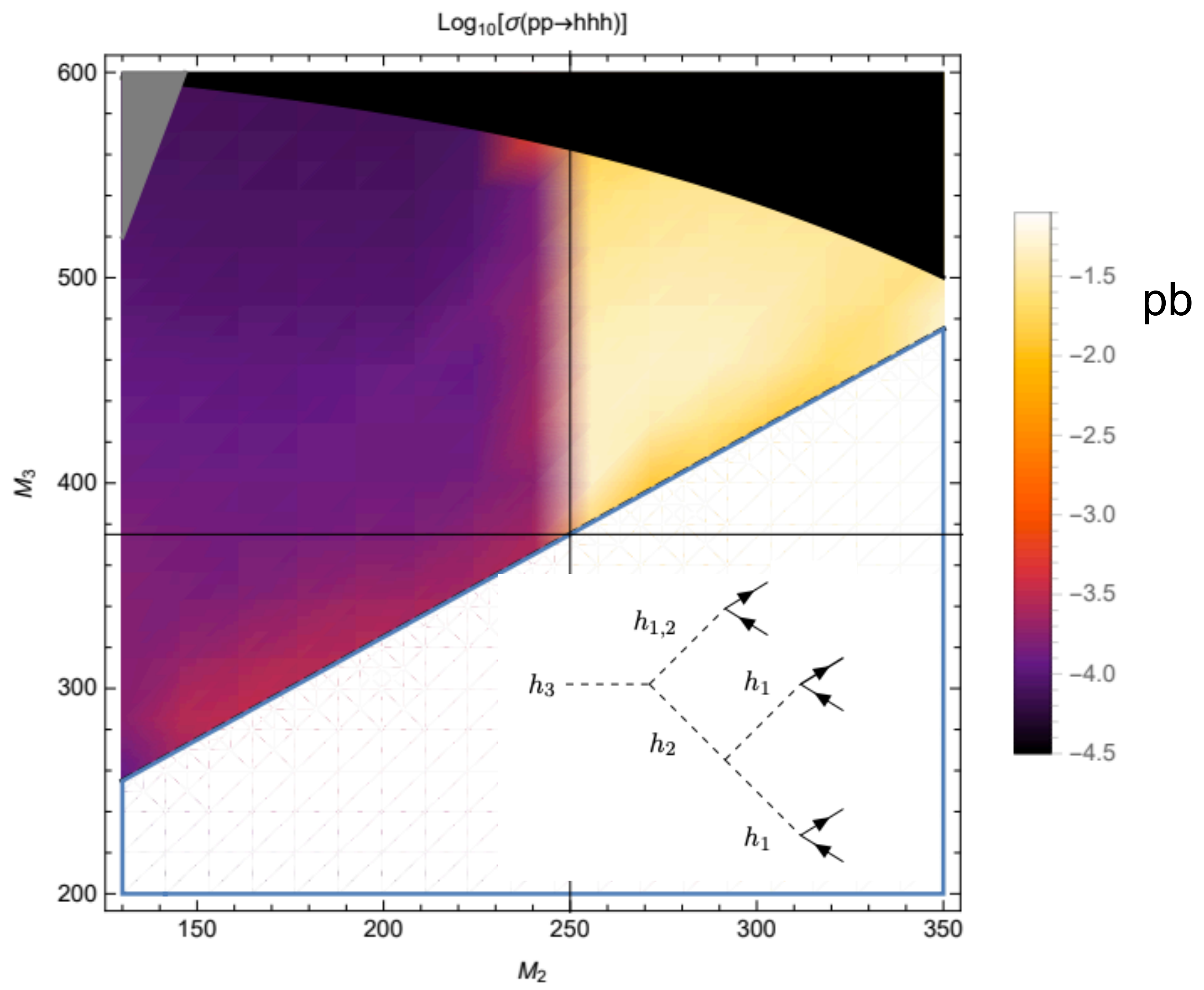




TRSM: HHH and EWPT

Looking at points with large HHH (see Andreas' Talk tmr)
Searching for FOPT





No FOPT | FOPT?

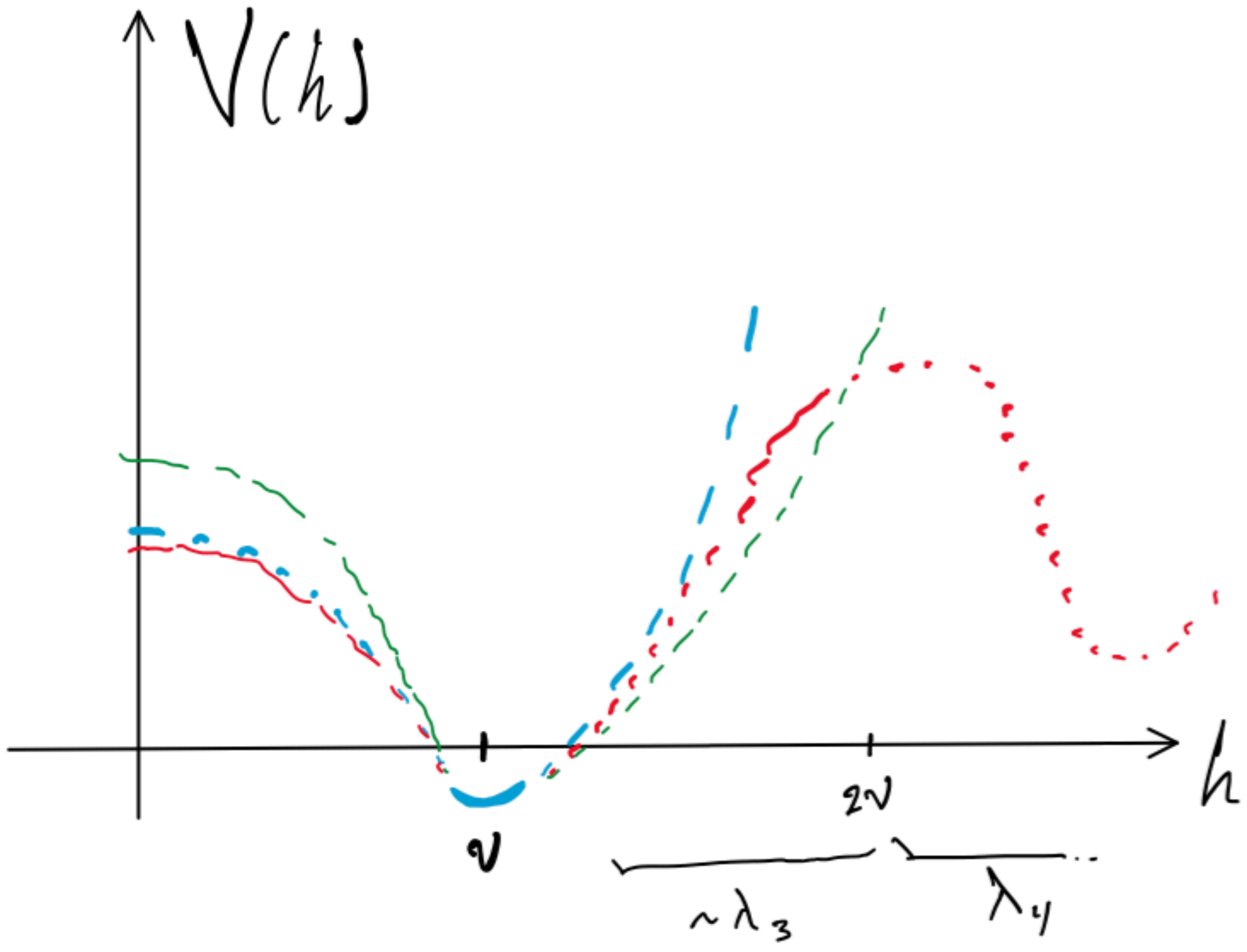
$\{M_2, M_3, v_s, v_x, \theta_1, \theta_2, \theta_3\}$

Backup

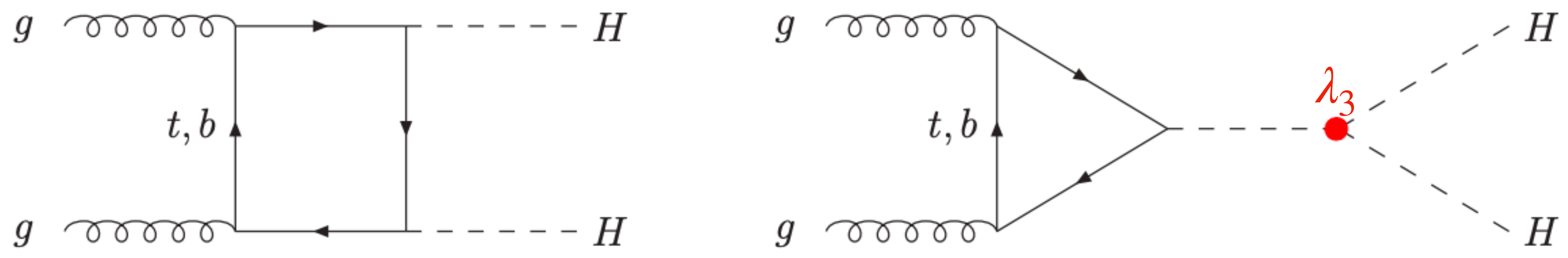
HHH production (experimental POV)

$$V(h) = \frac{1}{2}m_h^2 h^2 + \boxed{\lambda_3 v h^3} + \frac{1}{4}\lambda_4 h^4 + O(h^5) + O(h^6) + \ldots$$

HH



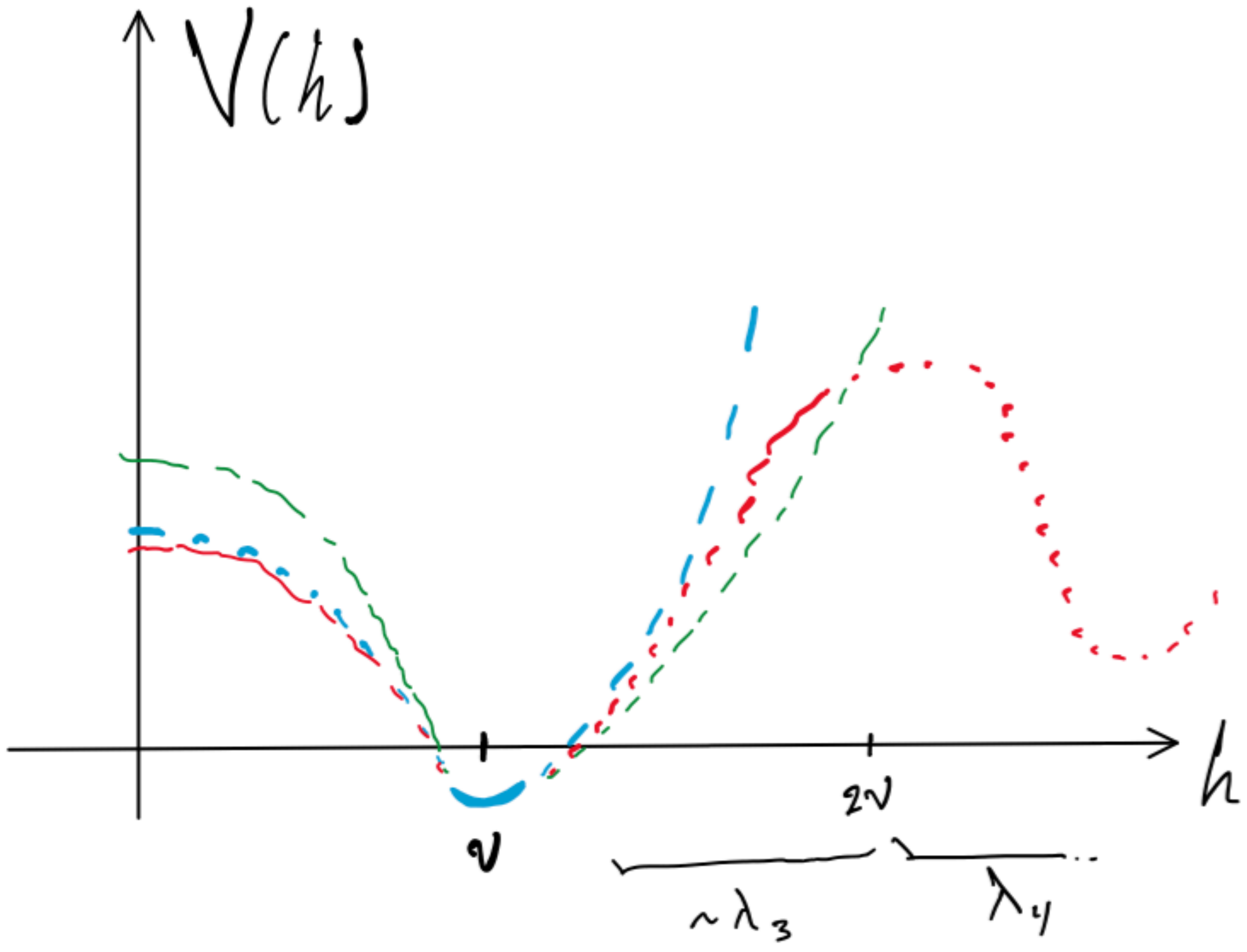
λ_3 is best measured from HH production:



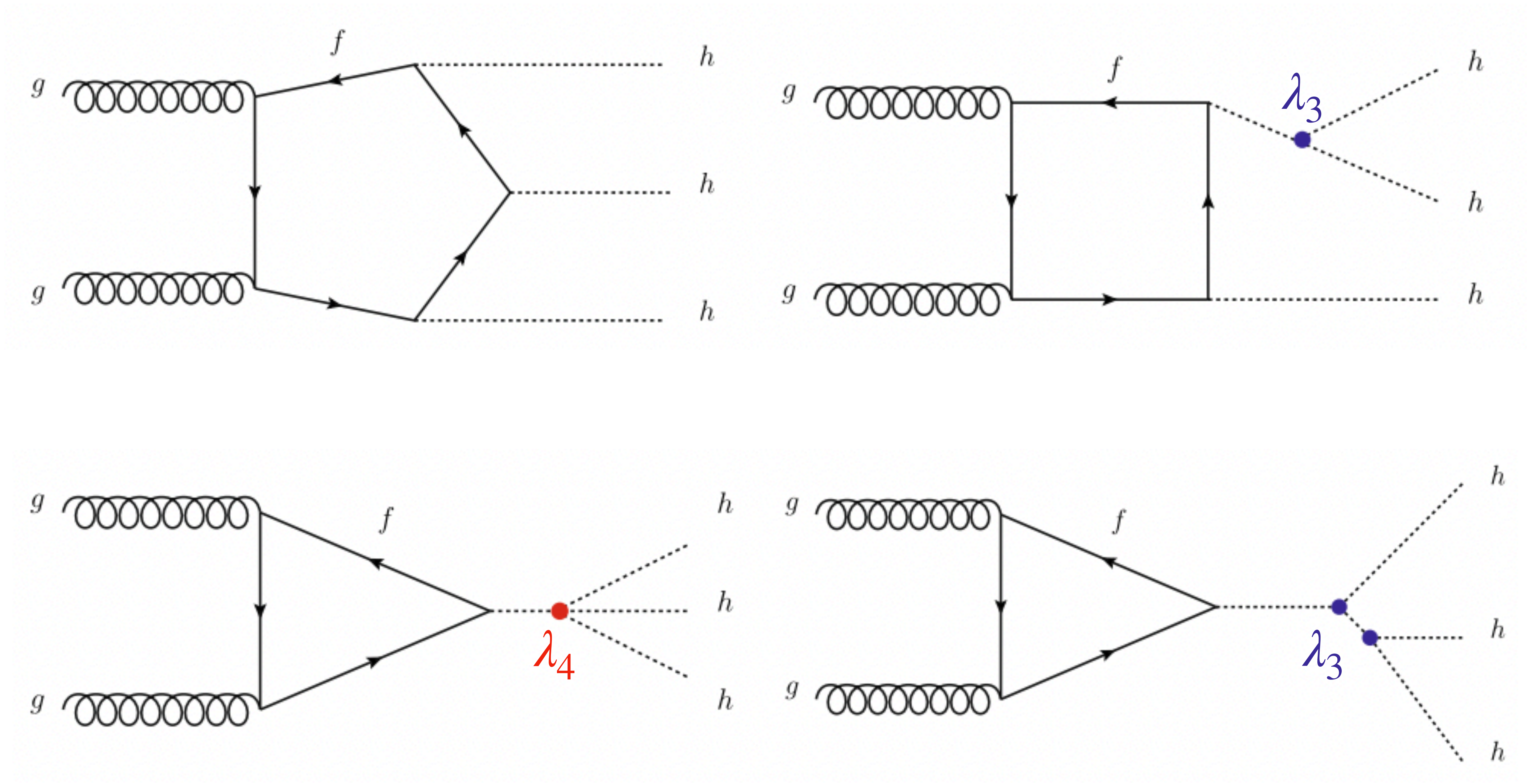
HHH production (experimental POV)

$$V(h) = \frac{1}{2}m_h^2h^2 + \lambda_3 v h^3 + \boxed{\frac{1}{4}\lambda_4 h^4} + O(h^5) + O(h^6) + \ldots$$

HHH



λ_4 is best measured from HHH production:



HHH production (theoretical POV)

Starting with a problem: for gauge bosons, a bare mass term breaks gauge symmetry.

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu})^2 + \frac{1}{2}m_A^2 A^\mu A_\mu + Fermions$$

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

Gauge transformation

$$\Delta\mathscr{L} = m_A^2\left(\frac{(\partial_\mu \alpha)^2}{2e^2} - \frac{1}{e}A^\mu \partial_\mu \alpha\right)$$

Gauge sym. Broken

Notice: fermion fields transform to preserve gauge sym!
Idea: introduce a gauge field to give mass and preserve gauge sym.

HHH production (theoretical POV)

Starting with a problem: for gauge bosons, a bare mass term breaks gauge symmetry.

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu})^2 + |D_\mu \phi|^2 + Fermions$$

$$D_\mu = \partial_\mu + ieA_\mu$$

Gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

$$\phi(x) \rightarrow e^{i\alpha(x)}\phi(x)$$

➡

$$\Delta\mathscr{L} = 0$$

Gauge sym. Perserved

$$< \phi(x) > = v$$

vacuum expectation value
vev

➡

$$|D_\mu \phi|^2 = e^2 v^2 A_\mu A^\mu + \ldots$$

Mass term for gauge boson!

HHH production (theoretical POV)

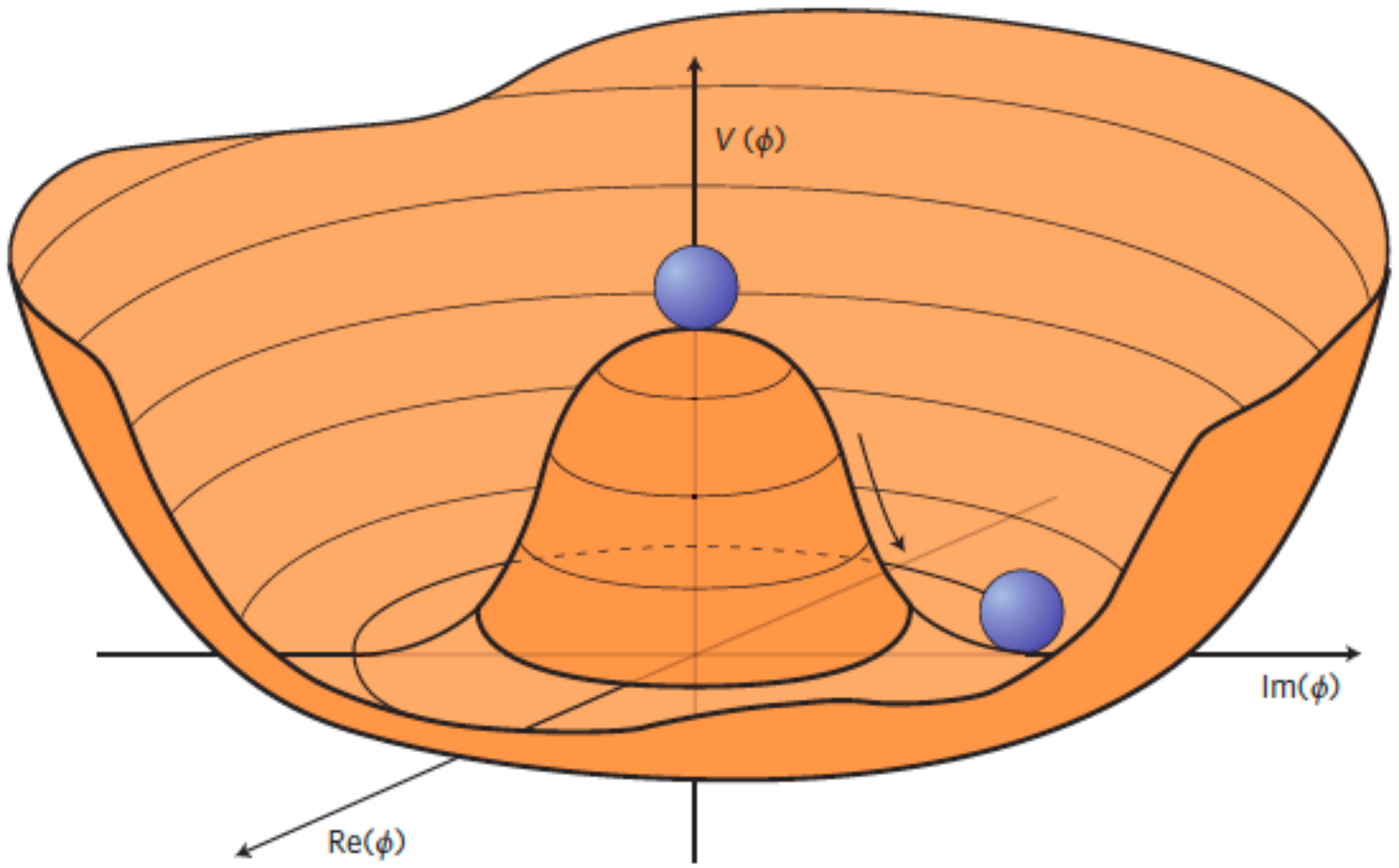
Notice: **no Higgs potential mentioned!**
Unsatisfied with a non-zero vev? Introduce a Higgs sector.
Minimal needed: scalar field with renormalizable potential leading to a vev:

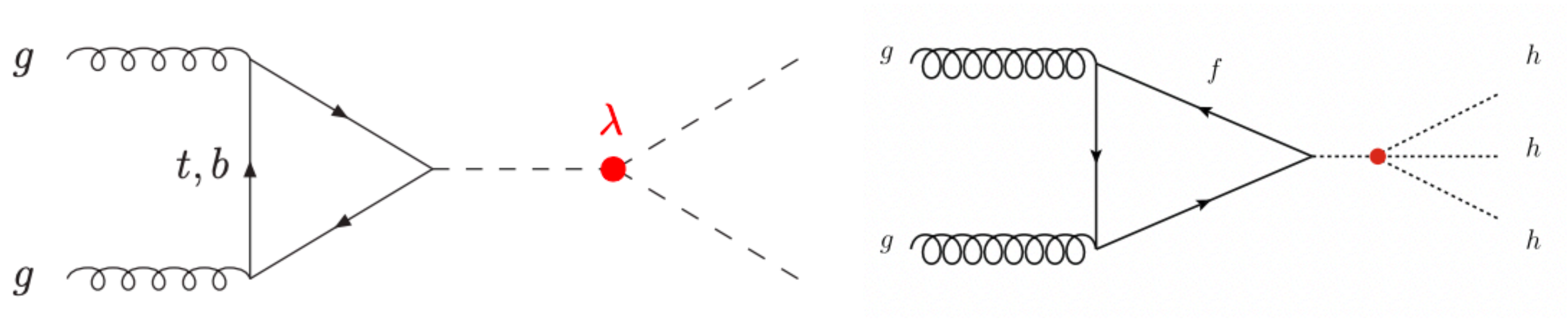
$$\phi(x) = \frac{1}{\sqrt{2}}[0,\ \ v + h(x)]$$

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

$$\mathscr{L}_\phi = |D_\mu \phi|^2 - V(\phi^\dagger \phi)$$

$$V(\phi^\dagger\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$





HHH production (theoretical POV)

Peskin and Schroeder:

However, there are many other quantum field theories that break $SU(2)$ spontaneously while leaving another global $SU(2)$ symmetry unbroken.

The question of the nature of the Higgs sector and the explicit mechanism of $SU(2) \times U(1)$ breaking is probably the most pressing open problem in the theory of elementary particles.

Since then, one scalar d.o.f found
Still much more to know!

$$V(h,?) = \frac{1}{2} m_h^2 h^2 + \ldots ?$$

Many possible Higgs sectors (composite Higgs, Susy, scalar extensions, etc)
Why? Many reasons (naturalness, hierarchy, my favourite: why not)
My second favourite: baryogenesis.

Baryogenesis

Problem: more matter than antimatter + CPT conservation in QFT!
=> need for dynamical mechanism to generate matter-antimatter asymmetry.
Sakharov conditions:
1. Baryon number violation

$$\Delta B = \Delta L = \pm 3 \tag{2.2}$$

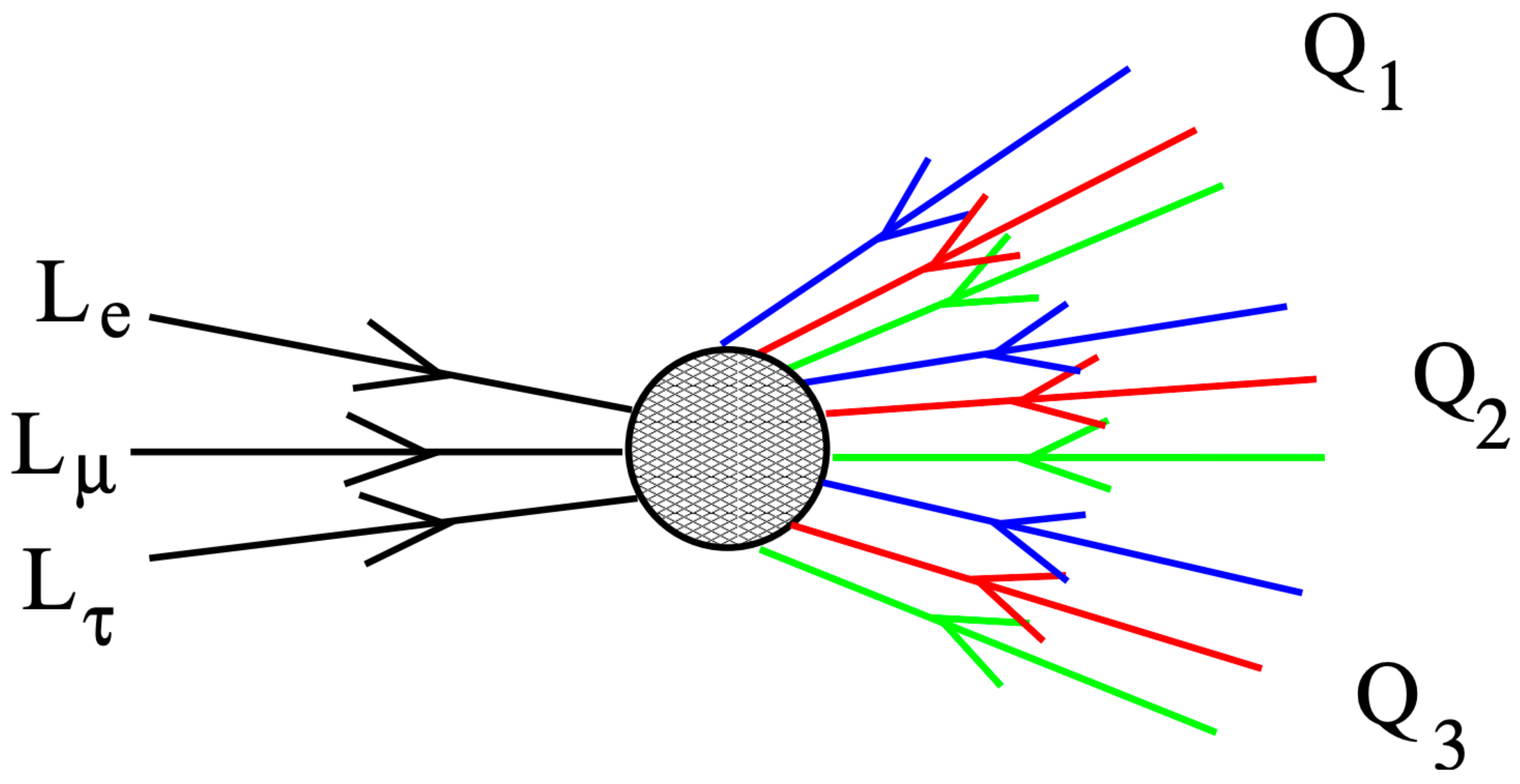


Fig. 4. The sphaleron.

In SM: triangle anomaly

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g^2}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}W_a^{\alpha\beta}W_a^{\gamma\delta}$$

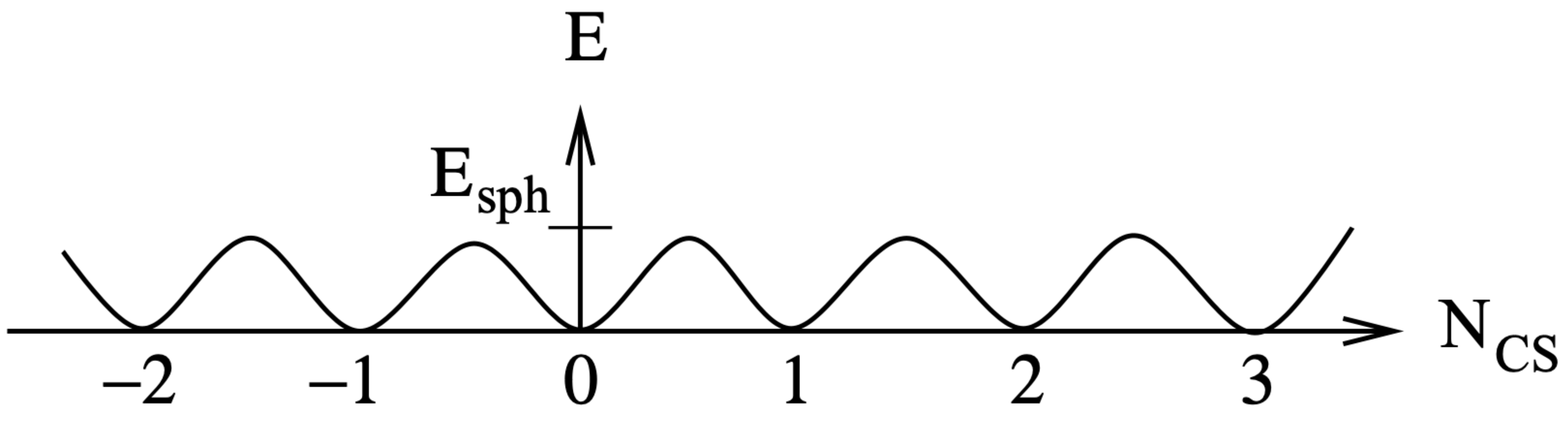
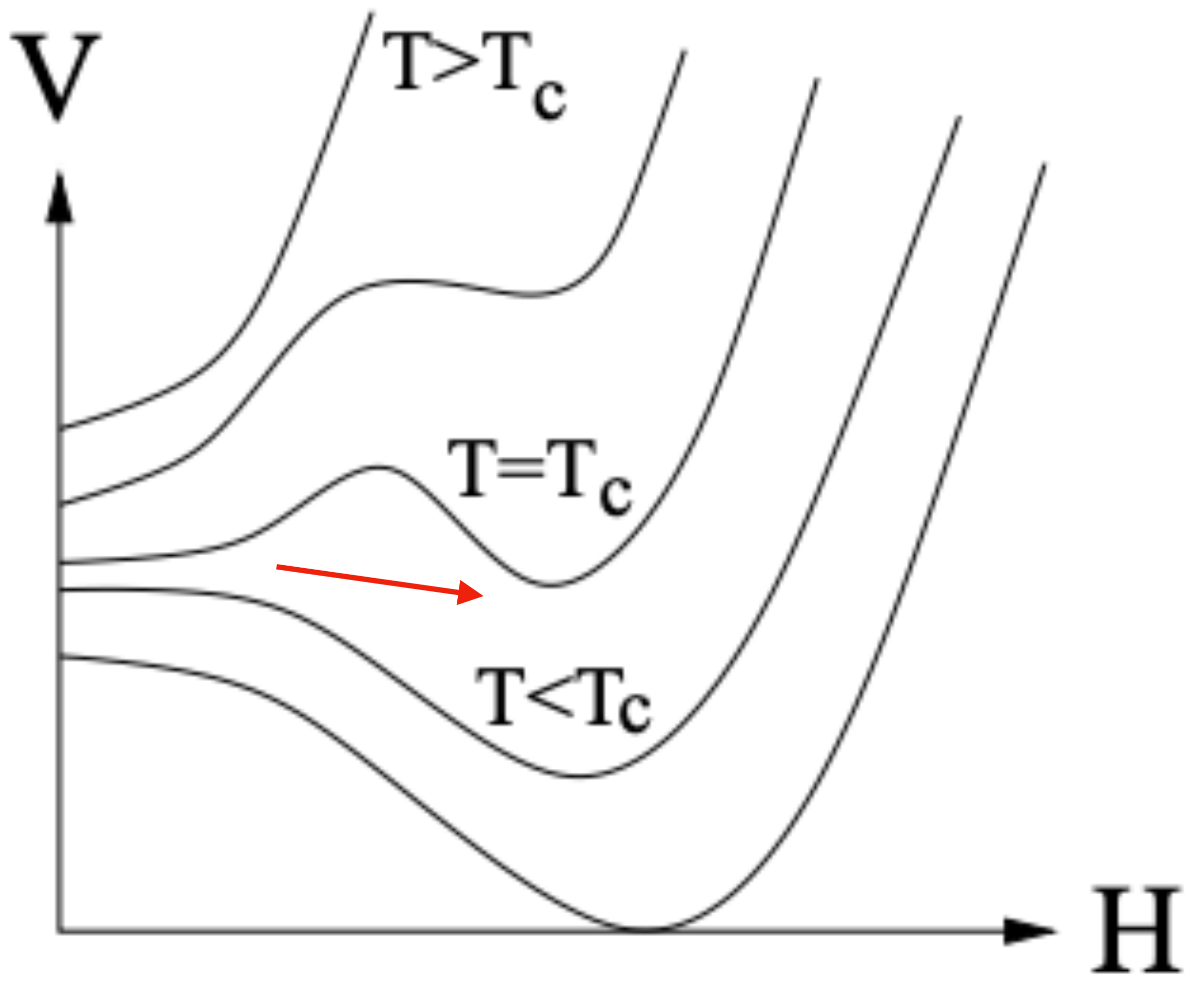


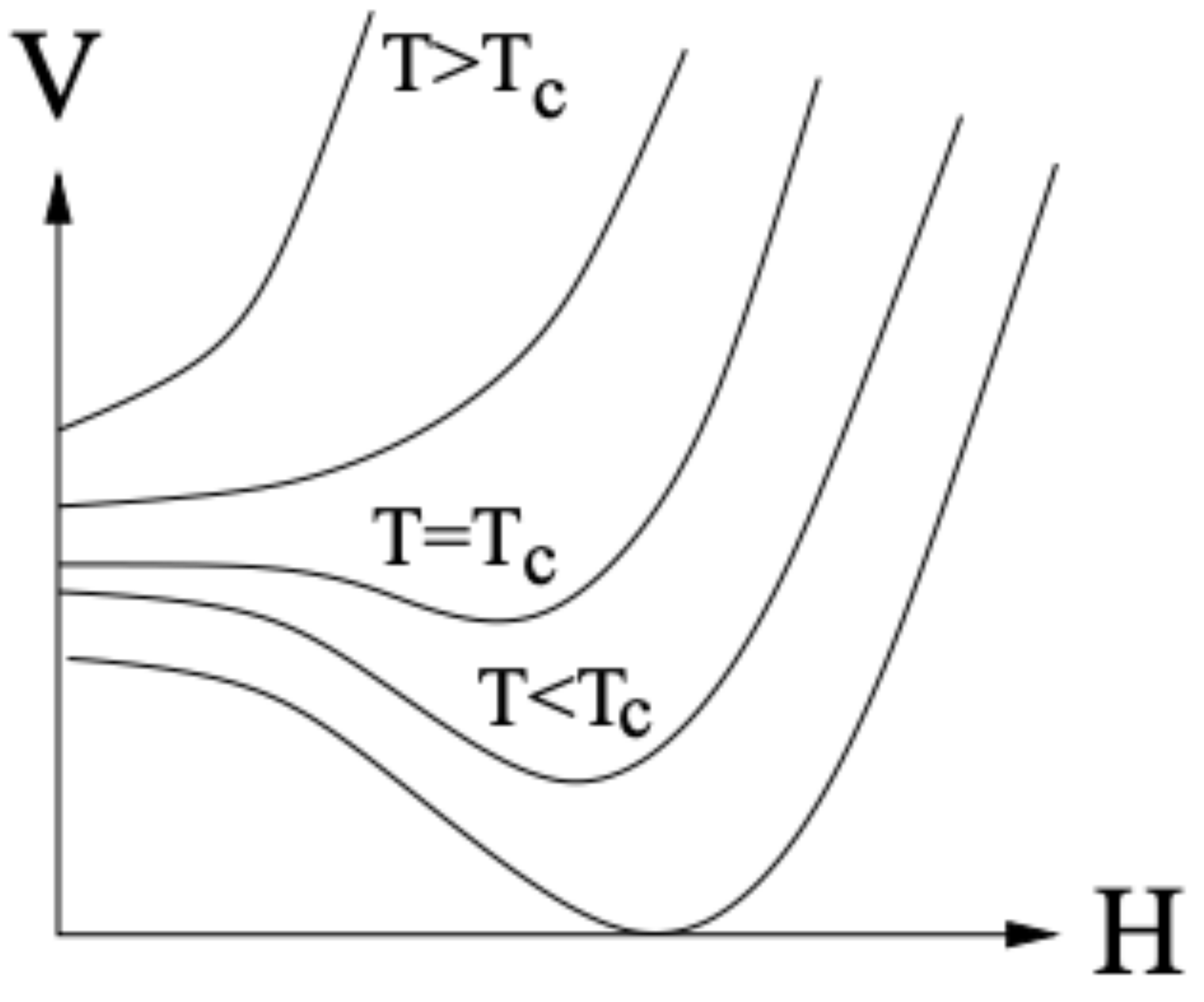
Fig. 8. Energy of gauge field configurations as a function of Chern-Simons number.

$$E_{sph} \sim \frac{8\pi v}{g} \to 0$$ before sym. breaking

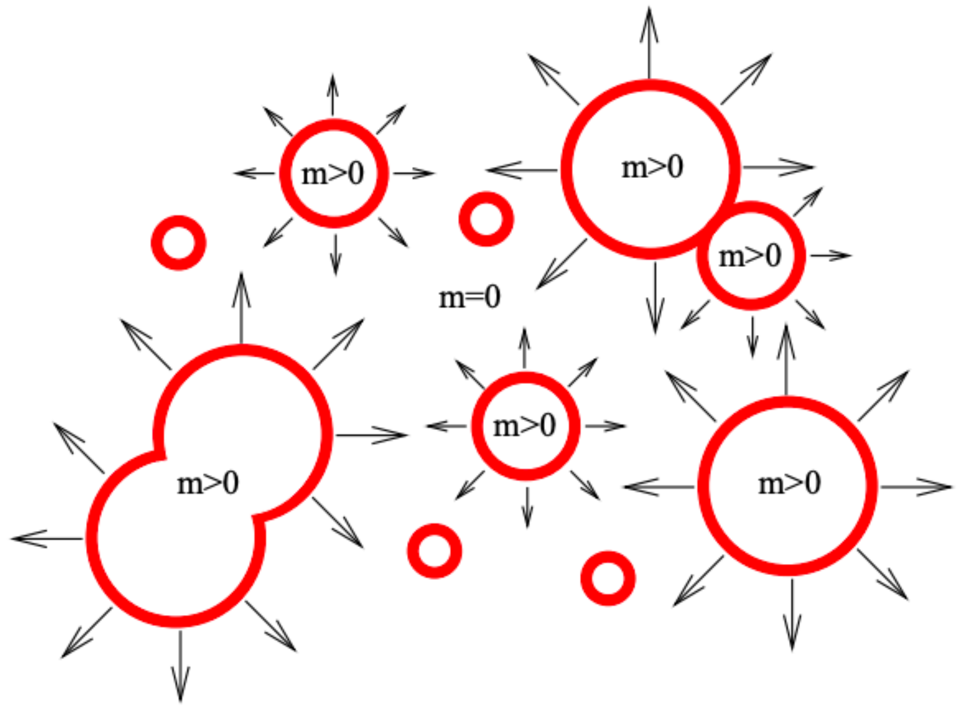
Electroweak Phase Transition

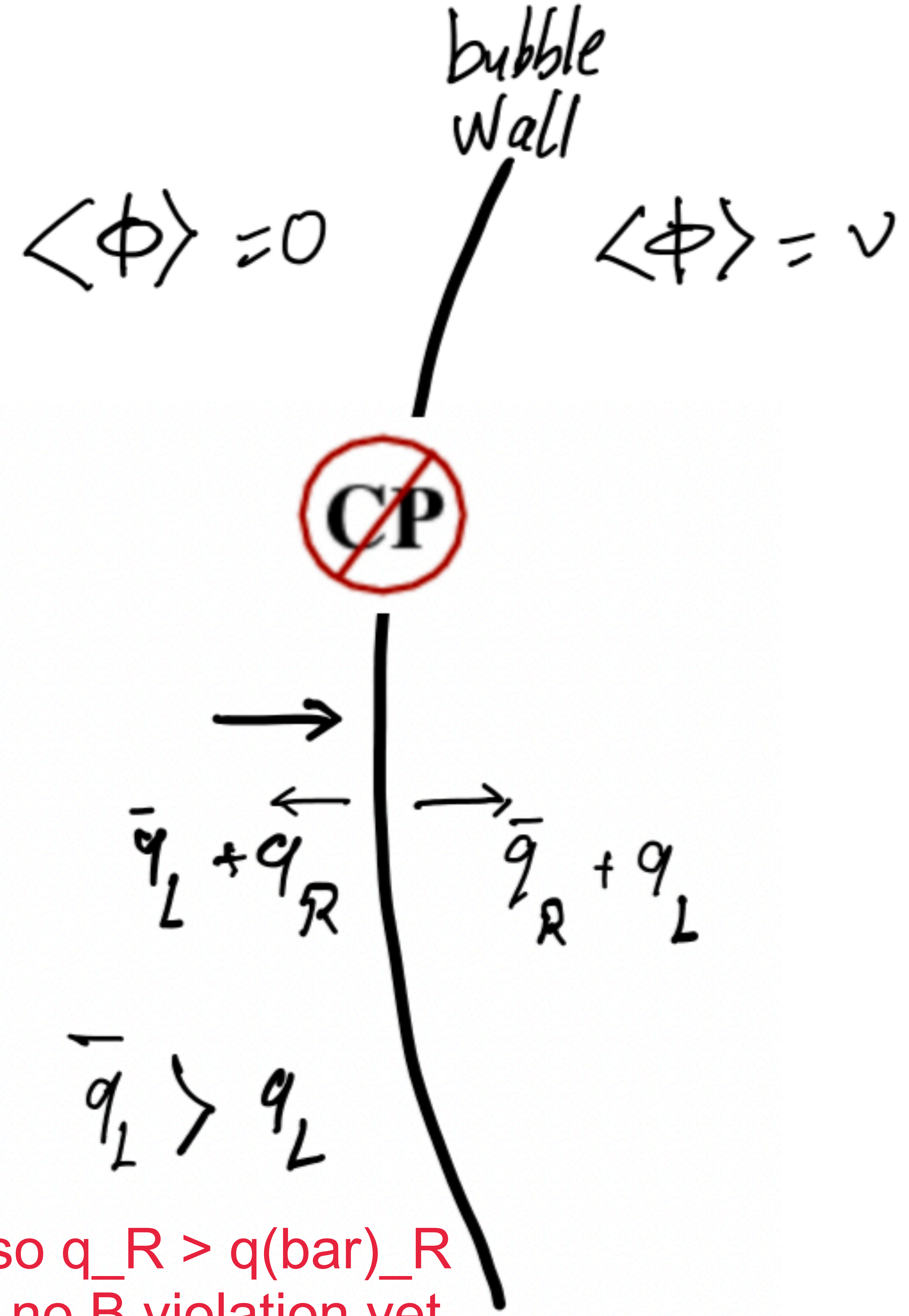


first order phase transition
FOPT



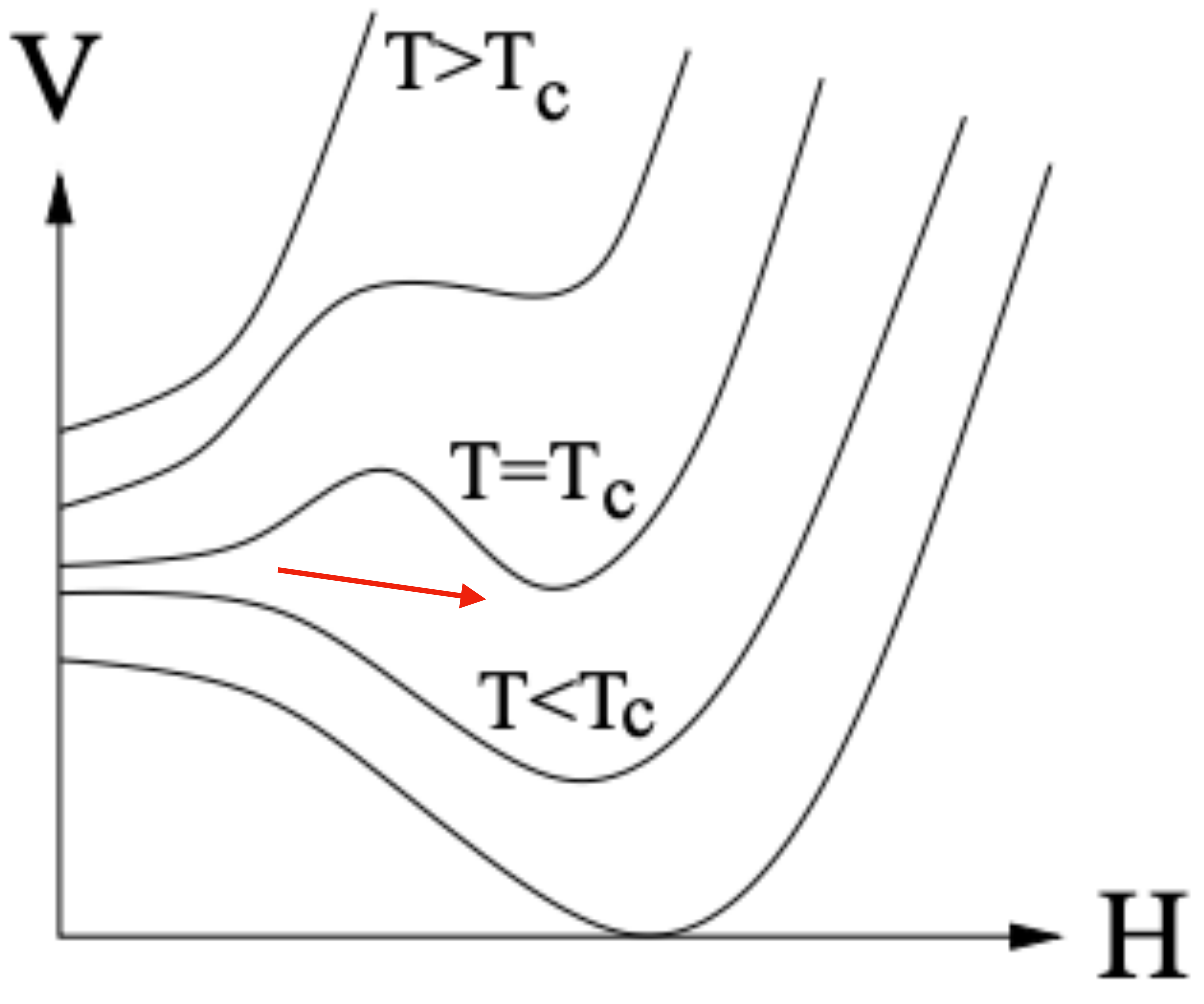
second order phase transition
SOPT
(or crossover)



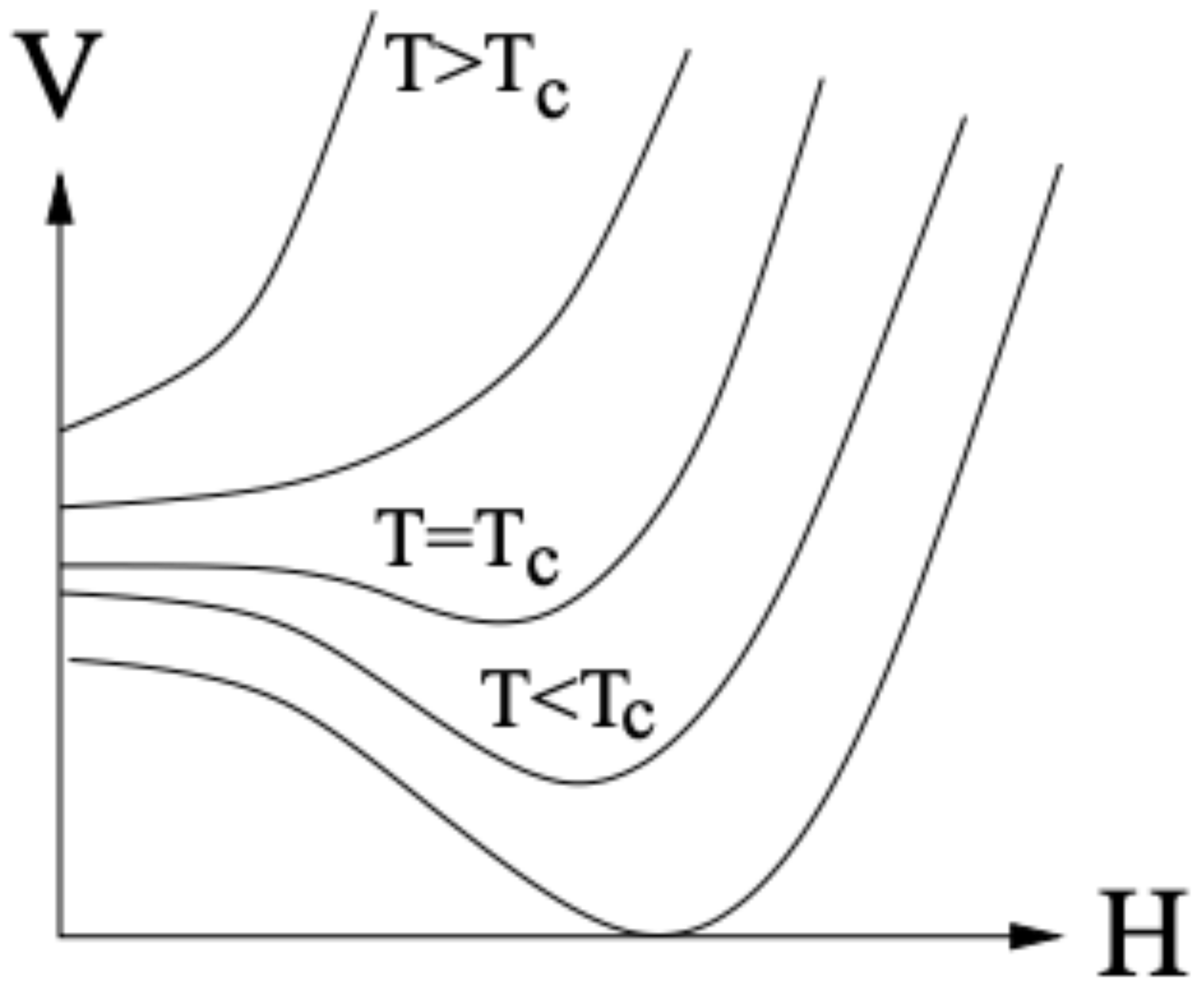


Also q_R > q(bar)_R
so no B violation yet.

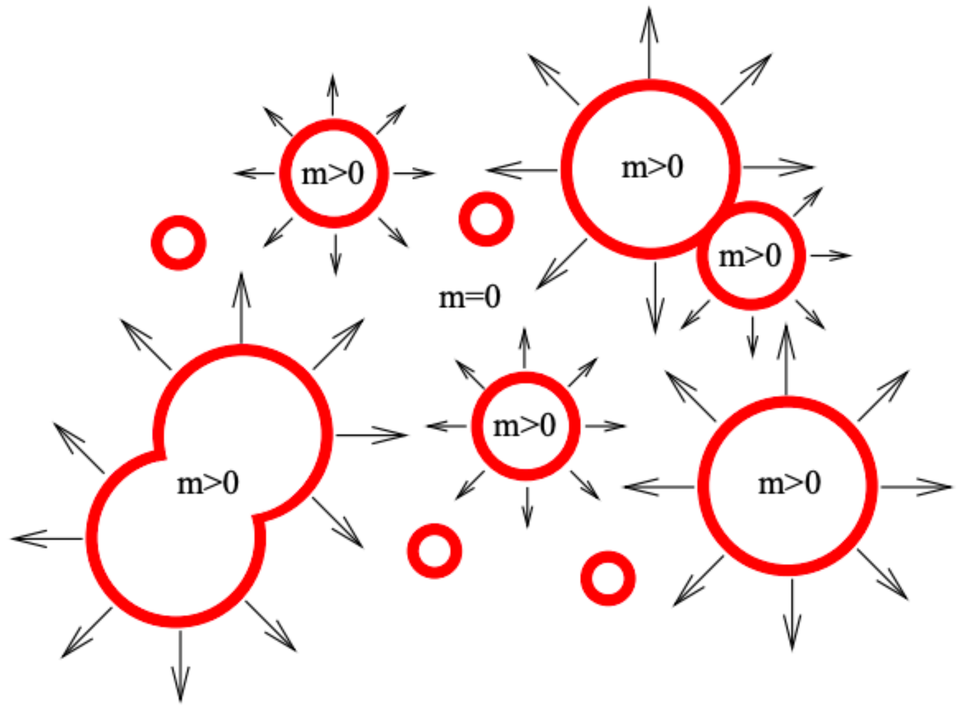
Electroweak Phase Transition

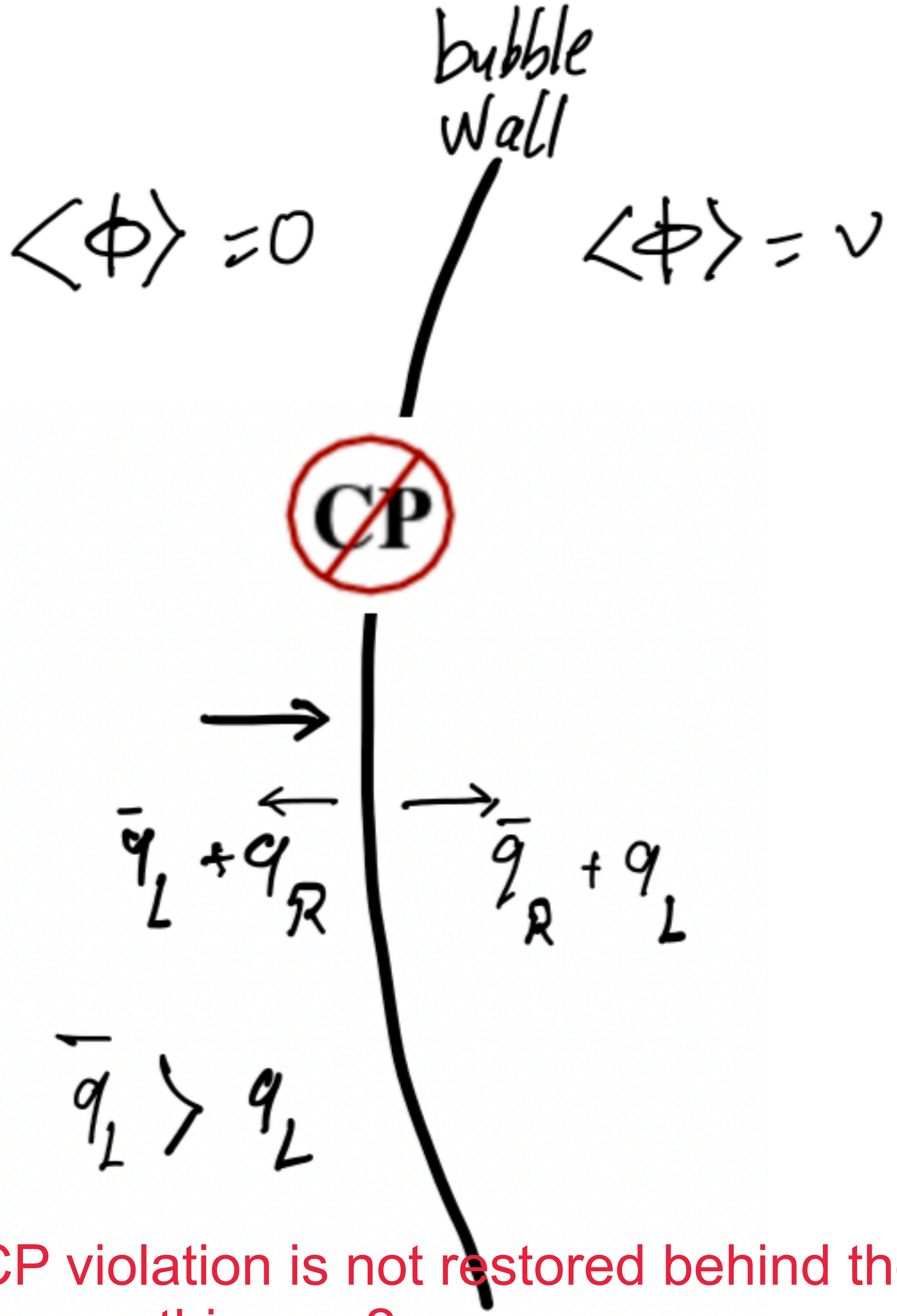


first order phase transition
FOPT



second order phase transition
SOPT
(or crossover)





Question: CP violation is not restored behind the wall!
Can we measure this now?