Scalars 2015, 3-7 Dec. 2015

Fate of false vacuum at one-loop

Yutaro Shoji
University of Tokyo

arXiv:1511.04860 [hep-ph]

Collaborators: Motoi Endo, Takeo Moroi, Mihoko Nojiri (KEK)

Scalars 2015, 3-7 Dec. 2015

Varia ~ Barrier
(for Japanese...)

Fate of false vacuum at one-loop

Yutaro Shoji
University of Tokyo

arXiv:1511.04860 [hep-ph]

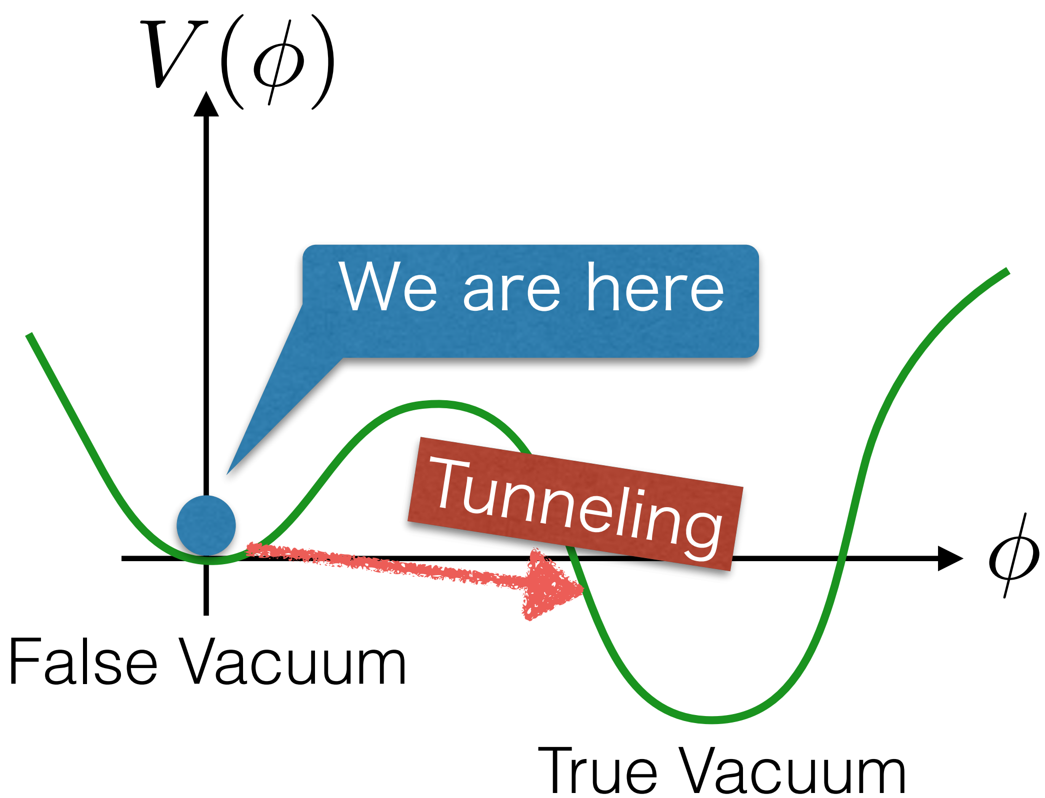
Collaborators: Motoi Endo, Takeo Moroi, Mihoko Nojiri (KEK)

Contents

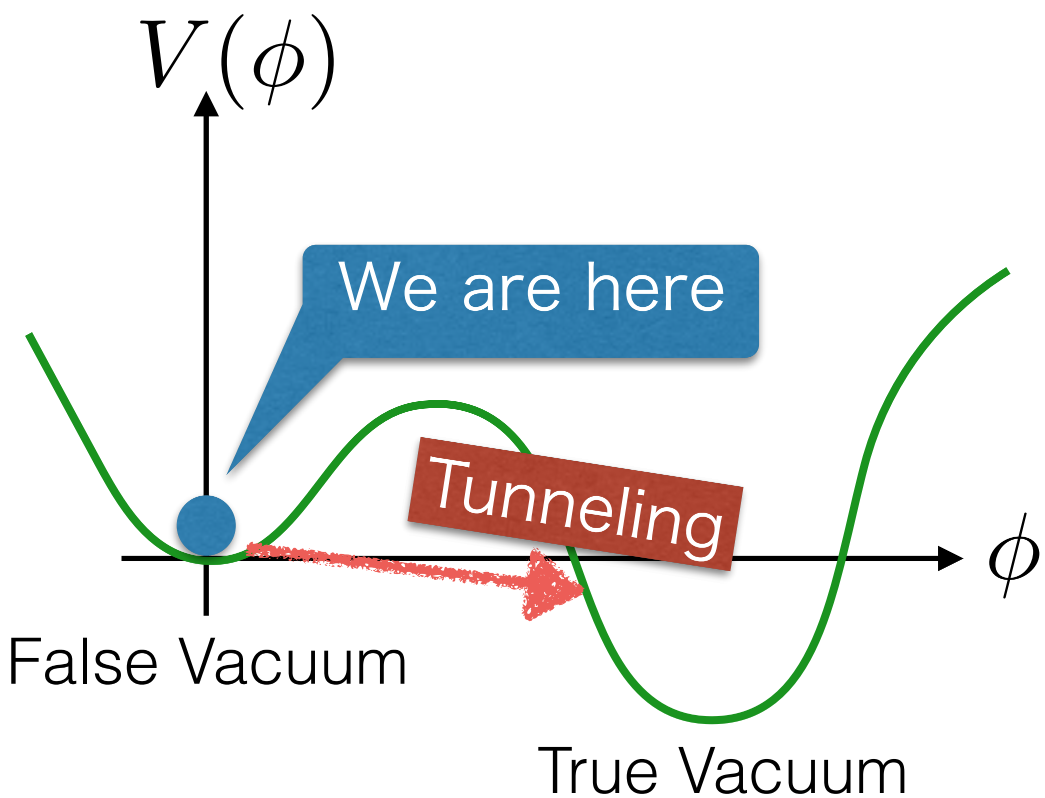
- Introduction
- SM + stau system
- Summary

Introduction

Vacuum decay



Vacuum decay



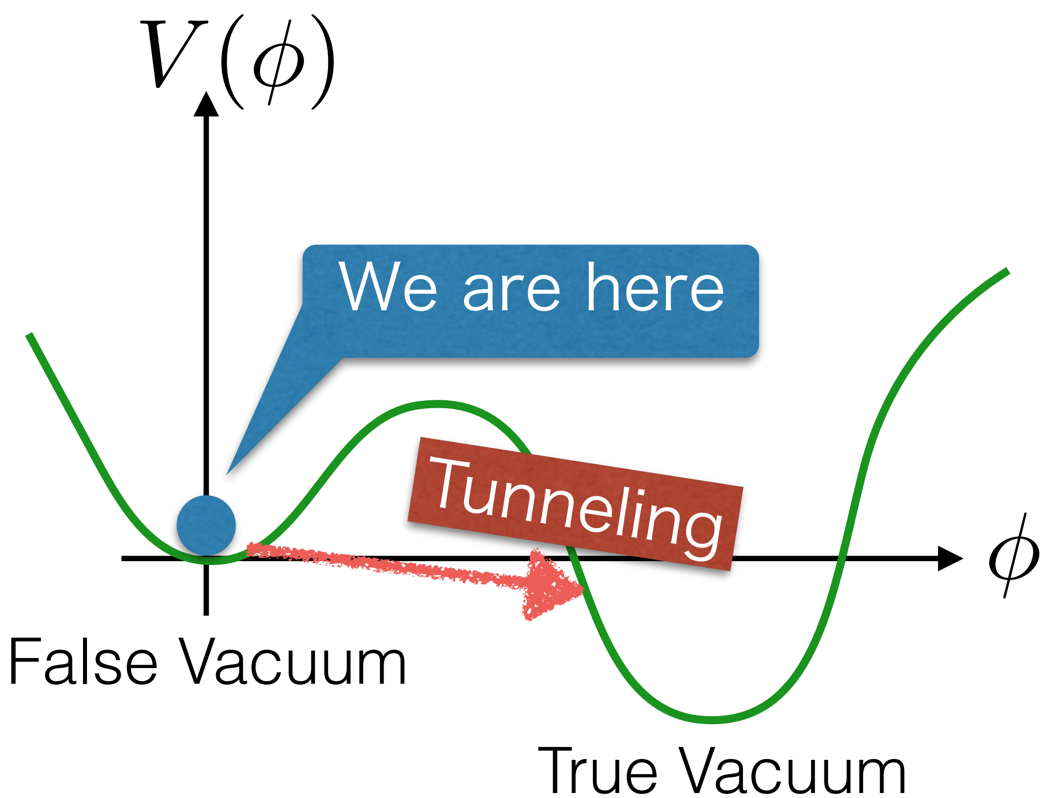
Tree level potential

ex.) Supersymmetry

$h\tilde{t}_L\tilde{t}_R$ Higgs mass, hgg, hγγ, …

$h\tilde{\ell}_L\tilde{\ell}_R$ muon g-2, hγγ, …

Vacuum decay



Tree level potential

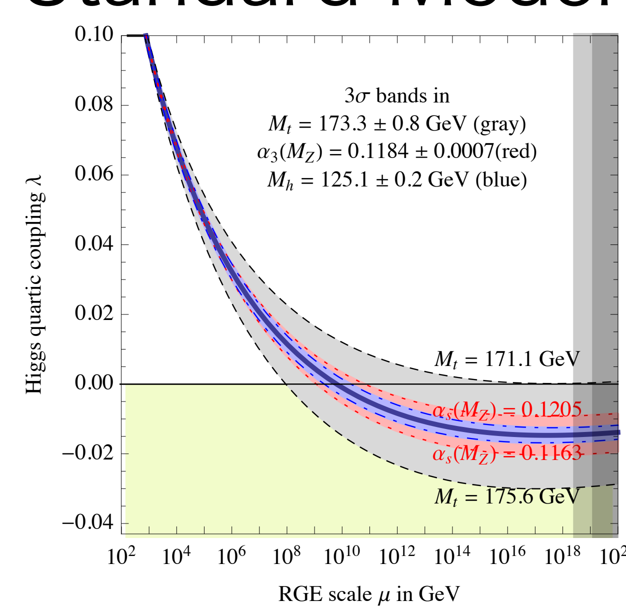
ex.) Supersymmetry

$h\tilde{t}_L\tilde{t}_R$ Higgs mass, hgg, hγγ, …

$h\tilde{\ell}_L\tilde{\ell}_R$ muon g-2, hγγ, …

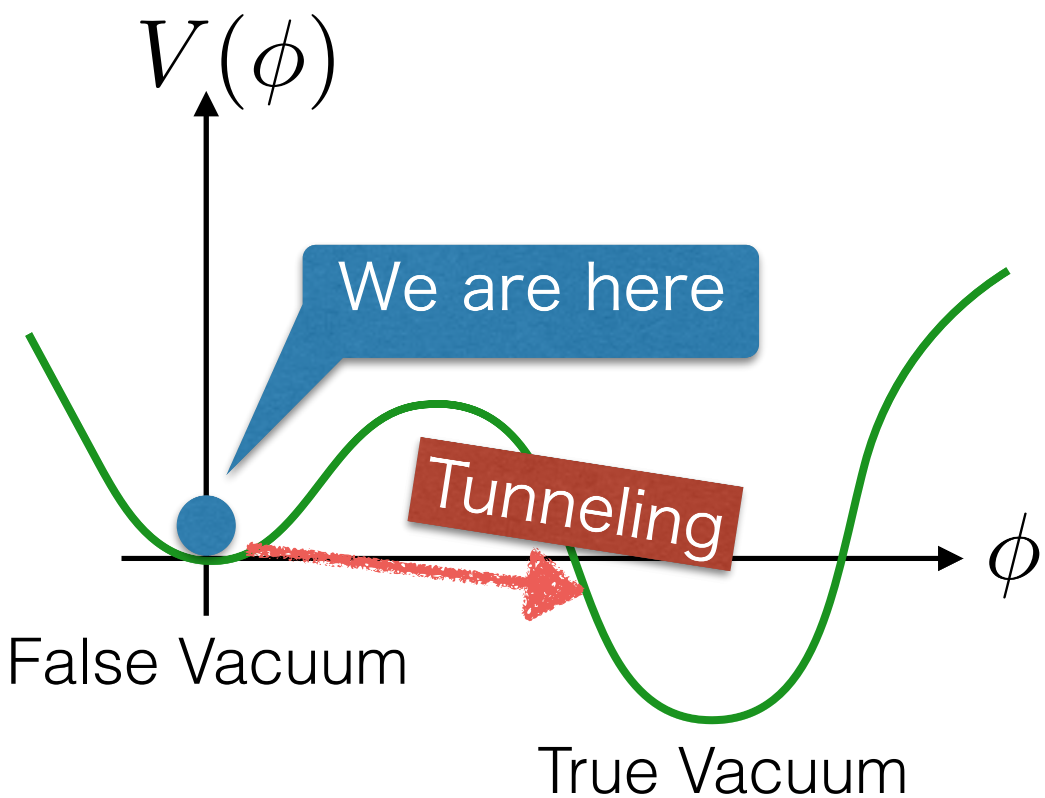
Effective potential

ex.) Standard Model



D. Buttazzo, et.al., 1307.3536/hep-ph

Vacuum decay



Tree level potential

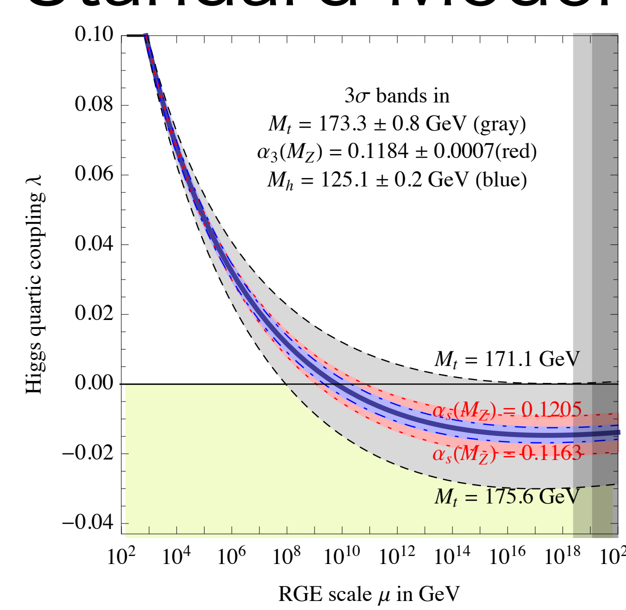
ex.) Supersymmetry

$h\tilde{t}_L\tilde{t}_R$ Higgs mass, hgg, hγγ, …

$h\tilde{\ell}_L\tilde{\ell}_R$ muon g-2, hγγ, …

Effective potential

ex.) Standard Model



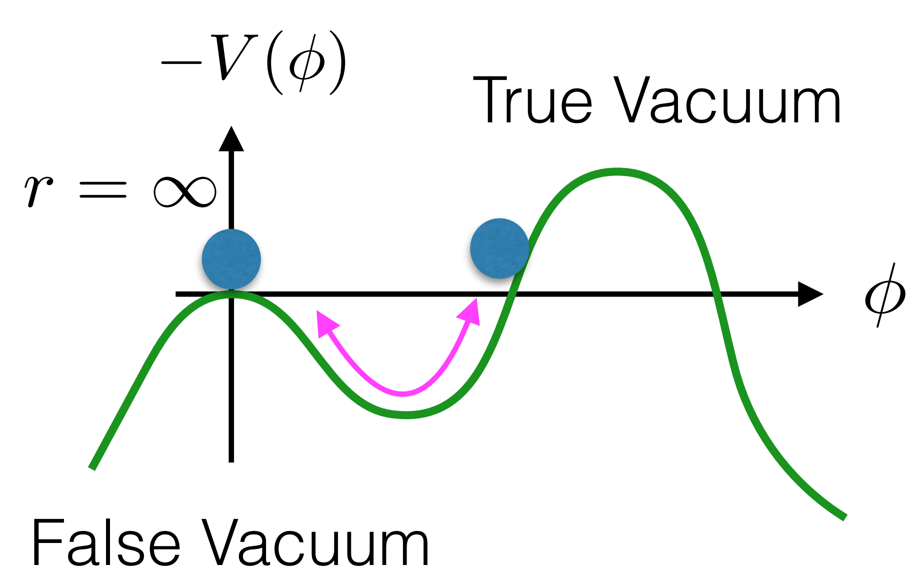
D. Buttazzo, et.al., 1307.3536/hep-ph

Decay rate

<u>Bubble nucleation rate</u>

$$\gamma = Ae^{-B}$$

classical bounce solution



<u>Pre-exponential factor</u>

$$A \sim \mu^4$$

typical scale

<u>1-bounce action</u>

$$B = S(\phi_B)$$

O(4) symmetric

Toy model

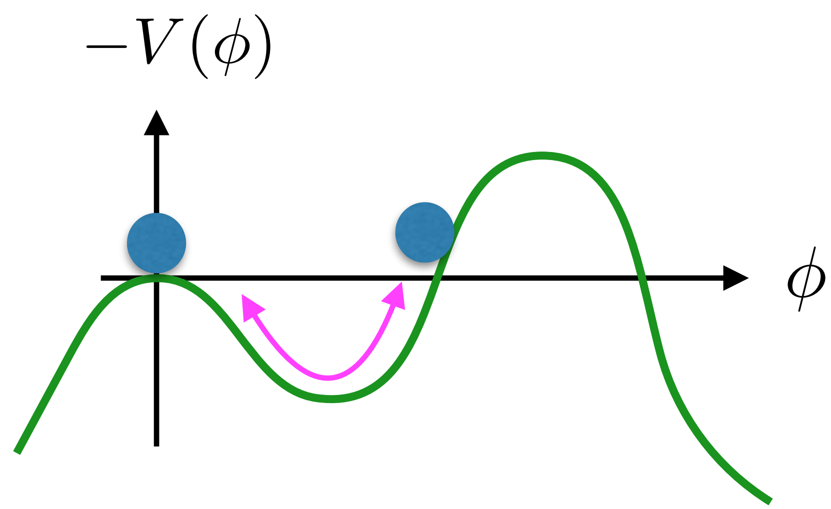
Potential

$$V = \frac{m^2}{2}\phi^2 - \frac{A}{2}\phi^3 + \frac{\alpha}{8}\phi^4$$

Toy model

Potential $$V = \frac{m^2}{2}\phi^2 - \frac{A}{2}\phi^3 + \frac{\alpha}{8}\phi^4$$

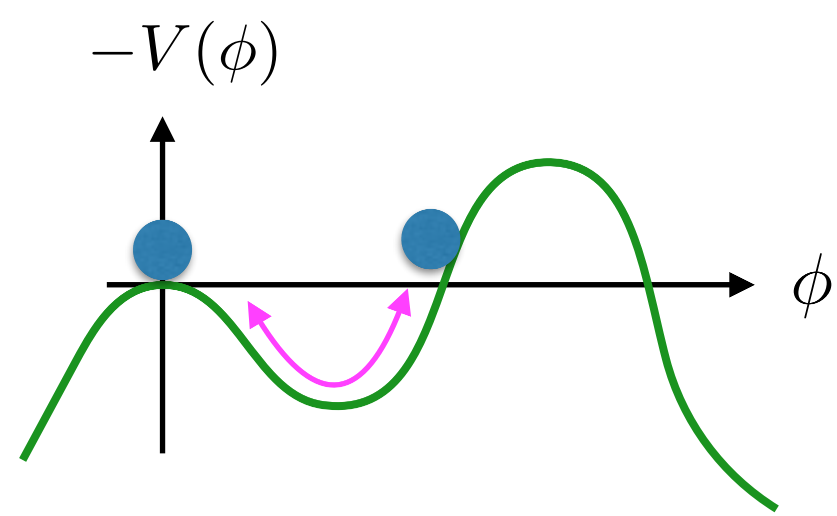
Bounce $$\partial^2\phi = V'(\phi)$$



Toy model

Potential $$V = \frac{m^2}{2}\phi^2 - \frac{A}{2}\phi^3 + \frac{\alpha}{8}\phi^4$$

Bounce $$\partial^2\phi = V'(\phi)$$

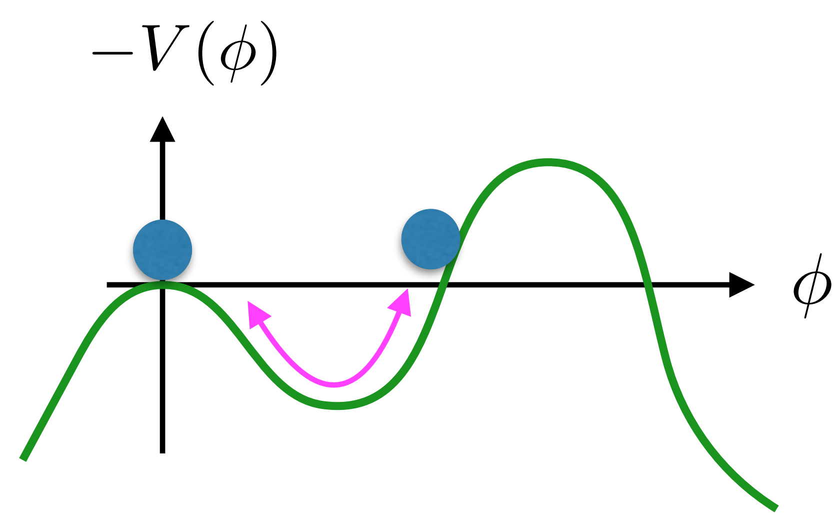


Action $$B = S_E(\phi_B) = \int d^4x \left[\frac{1}{2}(\partial\phi_B)^2 + V(\phi_B)\right]$$

Toy model

Potential
$$V = \frac{m^2}{2}\phi^2 - \frac{A}{2}\phi^3 + \frac{\alpha}{8}\phi^4$$

Bounce
$$\partial^2\phi = V'(\phi)$$



Action
$$B = S_E(\phi_B) = \int d^4x \left[\frac{1}{2}(\partial\phi_B)^2 + V(\phi_B)\right]$$

Decay rate
$$\gamma \simeq m^4 e^{-B}$$

Toy model

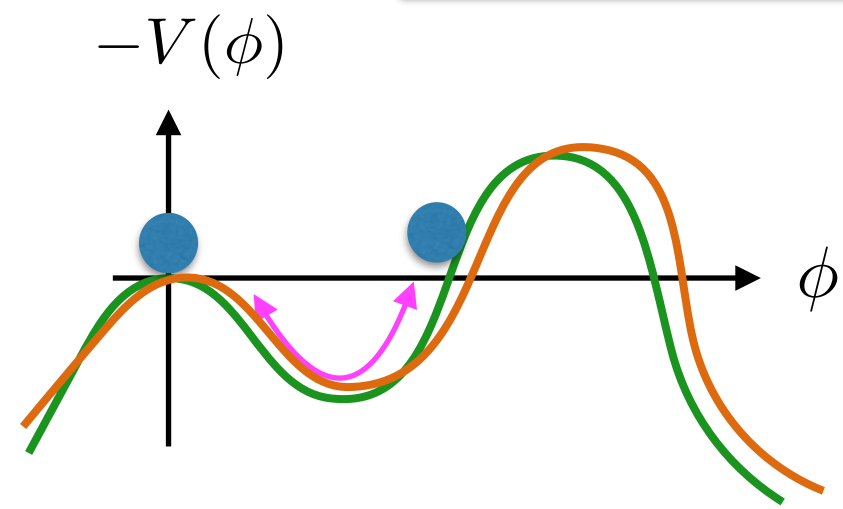
Potential

$$V = -\bar{t}(Q)\phi + \frac{\bar{m}^2(Q)}{2}\phi^2 - \frac{\bar{A}(Q)}{2}\phi^3 + \frac{\bar{\alpha}(Q)}{8}\phi^4$$

Scale dependent

Bounce

$$\partial^2\phi = V'(\phi)$$



Action

$$B = S_E(\phi_B) = \int d^4x \left[\frac{1}{2}(\partial\phi_B)^2 + V(\phi_B)\right]$$

Decay rate

$$\gamma \simeq m^4 e^{-B}$$

Toy model

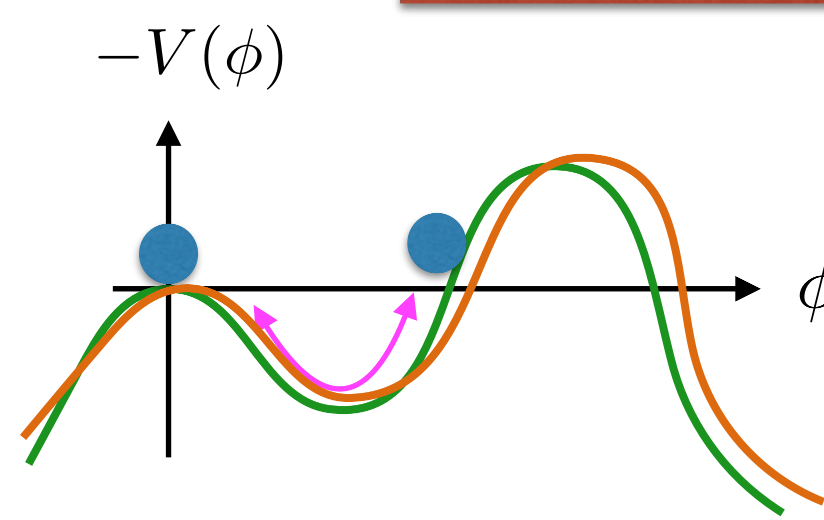
Potential

$$V = -\bar{t}(Q)\phi + \frac{\bar{m}^2(Q)}{2}\phi^2 - \frac{\bar{A}(Q)}{2}\phi^3 + \frac{\bar{\alpha}(Q)}{8}\phi^4$$

Scale dependent

Bounce

$$\partial^2\phi = V'(\phi)$$



Action

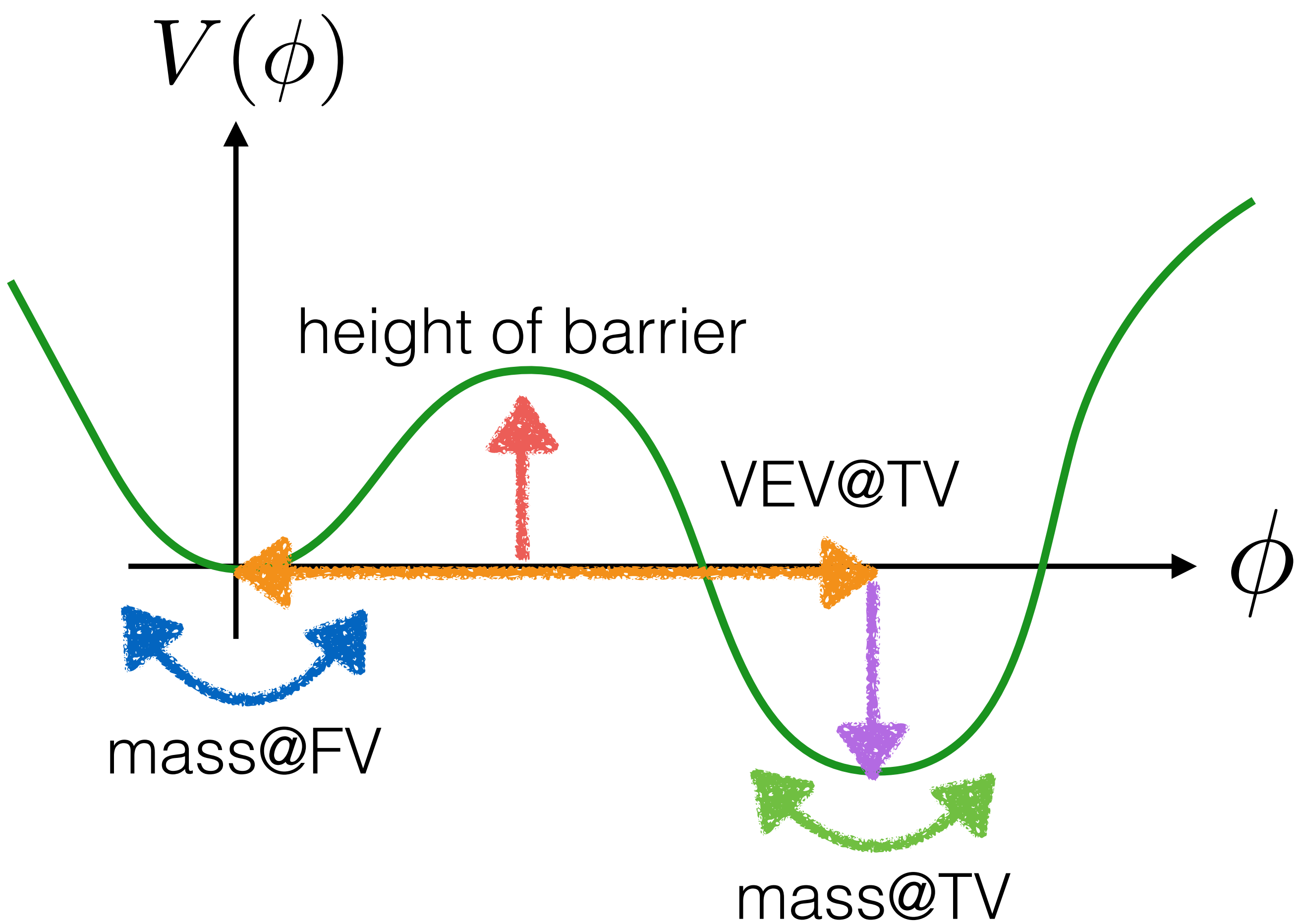
$$B = S_E(\phi_B) = \int d^4x \left[\frac{1}{2}(\partial\phi_B)^2 + V(\phi_B)\right]$$

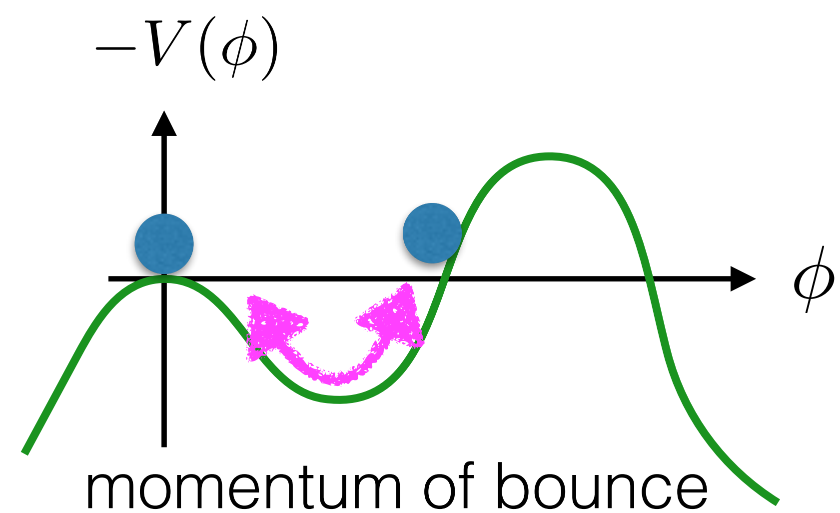
Decay rate

$$\gamma \simeq m^4 e^{-B}$$

OK, use a "typical" scale!

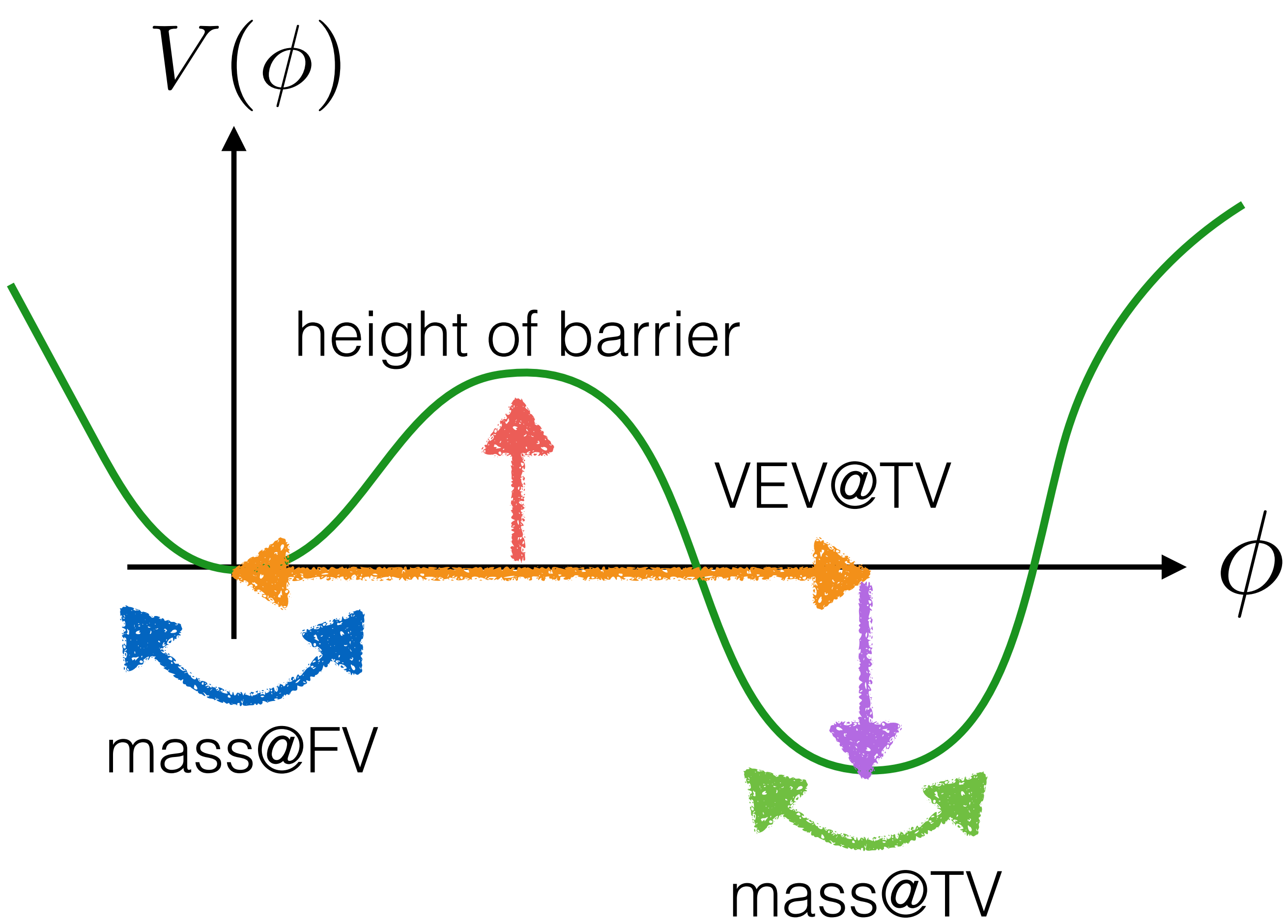
Renormalization scale

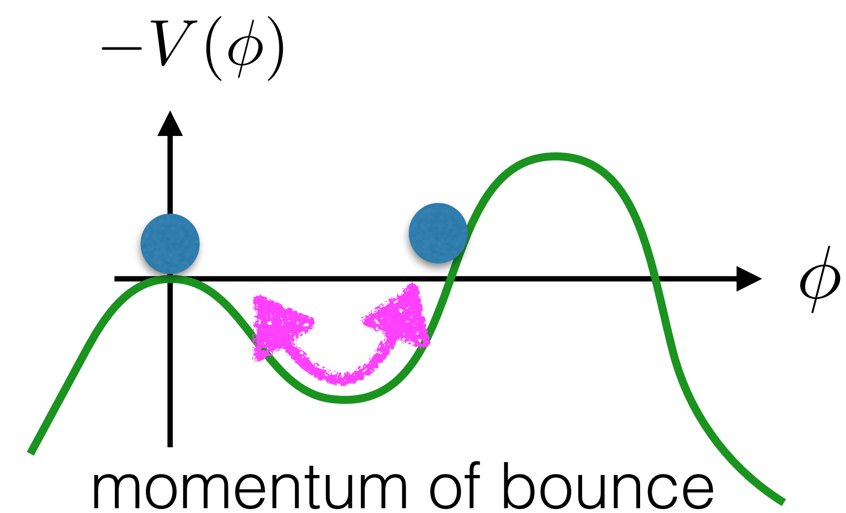




OK, use a “typical” scale!

Renormalization scale

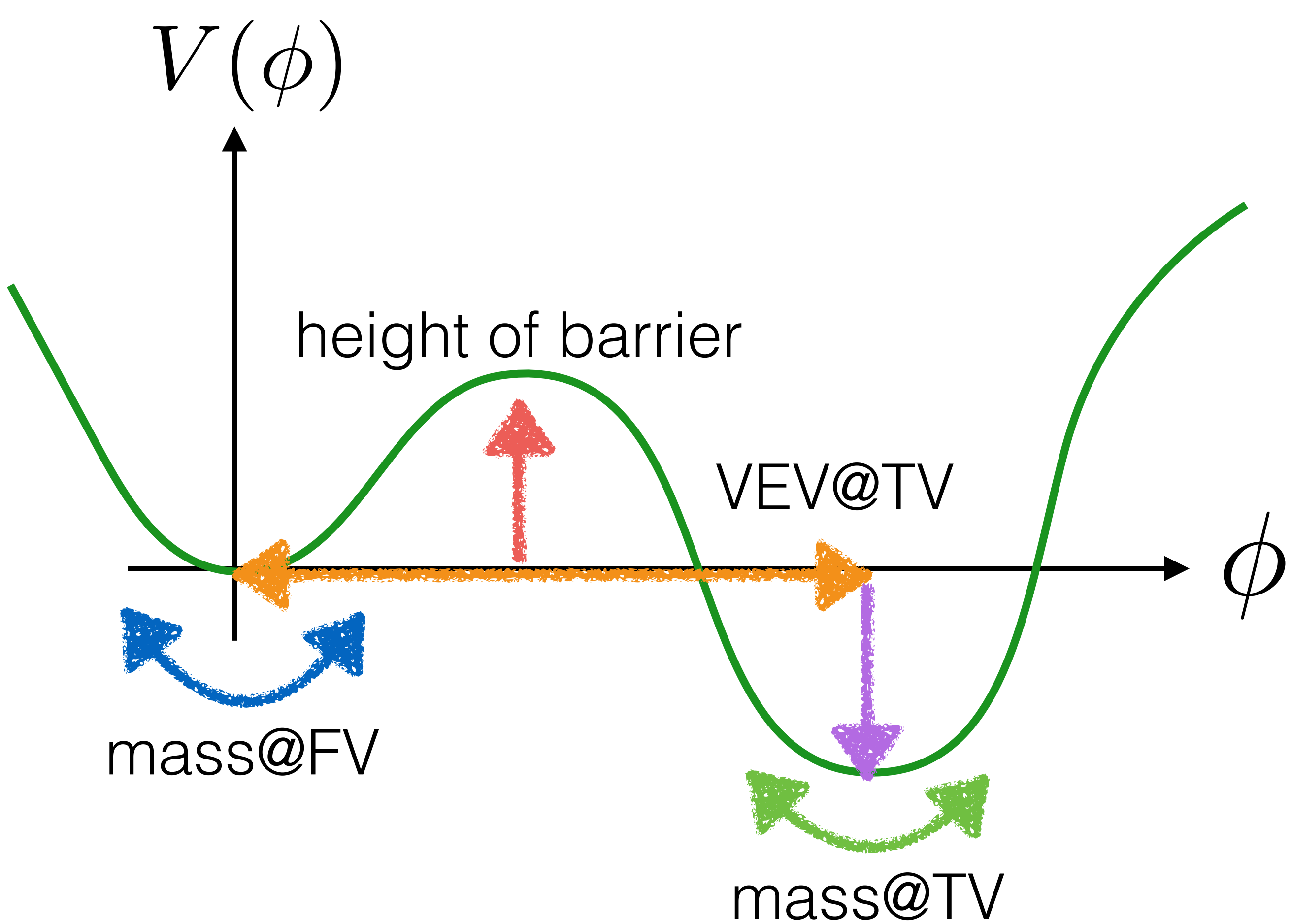


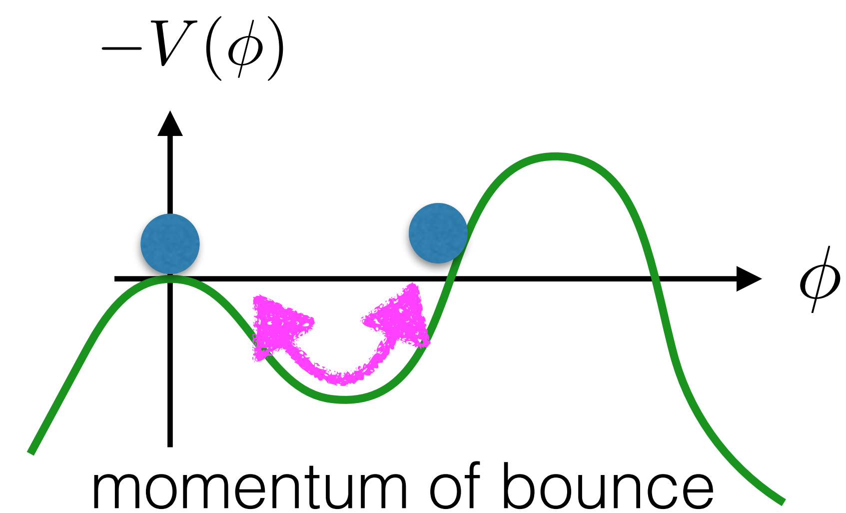


OK, use a “typical” scale!

But,... I don’t know what is the best scale.

Renormalization scale





OK, use a “typical” scale!

But,… I don’t know what is the best scale.

Does the decay rate change so much?

How large is the scale dependence?

$$V = -\bar{t}(Q)\phi + \frac{\bar{m}^2(Q)}{2}\phi^2 - \frac{\bar{A}(Q)}{2}\phi^3 + \frac{\bar{\alpha}(Q)}{8}\phi^4$$

Beta functions

$$\beta_t = \frac{3Am^2}{16\pi^2} \qquad \beta_{m^2} = \frac{3}{16\pi^2}(\alpha m^2 + 3A^2)$$

$$\beta_A = \frac{9\alpha A}{16\pi^2} \qquad \beta_\alpha = \frac{9\alpha^2}{16\pi^2}$$

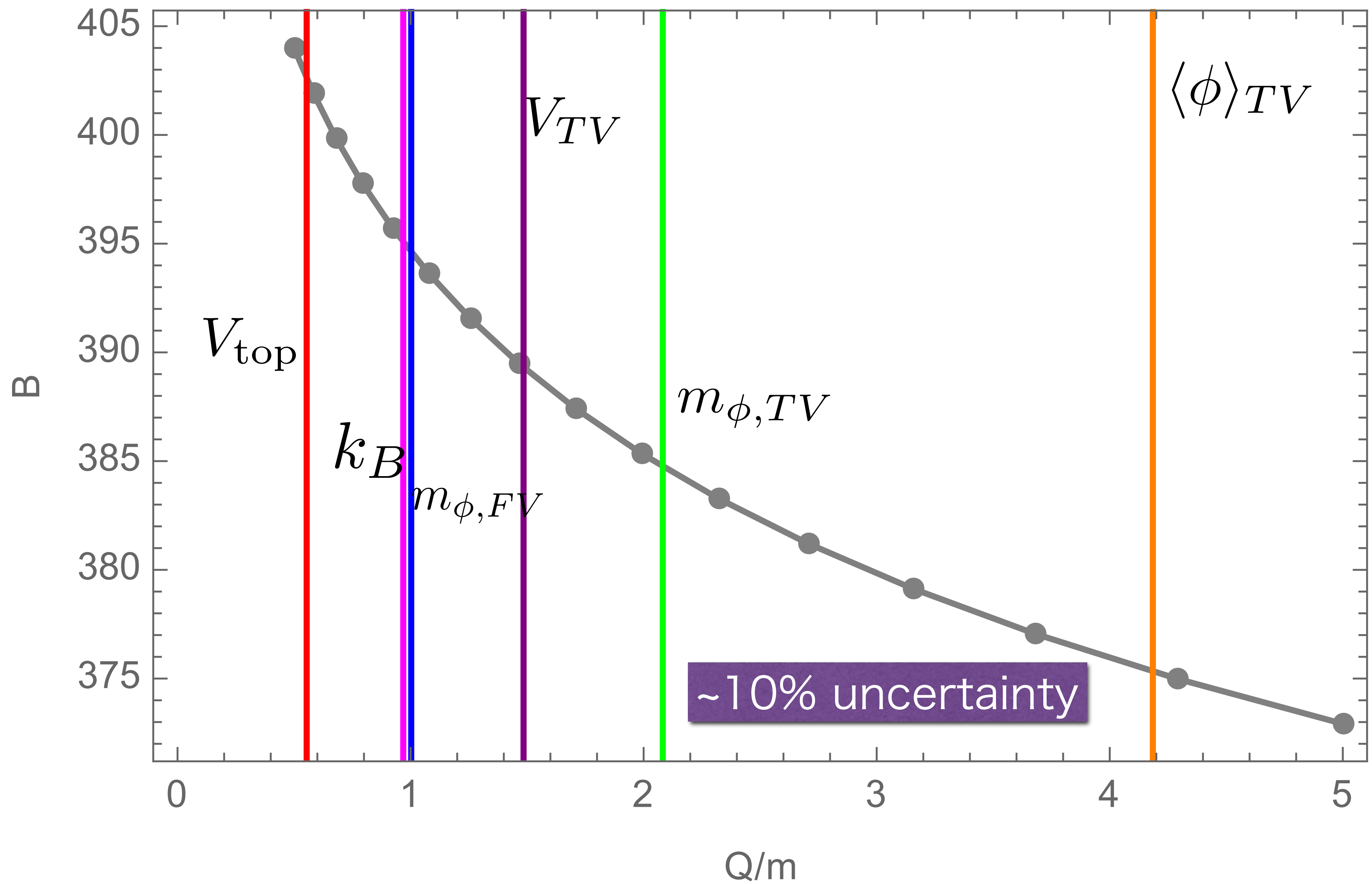
Renormalization conditions

@ $Q = m$

$$\bar{m}^2(m) = m^2,\ \bar{A}(m) = m,\ \bar{t}(m) = 0,\ \bar{\alpha}(m) = 0.6$$

How large is the scale dependence?

CosmoTransitions

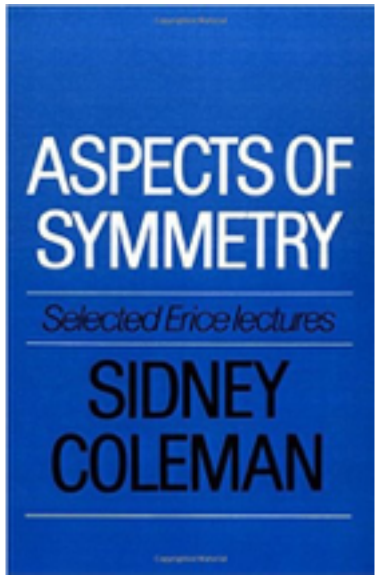


can be much larger in a realistic model (top loop)

Pre-exponential factor

$$\gamma = A e^{-B}$$

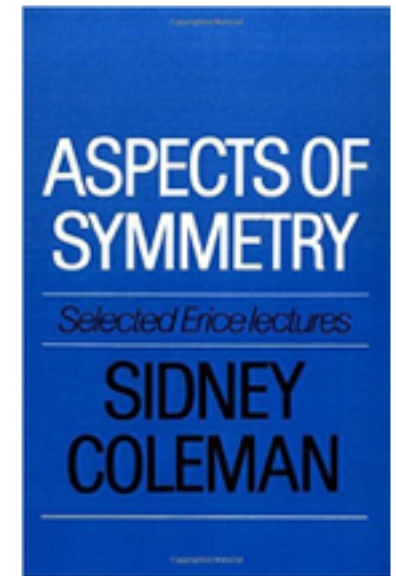
$$A = \frac{B^2}{4\pi^2}\left(\frac{\det' S''|_{\mathrm{Bounce}}}{\det S''|_{\mathrm{False}}}\right)^{-1/2}$$

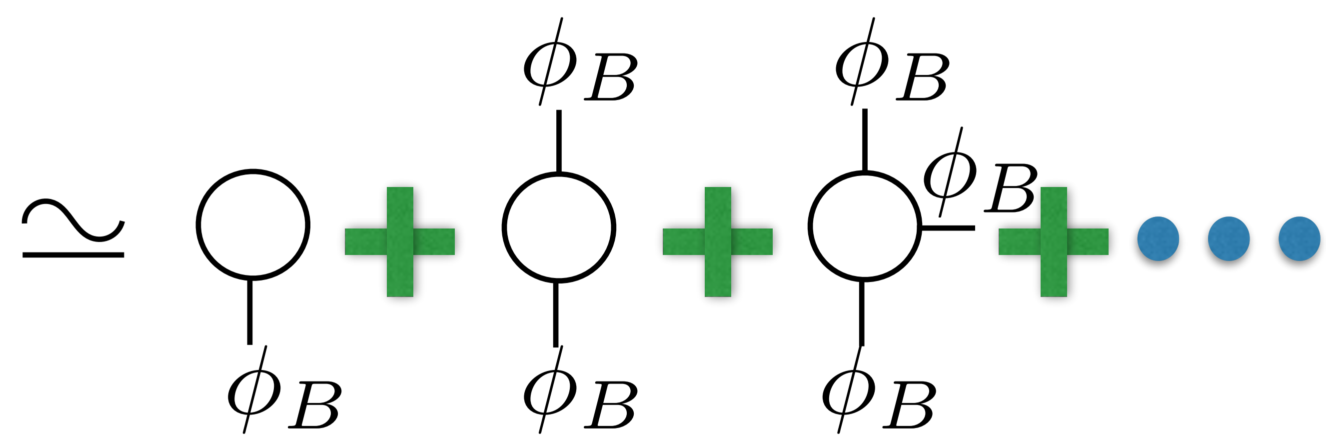


Pre-exponential factor

$$\gamma = Ae^{-B}$$

$$A = \frac{B^2}{4\pi^2}\left(\frac{\det' S''|_{\mathrm{Bounce}}}{\det S''|_{\mathrm{False}}}\right)^{-1/2}$$

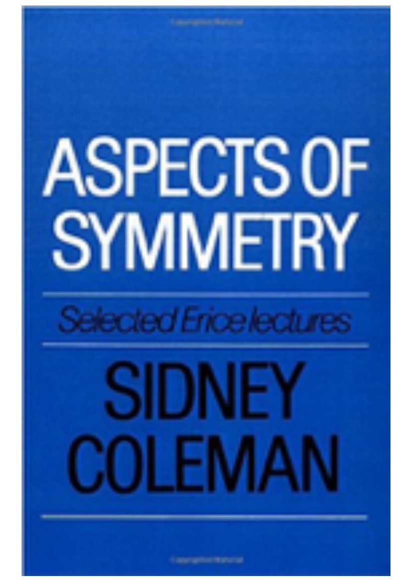




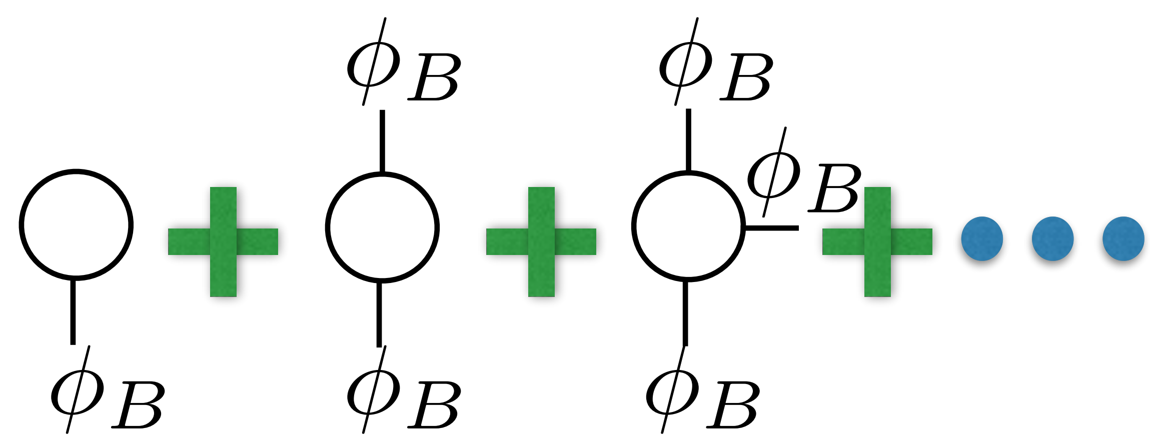
Pre-exponential factor

$$\gamma = Ae^{-B}$$

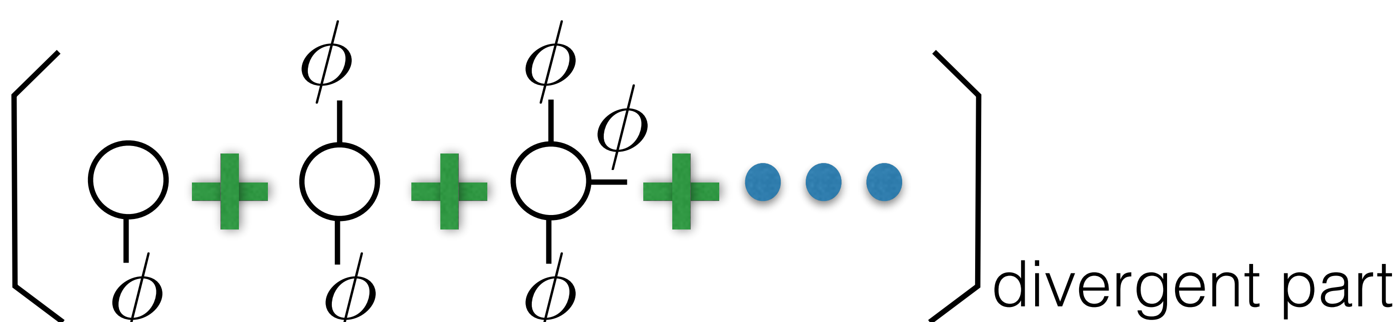
$$A = \frac{B^2}{4\pi^2}\left(\frac{\det' S''|_{\mathrm{Bounce}}}{\det S''|_{\mathrm{False}}}\right)^{-1/2}$$



$\simeq$



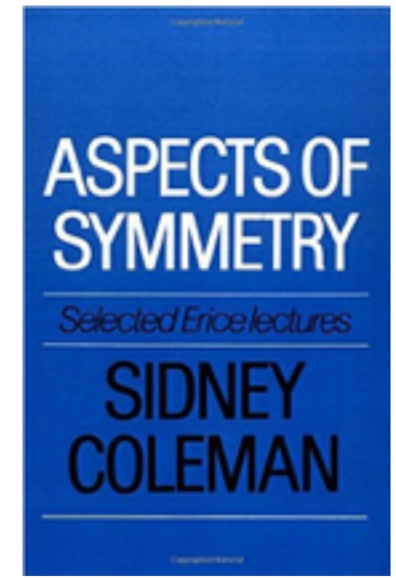
cf.) RGE is related to



Pre-exponential factor

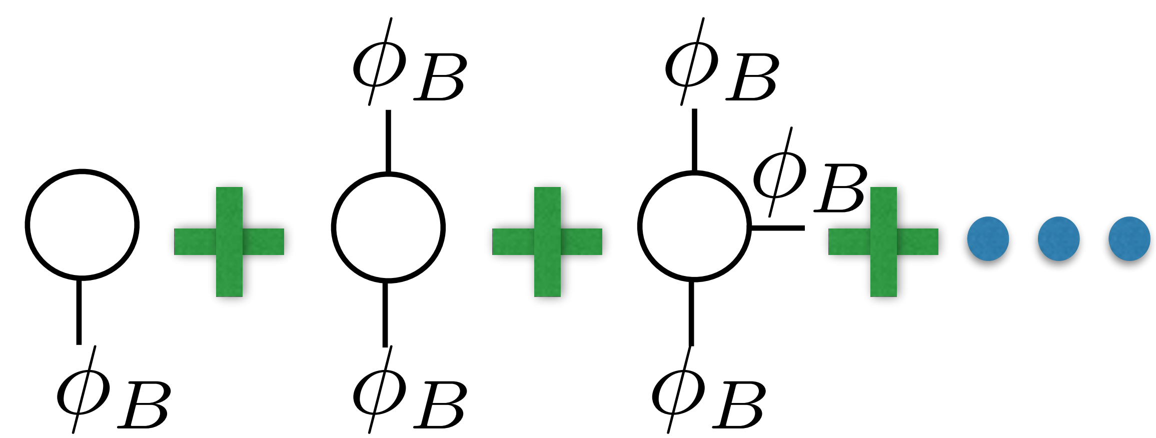
$$\gamma = Ae^{-B}$$

$$A = \frac{B^2}{4\pi^2}\left(\frac{\det' S''|_{\mathrm{Bounce}}}{\det S''|_{\mathrm{False}}}\right)^{-1/2}$$

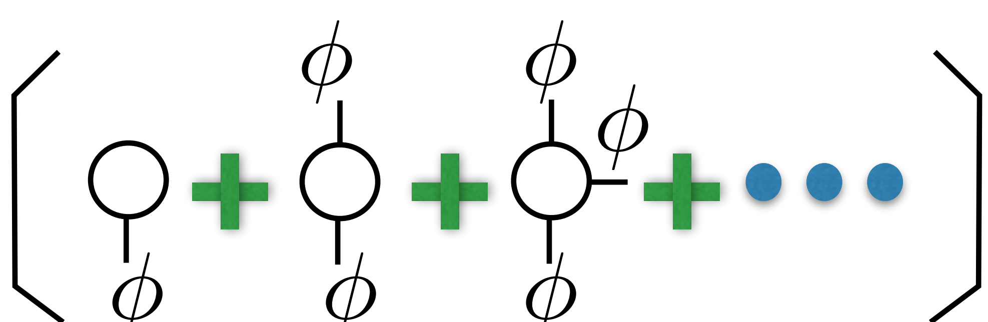


Expectation

cancellation of
the scale dependence
@1-loop

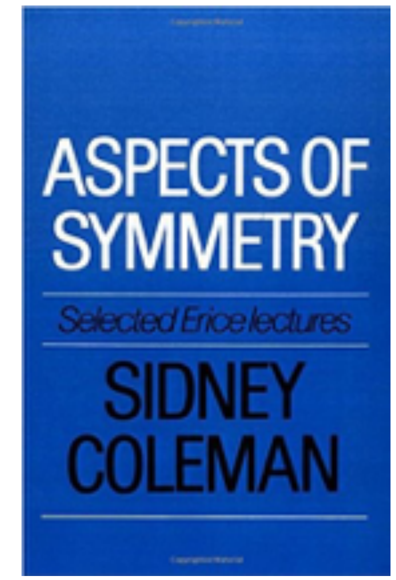
$\simeq$ 

cf.) RGE is related to


divergent part

Pre-exponential factor

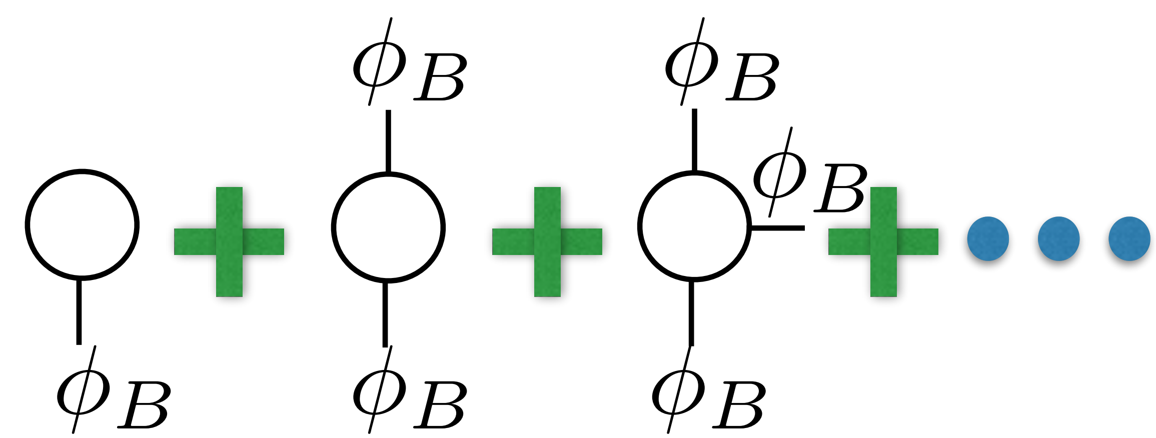
A way to calculate



$$\gamma = Ae^{-B}$$

$$A = \frac{B^2}{4\pi^2}\left(\frac{\det' S''|_{\text{Bounce}}}{\det S''|_{\text{False}}}\right)^{-1/2}$$

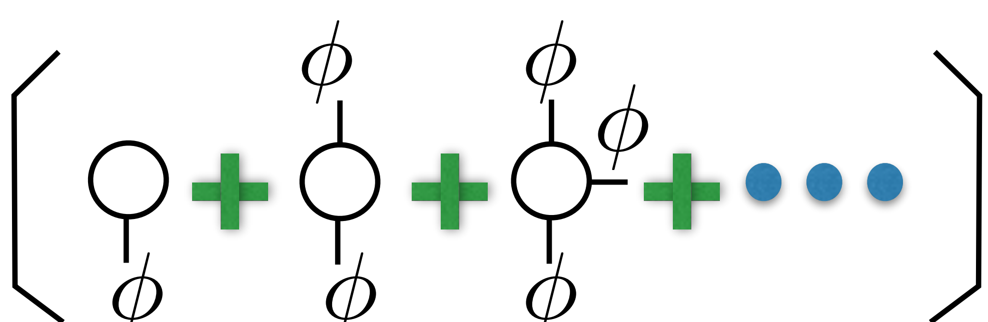
$\simeq$



<u>Expectation</u>

cancellation of
the scale dependence
@1-loop

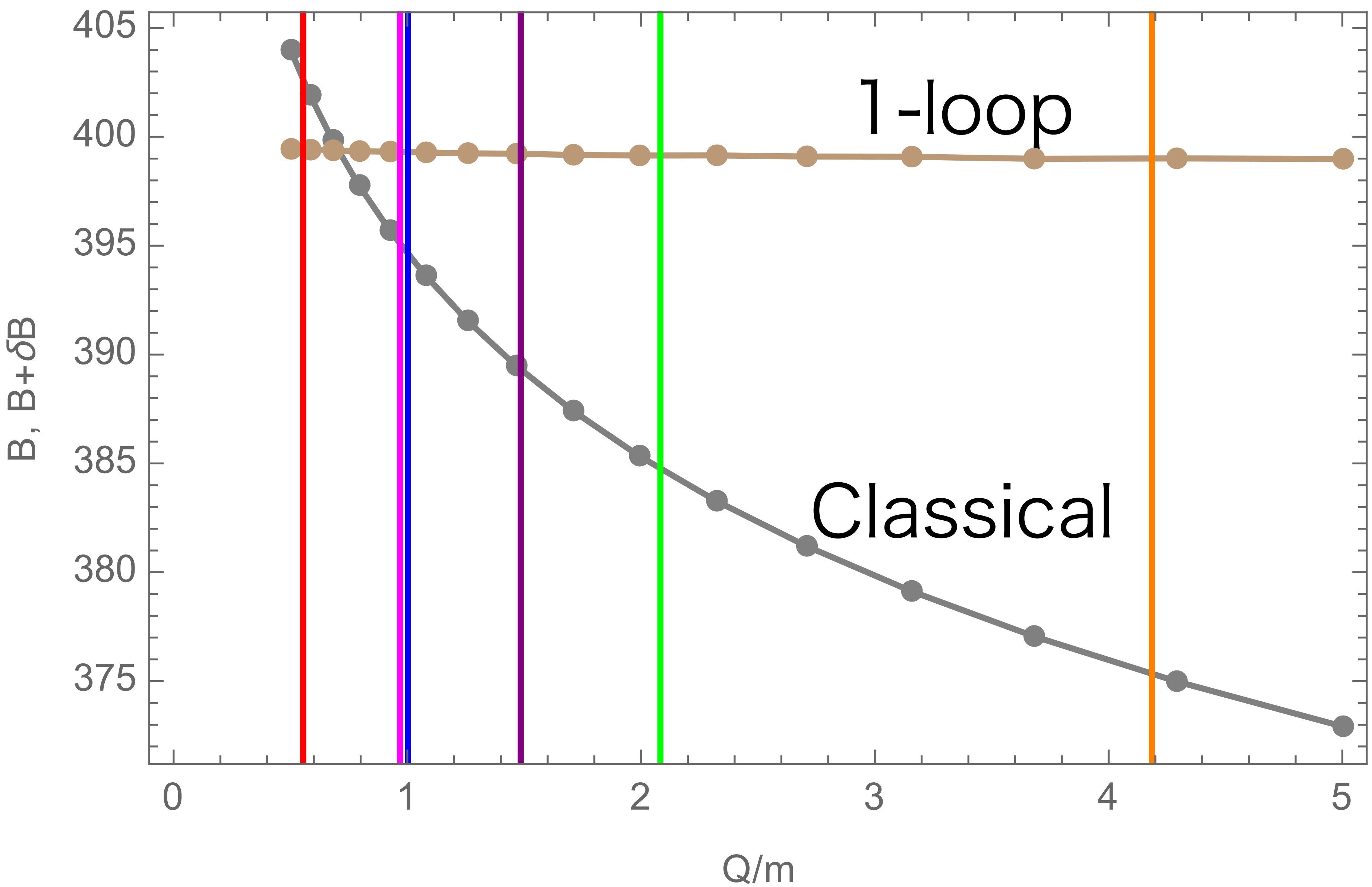
cf.) RGE is related to



divergent part

Result

$$\gamma = Ae^{-B} \equiv m^4 e^{-B-\delta B}$$



SM + stau system

Light stau

Stau can be light

$m_{\tilde{\tau}} > 103.5\mathrm{GeV}$ (LEP)

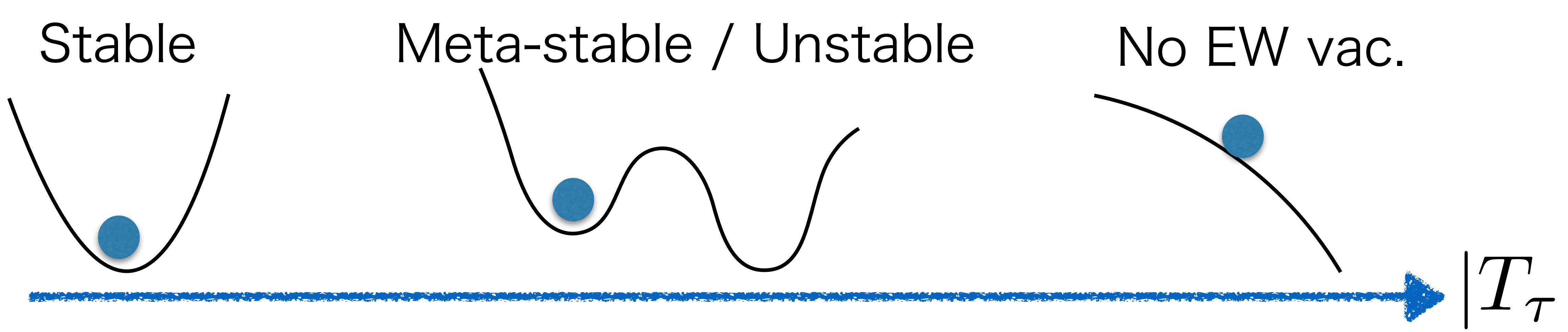
h$\gamma\gamma$ coupling, co-annihilation with bino, $\cdots$

But, the potential may become unstable towards the stau direction

$$V = T_\tau (H^\dagger \tilde{\ell}_L \tilde{\tau}_R^* + h.c.) + m_{\tilde{\ell}_L}^2 |\tilde{\ell}_L|^2 + m_{\tilde{\tau}_R}^2 |\tilde{\tau}_R|^2 + \cdots$$

$T_\tau = y_\tau (A_\tau - \mu \tan\beta)$

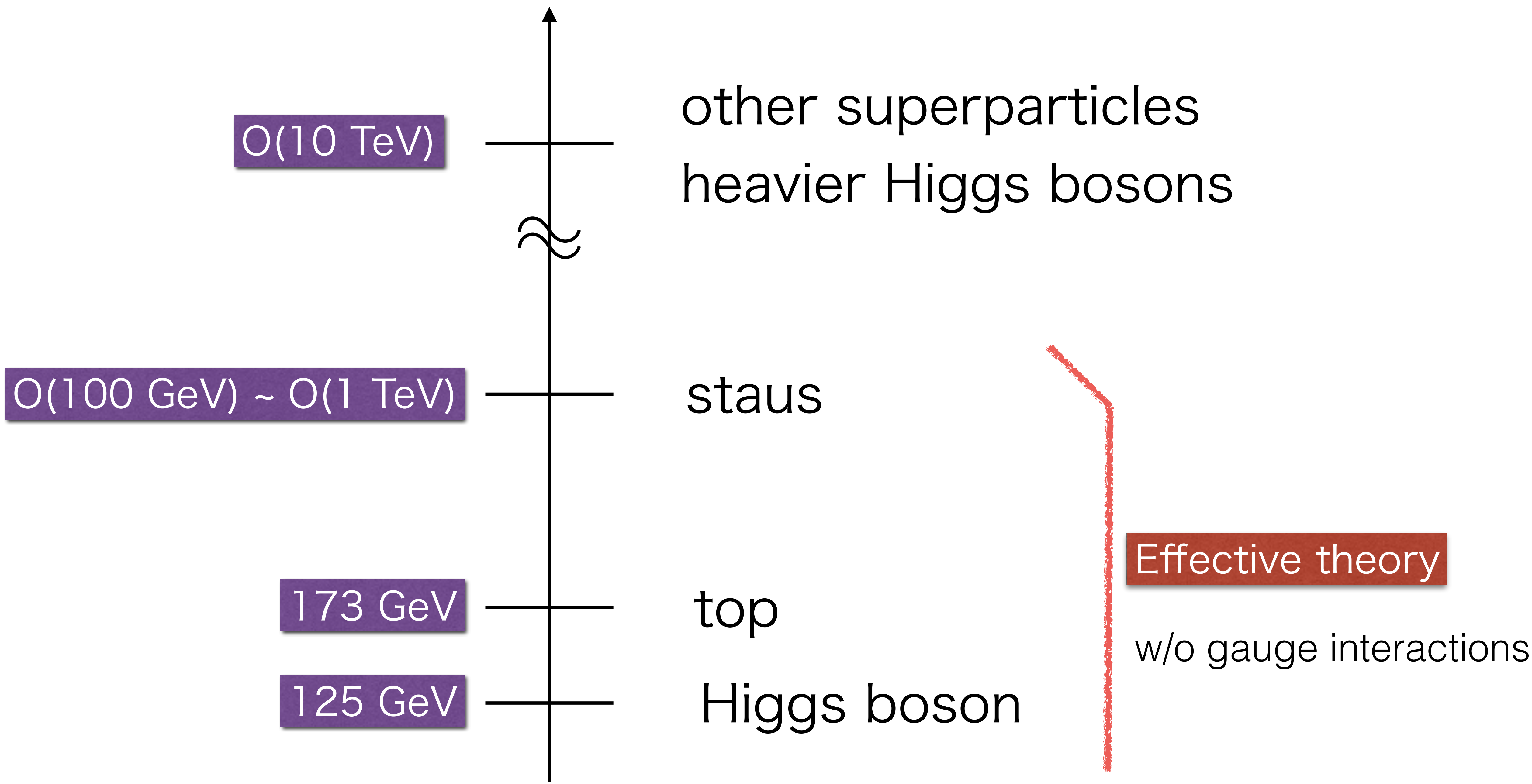
$\tan\beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$



Spectrum

For simplicity,

we assume only the staus are light



Effective theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm kin} - y_t (H q_L t_R^c + {\rm h.c.}) - m_H^2 |H|^2 - \frac{1}{4}\lambda_H |H|^4$$
$$- m_{\tilde{\ell}_L}^2 |\tilde{\ell}_L|^2 - m_{\tilde{\tau}_R}^2 |\tilde{\tau}_R|^2 - T_\tau (H^\dagger \tilde{\ell}_L \tilde{\tau}_R^* + {\rm h.c.}) - \frac{1}{4}\kappa^{(1)} |\tilde{\ell}_L|^4 - \frac{1}{4}\kappa^{(2)} |\tilde{\tau}_R|^4$$
$$- \frac{1}{4}\lambda^{(1)} |H|^2 |\tilde{\ell}_L|^2 - \frac{1}{4}\lambda^{(2)} |H^\dagger \tilde{\ell}_L|^2 - \frac{1}{4}\lambda^{(3)} |H|^2 |\tilde{\tau}_R|^2 - \frac{1}{4}\kappa^{(3)} |\tilde{\ell}_L|^2 |\tilde{\tau}_R|^2,$$

Boundary conditions

EW scale

$$y_t = \frac{M_t}{v},$$
$$m_H^2(M_t) = -\frac{1}{2} M_h^2,$$
$$\lambda_H(M_h) = \frac{M_h^2}{2v^2},$$

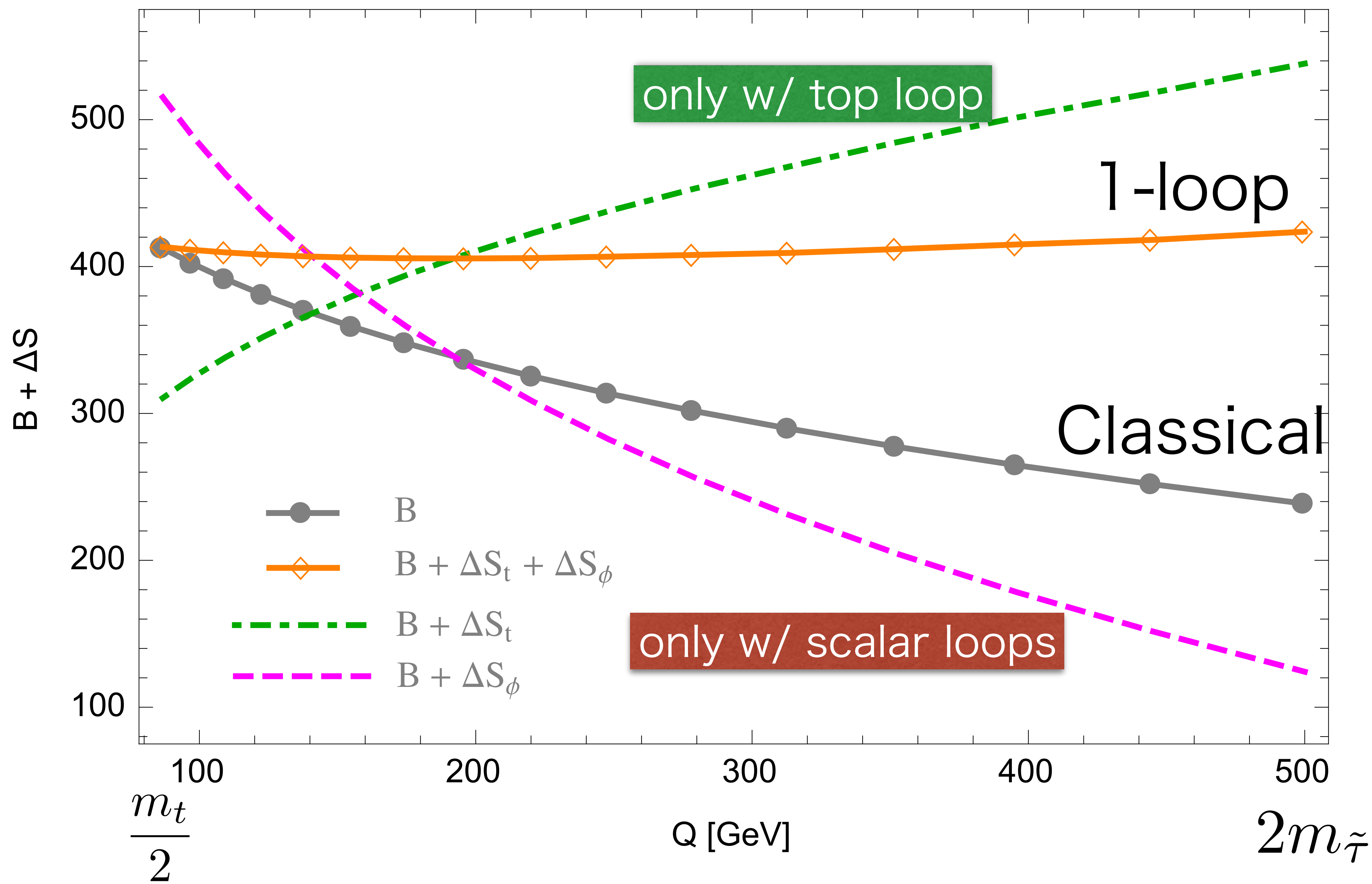
stau mass

$$m_{\tilde{\tau}} \equiv m_{\tilde{\ell}_L} = m_{\tilde{\tau}_R} = 250\,{\rm GeV},$$
$$T_\tau = 300\,{\rm GeV}.$$

SUSY scale (10TeV)

$$\lambda^{(1)}(M_{\rm SUSY}) = (g^2 + g'^2)\cos 2\beta,$$
$$\lambda^{(2)}(M_{\rm SUSY}) = 4y_\tau^2 - 2g^2 \cos 2\beta,$$
$$\lambda^{(3)}(M_{\rm SUSY}) = 4y_\tau^2 - 2g'^2 \cos 2\beta,$$
$$\kappa^{(1)}(M_{\rm SUSY}) = \frac{1}{2}(g^2 + g'^2),$$
$$\kappa^{(2)}(M_{\rm SUSY}) = -\kappa^{(3)}(M_{\rm SUSY}) = 2g'^2,$$

Result


only w/ top loop
1-loop
Classical
only w/ scalar loops
B
B + ΔSt + ΔSϕ
B + ΔSt
B + ΔSϕ
B + ΔS
Q [GeV]
100
200
300
400
500
$\frac{m_t}{2}$
$2m_{\tilde{\tau}}$

Summary

- The bubble nucleation rate has often been estimated without calculating the pre-exponential factor.
- This estimate involves uncertainty in the renormalization scale, which, we showed, results in O(10%) uncertainty in the exponent of the bubble nucleation rate.
- To reduce the uncertainty, we explicitly calculated the pre-exponential factor and showed that it is greatly reduced.
- Scalars and fermions have already been implemented, but the gauge bosons are now ongoing.

Backup

Effective theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm kin} - y_t(Hq_Lt_R^c + {\rm h.c.}) - m_H^2|H|^2 - \frac{1}{4}\lambda_H|H|^4$$
$$- m_{\tilde{\ell}_L}^2|\tilde{\ell}_L|^2 - m_{\tilde{\tau}_R}^2|\tilde{\tau}_R|^2 - T_\tau(H^\dagger\tilde{\ell}_L\tilde{\tau}_R^* + {\rm h.c.}) - \frac{1}{4}\kappa^{(1)}|\tilde{\ell}_L|^4 - \frac{1}{4}\kappa^{(2)}|\tilde{\tau}_R|^4$$
$$- \frac{1}{4}\lambda^{(1)}|H|^2|\tilde{\ell}_L|^2 - \frac{1}{4}\lambda^{(2)}|H^\dagger\tilde{\ell}_L|^2 - \frac{1}{4}\lambda^{(3)}|H|^2|\tilde{\tau}_R|^2 - \frac{1}{4}\kappa^{(3)}|\tilde{\ell}_L|^2|\tilde{\tau}_R|^2,$$

Beta functions (leading in y_t and T_tau)

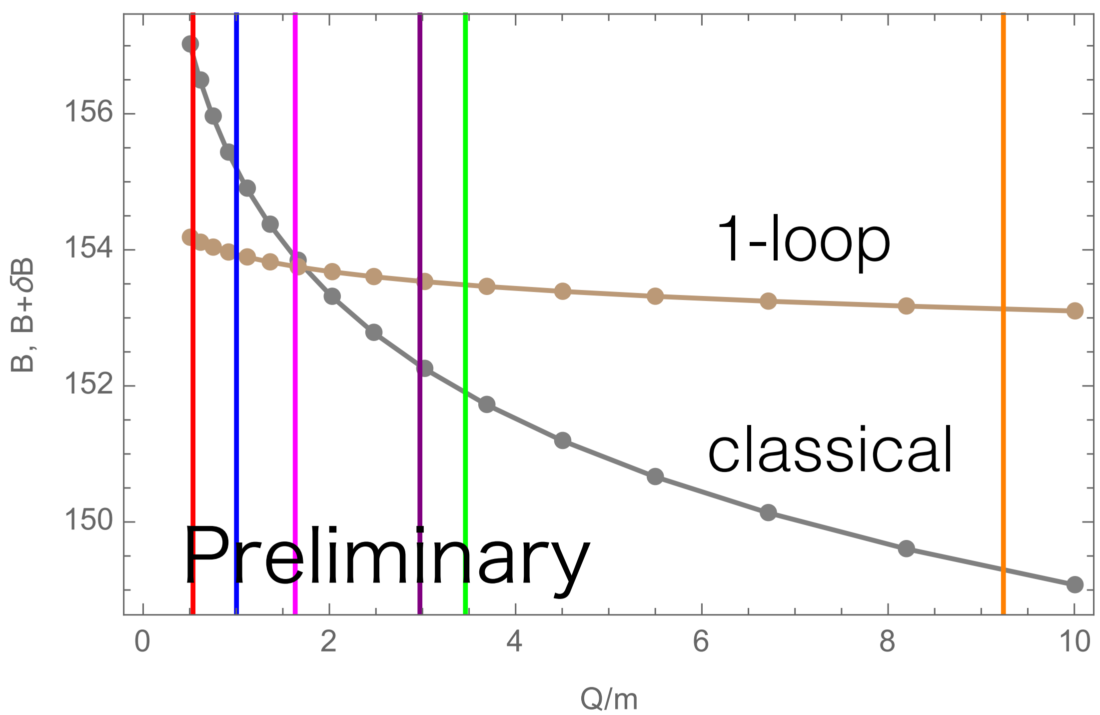
$$\frac{d\lambda_H}{d\ln Q} = \frac{3y_t^2}{4\pi^2}\lambda_H - \frac{3}{8\pi^2}y_t^4,$$
$$\frac{dT_\tau}{d\ln Q} = \frac{3y_t^2}{16\pi^2}T_\tau,$$
$$\frac{d\lambda^{(I)}}{d\ln Q} = \frac{3y_t^2}{8\pi^2}\lambda^{(I)},$$
$$\frac{d\kappa^{(I)}}{d\ln Q} = 0,$$

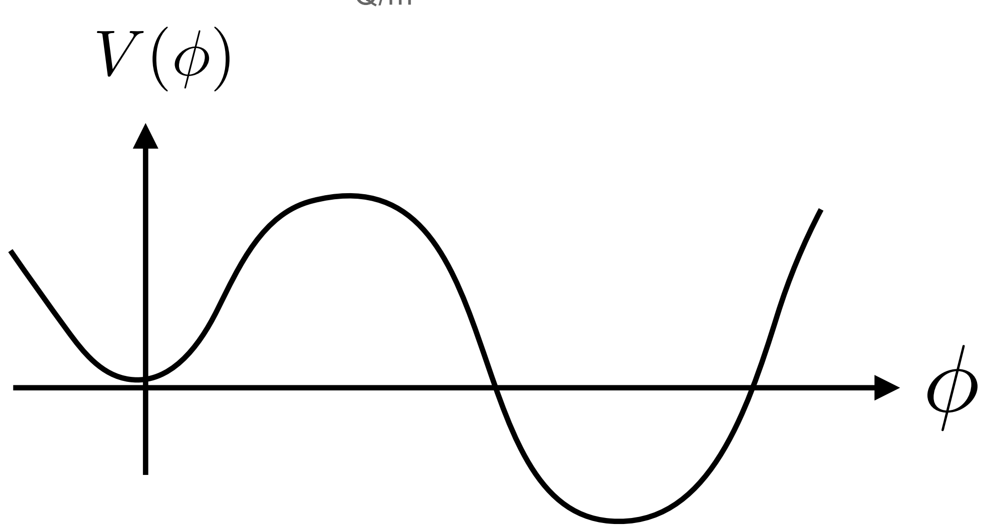
$$\frac{dm_H^2}{d\ln Q} = \frac{3y_t^2}{8\pi^2}m_H^2 + \frac{1}{8\pi^2}T_\tau^2,$$
$$\frac{dm_{\tilde{\ell}_L}^2}{d\ln Q} = \frac{1}{8\pi^2}T_\tau^2,$$
$$\frac{dm_{\tilde{\tau}_R}^2}{d\ln Q} = \frac{1}{4\pi^2}T_\tau^2,$$

Results

$$V = \frac{m^2}{2}\phi^2 - \frac{A}{2}\phi^3 + \frac{\alpha}{8}\phi^4$$

$\alpha = 0.3$





$\alpha = 0.9$