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Upper bound on the smuon mass from vacuum stability in the light of muon g-2 anomaly

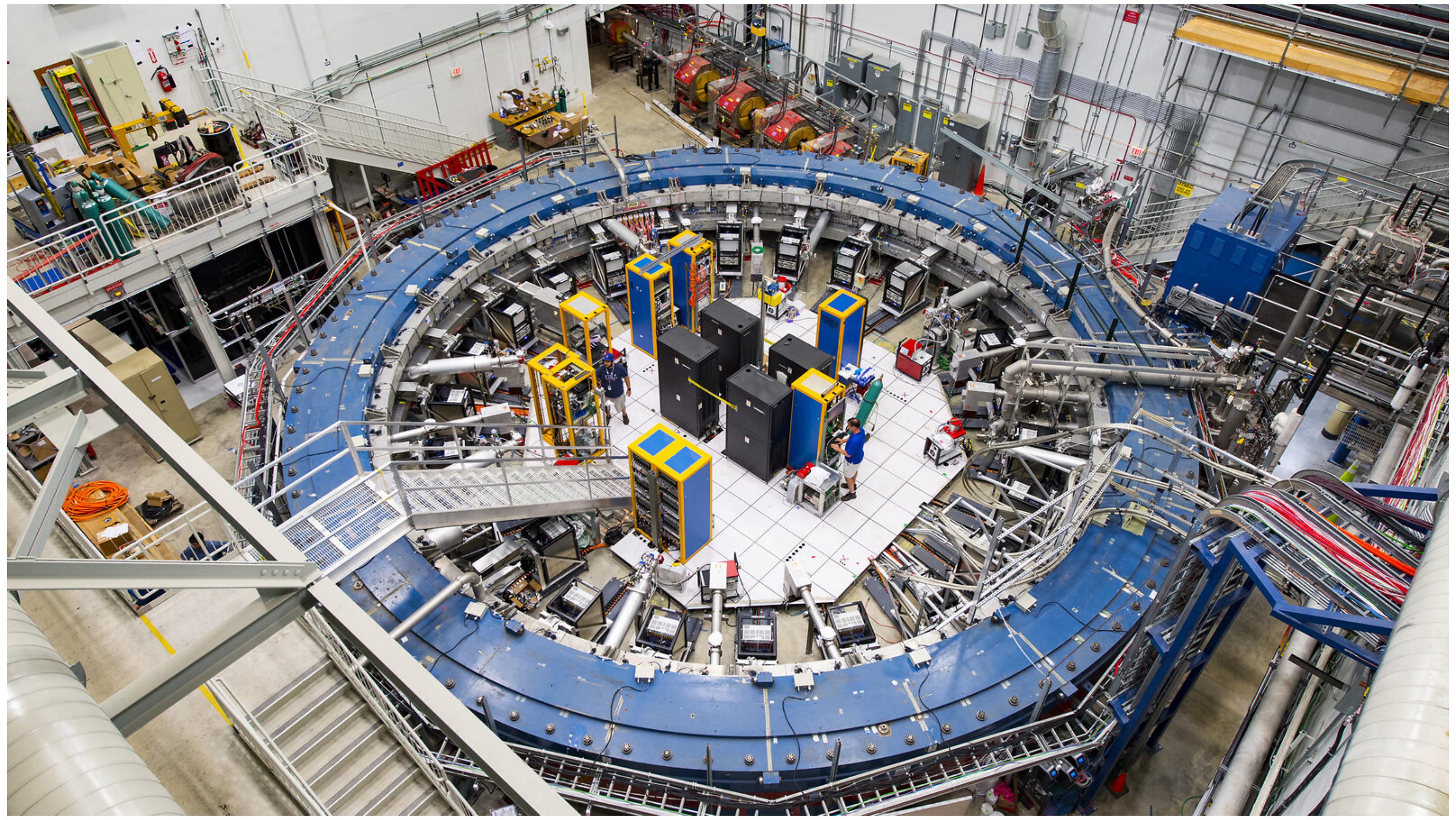
arXiv: 2203.08062 (accepted by PLB)

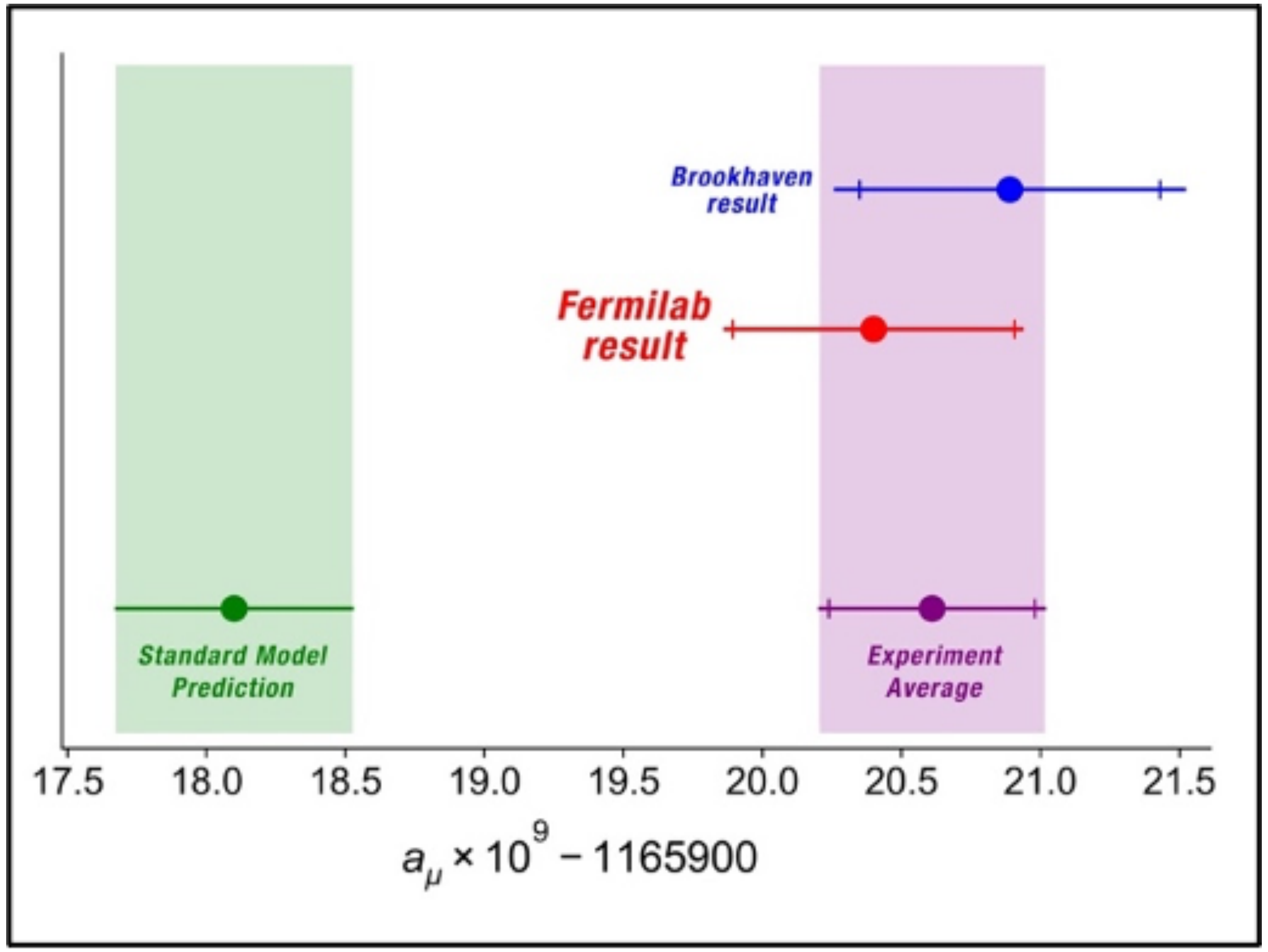
Physics in LHC and Beyond (12-15 May 2022)

Yutaro Shoji w/ So Chigusa and Takeo Moroi

Muon g-2

cf. Mibe-san's talk





[Muon g-2 collaboration '21]

$$a_\mu^{(\mathrm{exp})} = (11\,659\,206.1 \pm 4.1) \times 10^{-10}$$

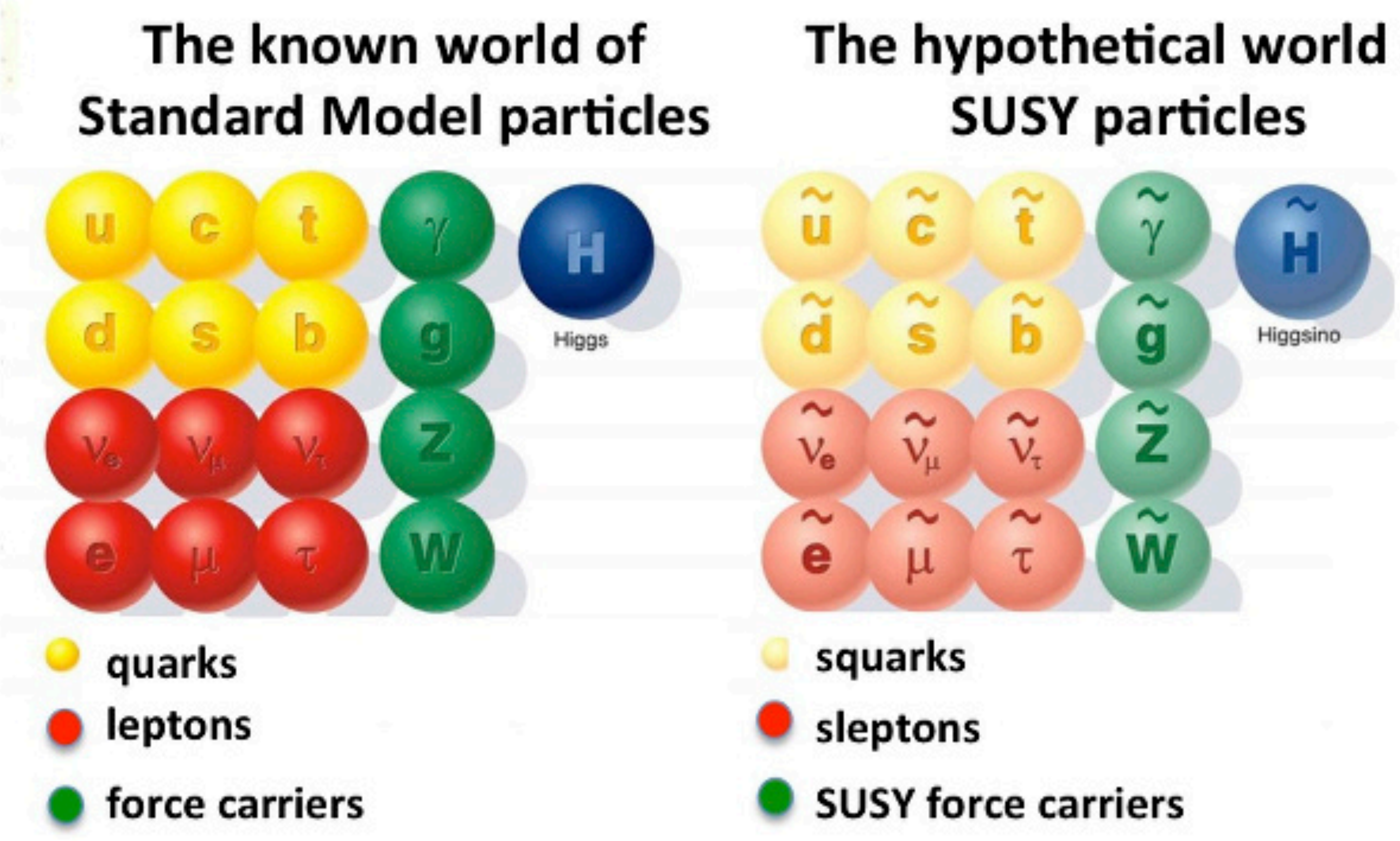
$$a_\mu^{(\mathrm{SM})} = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$$

$$\Delta a_\mu \equiv a_\mu^{(\mathrm{exp})} - a_\mu^{(\mathrm{SM})} = (25.1 \pm 5.9) \times 10^{-10}$$

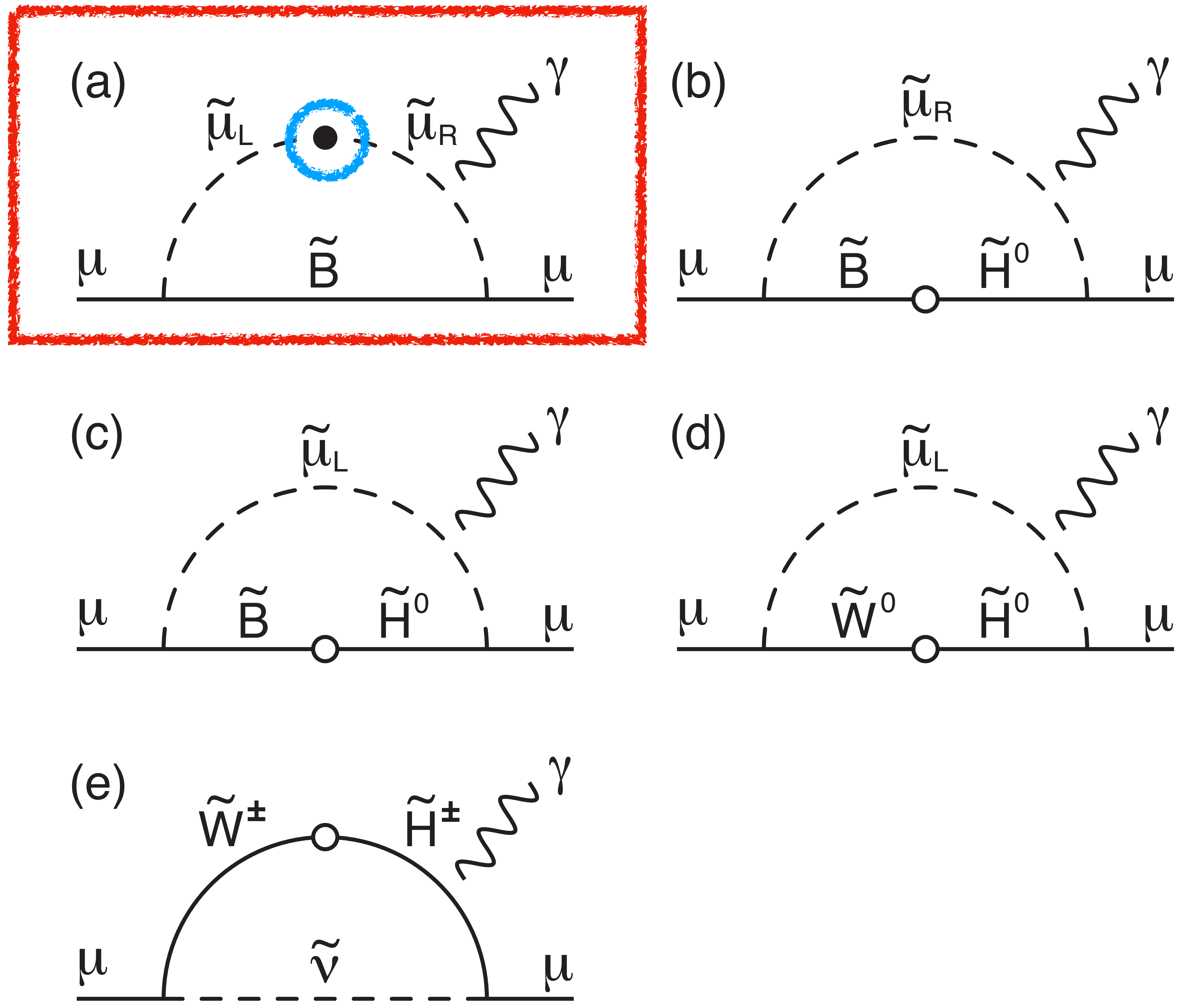
Muon g-2 in the MSSM

[J. L. Lopes, D. V. Nanopoulos, X. Wang, ’93; U. Chattopadhyay, P. Nath, ’96; T. Moroi, 96,…]

Minimal Supersymmetric Standard Model



We consider the case where only the smuons and the bino are light



$$M^2_{\tilde{\mu}} = \begin{pmatrix} m_L^2 + (\lambda_{HL} + \kappa)v^2 & -Tv \\ -Tv & m_R^2 + \lambda_{HR} v^2 \end{pmatrix}$$

Vacuum instability

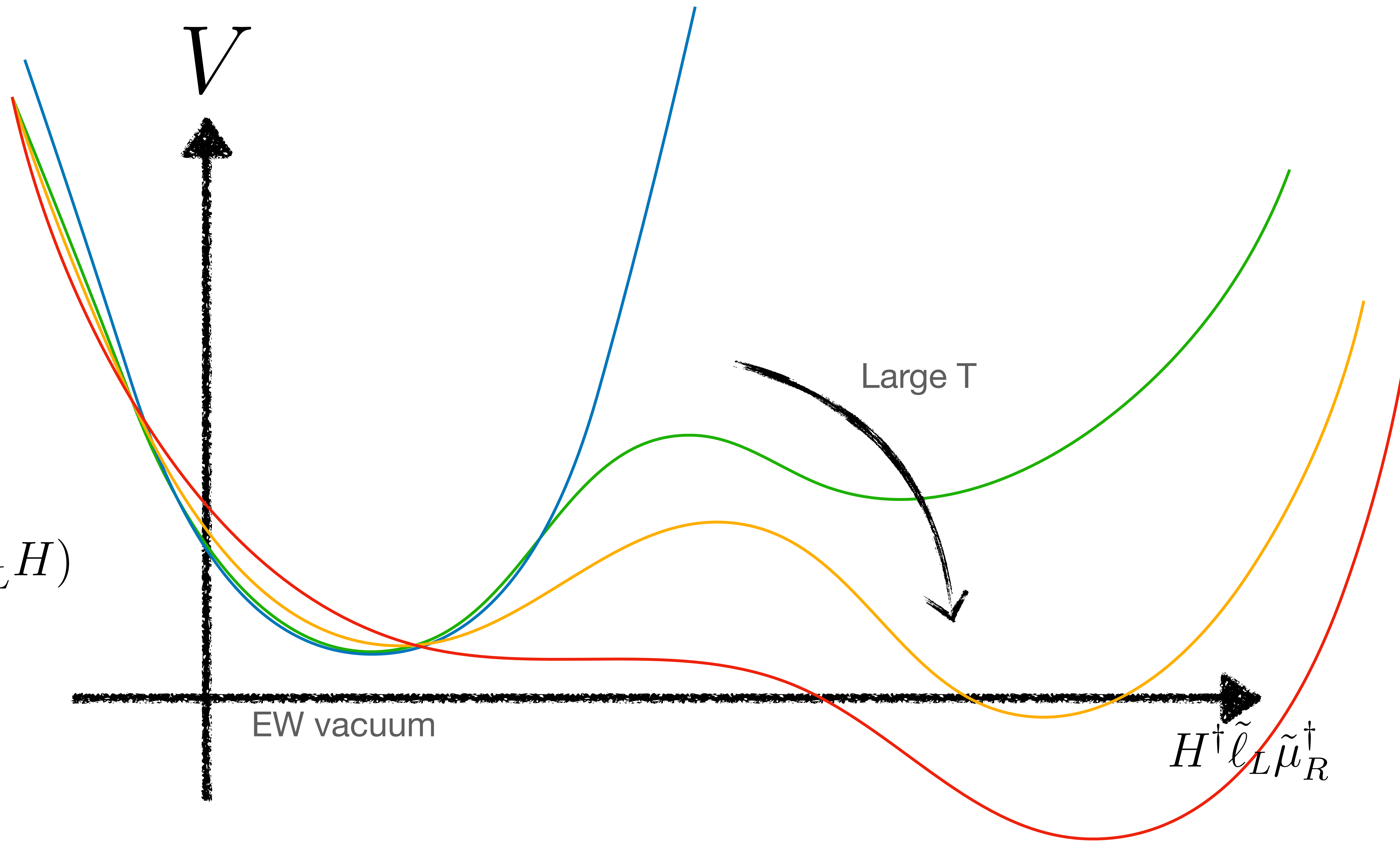
Scalar potential

$$V = V_2 + V_3 + V_4,$$

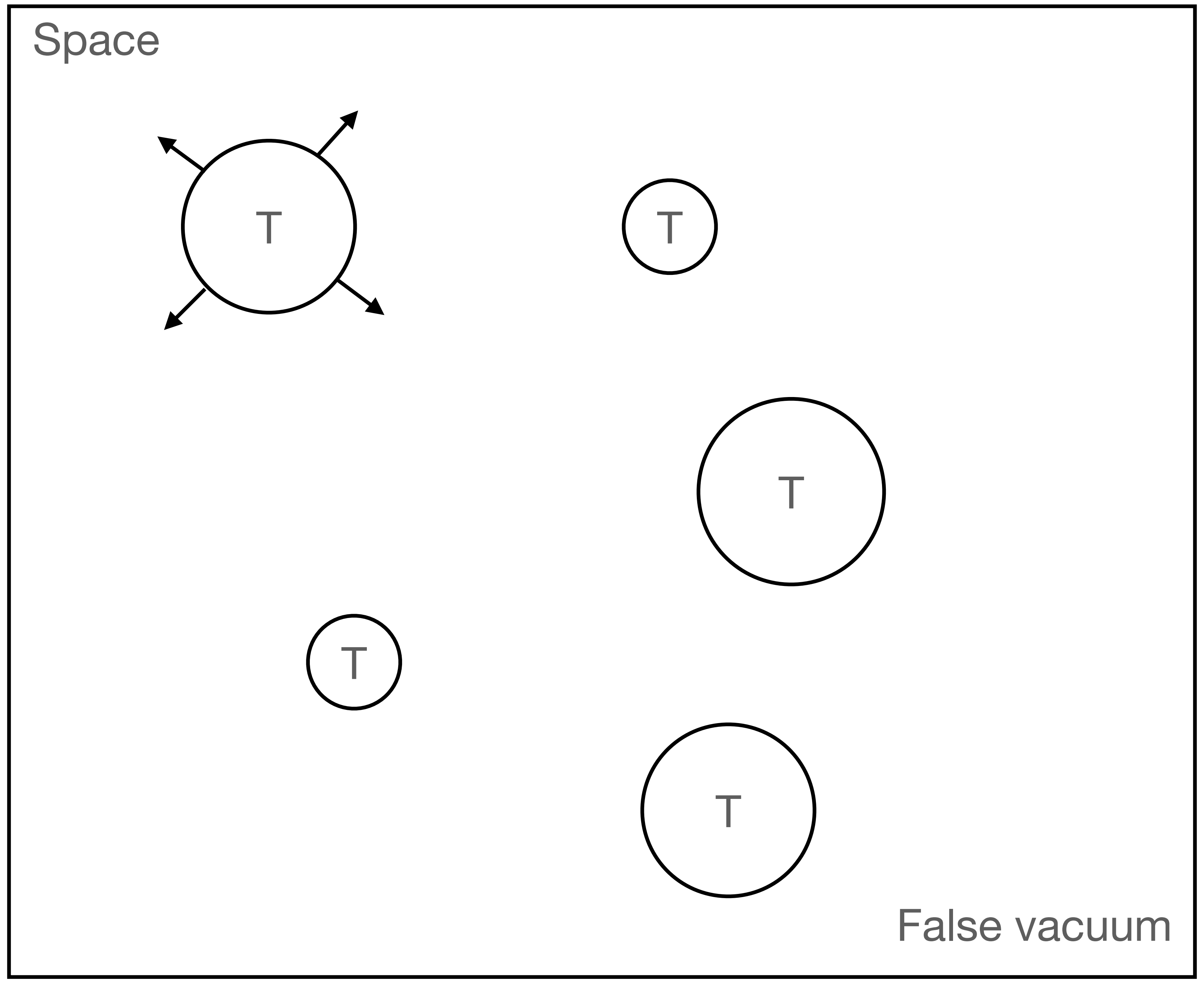
$$V_2 = m_H^2|H|^2 + m_L^2\,|\tilde{\ell}_L|^2 + m_R^2\,|\tilde{\mu}_R|^2,$$

$$V_3 = -T H^\dagger \tilde{\ell}_L \tilde{\mu}_R^\dagger + \text{h.c.},$$

$$V_4 = \lambda_H|H|^4 + \lambda_{HL}|H|^2|\tilde{\ell}_L|^2 + \lambda_{HR}|H|^2|\tilde{\mu}_R|^2 + \kappa(H^\dagger\tilde{\ell}_L)(\tilde{\ell}_L^\dagger H)$$
$$+ \lambda_L|\tilde{\ell}_L|^4 + \lambda_R|\tilde{\mu}_R|^4 + \lambda_{LR}|\tilde{\ell}_L|^2|\tilde{\mu}_R|^2,$$

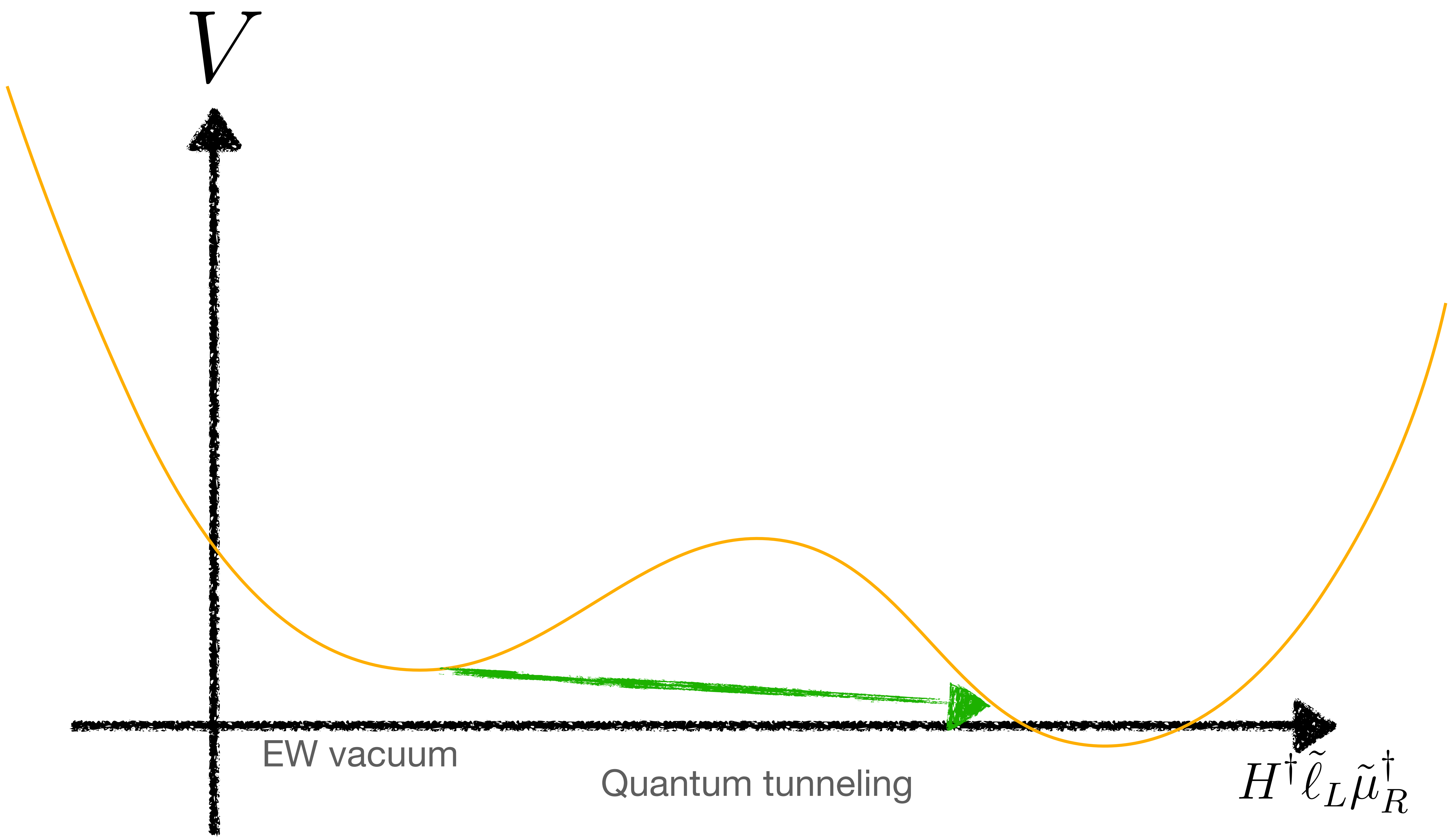


Vacuum metastability



Bubble nucleation rate (rate per volume)

$$\gamma < \frac{1}{V_H t_H} \sim H_0^4$$



Bubble nucleation rate

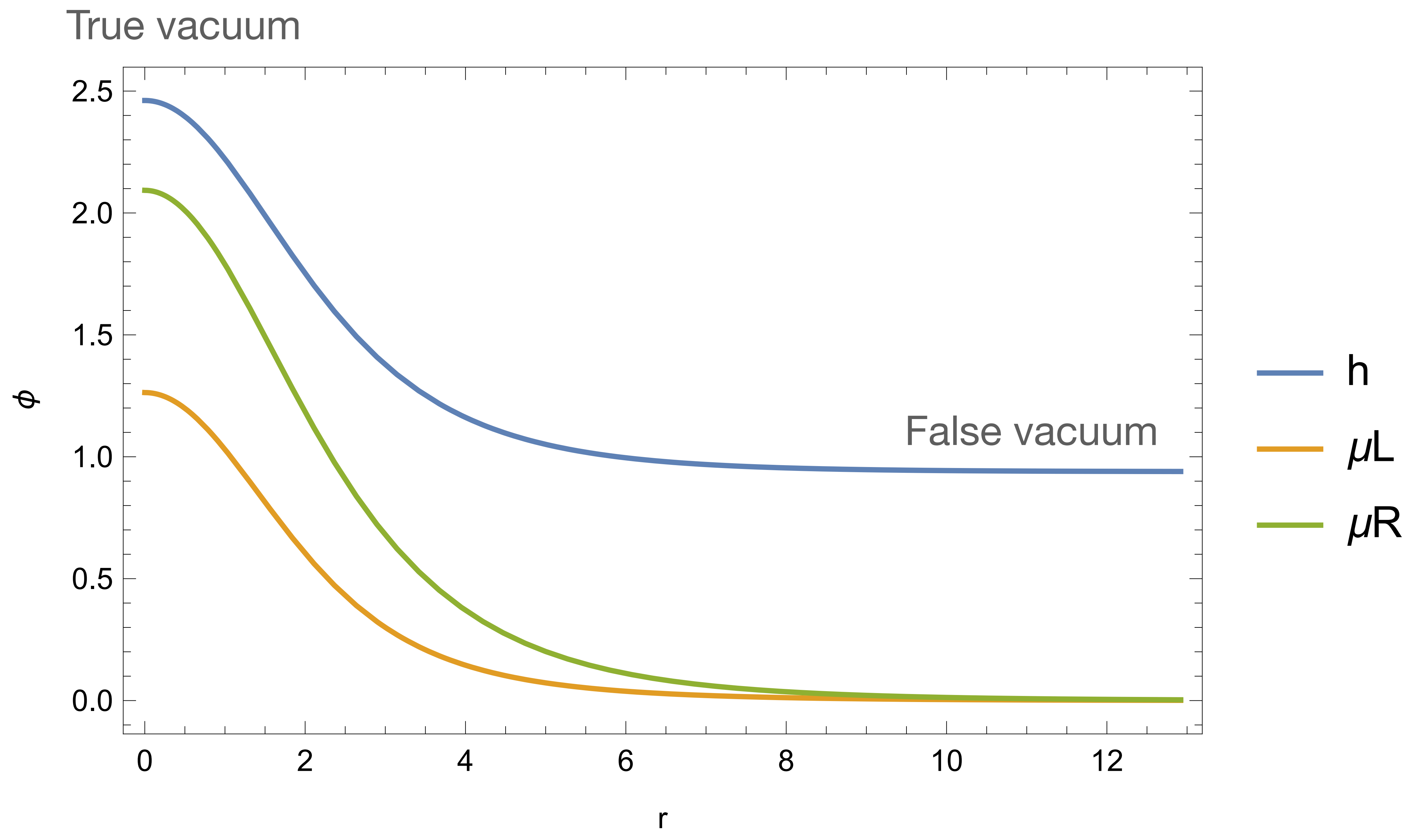
[S. R. Coleman, ’77; C. G. Callan Jr., S. R. Coleman, ’77]

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

$$\mathcal{B} = S_E(\phi_B) - S_E(v_F)$$

Bounce

O(4) symmetric solution of Euclidean EoM
connecting the true vacuum and the false vacuum



[gradient flow method: S. Chigusa, T. Moroi, Y.Shoji, ’19; R. Sato, ’19]

Bubble nucleation rate

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

$$\mathcal{B} = S_E(\phi_B) - S_E(v_F)$$

$$\mathcal{A} = 2\pi \mathcal{J}_{\mathrm{EM}} \frac{\mathcal{B}}{4\pi^2} \mathcal{A}^{(A,\varphi,c\bar{c})} \mathcal{A}^{(\psi)}$$

$$\mathcal{A}^{(A,\varphi,c\bar{c})} = \frac{\det \mathcal{M}_0^{(c\bar{c})}}{\det \widehat{\mathcal{M}}_0^{(c\bar{c})}} \left(\frac{\det' \mathcal{M}_0^{(S\varphi)}}{\det \widehat{\mathcal{M}}_0^{(S\varphi)}} \right)^{-1/2} \left(\frac{\det' \mathcal{M}_1^{(SL\varphi)}}{\det \widehat{\mathcal{M}}_1^{(SL\varphi)}} \right)^{-2} \prod_{\ell=2}^{\infty} \left(\frac{\det \mathcal{M}_\ell^{(SL\varphi)}}{\det \widehat{\mathcal{M}}_\ell^{(SL\varphi)}} \right)^{-\frac{(\ell+1)^2}{2}},$$

$$\mathcal{A}^{(\psi)} = \prod_{\ell=0}^{\infty} \left(\frac{\det \mathcal{M}_\ell^{(\psi)}}{\det \widehat{\mathcal{M}}_\ell^{(\psi)}} \right)^{\frac{(\ell+1)(\ell+2)}{2}},$$

[S. R. Coleman, ’77; C. G. Callan Jr., S. R. Coleman, ’77]

Calculation of prefactor in phenomenology

Standard model
[G. Isidori, G. Ridolfi, A. Strumia, 01]

MSSM slepton w/o gauge
[M. Endo, T. Moroi, M. M. Nojiri, YS, 15]

Prescription for gauge zero modes
[M. Endo, T. Moroi, M. M. Nojiri, YS, 17]

Standard model w/ correct treatment of zero modes
[A. Andreassen, W. Frost, M. D. Schwartz, 17;
S. Chigusa, T. Moroi, YS, 17, 18]

Gauge zero modes for multi-field bounce
[S. Chigusa, T. Moroi, YS, 20]

MSSM smuon full one-loop
[S. Chigusa, T. Moroi, YS, 22]

Analysis

Energy scale

$Q = M_S \simeq \mu$ **MSSM**

SUSY relations

Two loop RGE

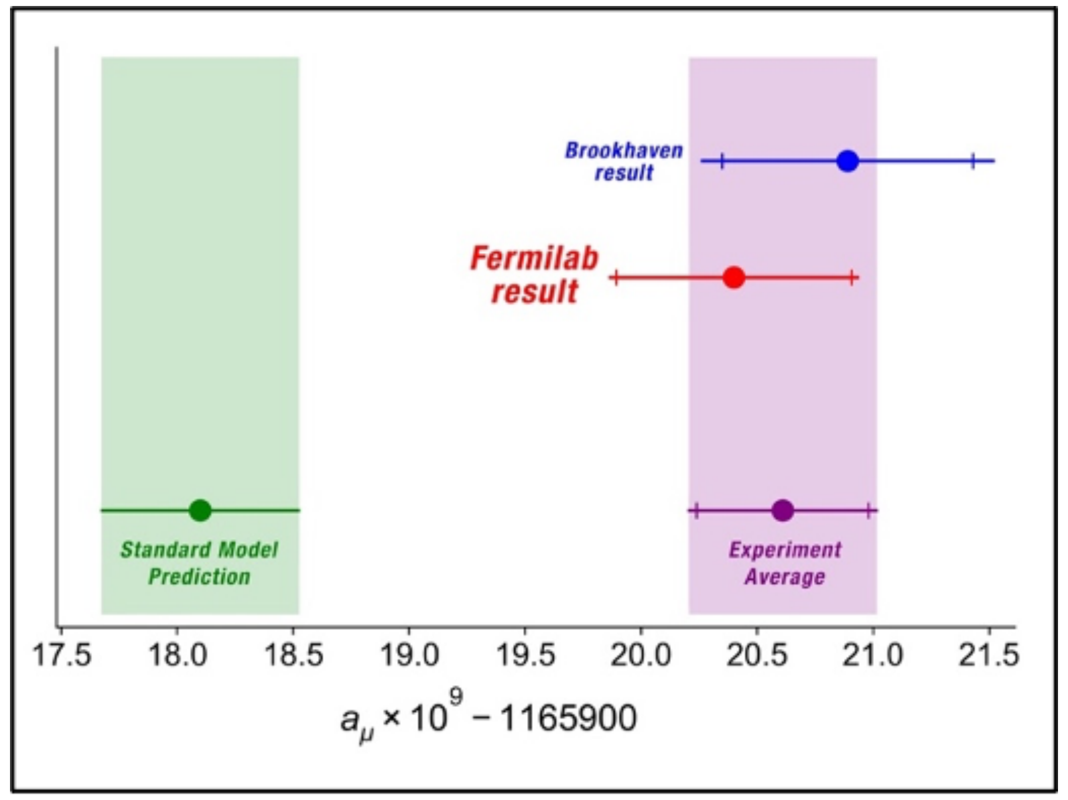
Standard Model + Smuons + Bino EFT

Match SM couplings

$Q = M_t$ **Standard Model**

Calculate muon g-2

Determine the tri-linear coupling



Calculate the vacuum decay rate

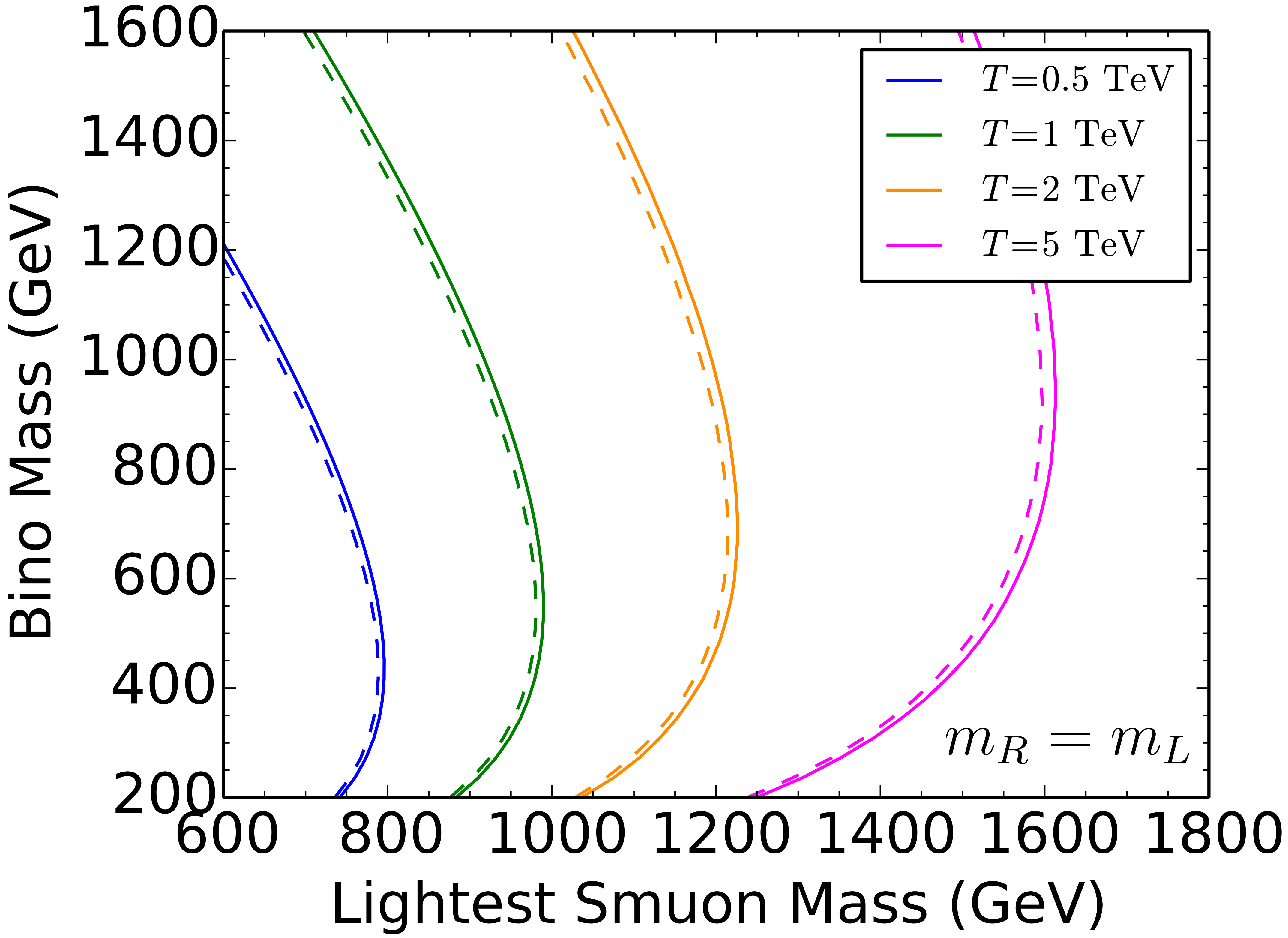
Set an upper bound on the smuon mass

$$\gamma < \frac{1}{V_H t_H} \sim H_0^4$$

Muon g-2

Required size of the tri-linear coupling

(to explain the central value)



$$a_\mu^{(\mathrm{SUSY})} = a_\mu^{(\mathrm{SUSY,\,1\text{-}loop})} + a_\mu^{(\mathrm{SUSY,\,photonic})},$$

$$a_\mu^{(\mathrm{SUSY,\,1\text{-}loop})} = \frac{m_\mu^2}{16\pi^2}\sum_{A=1}^{2}\frac{1}{m_{\tilde\mu_A}^2}\left[-\frac{1}{12}\mathcal{A}_A f_1(x_A) - \frac{1}{3}\mathcal{B}_A f_2(x_A)\right],$$

$$a_\mu^{(\mathrm{SUSY,\,photonic})} = \frac{m_\mu^2}{16\pi^2}\frac{\alpha}{4\pi}\sum_{A=1}^{2}\frac{1}{m_{\tilde\mu_A}^2}\left[16\left\{-\frac{1}{12}\mathcal{A}_A f_1(x_A) - \frac{1}{3}\mathcal{B}_A f_2(x_A)\right\}\ln\frac{m_\mu}{m_{\tilde\mu_A}} - \left\{-\frac{35}{75}\mathcal{A}_A f_3(x_A) - \frac{16}{9}\mathcal{B}_A f_4(x_A)\right\} + \frac{1}{4}\mathcal{A}_A f_1(x_A)\ln\frac{m_{\tilde\mu_A}^2}{Q_{\mathrm{DREG}}^2}\right],$$

$$\mathcal{A}_A \equiv Y_L^2 U_{L,A}^2 + Y_R^2 U_{R,A}^2, \quad \mathcal{B}_A \equiv \frac{M_1 Y_L Y_R U_{L,A} U_{R,A}}{m_\mu},$$

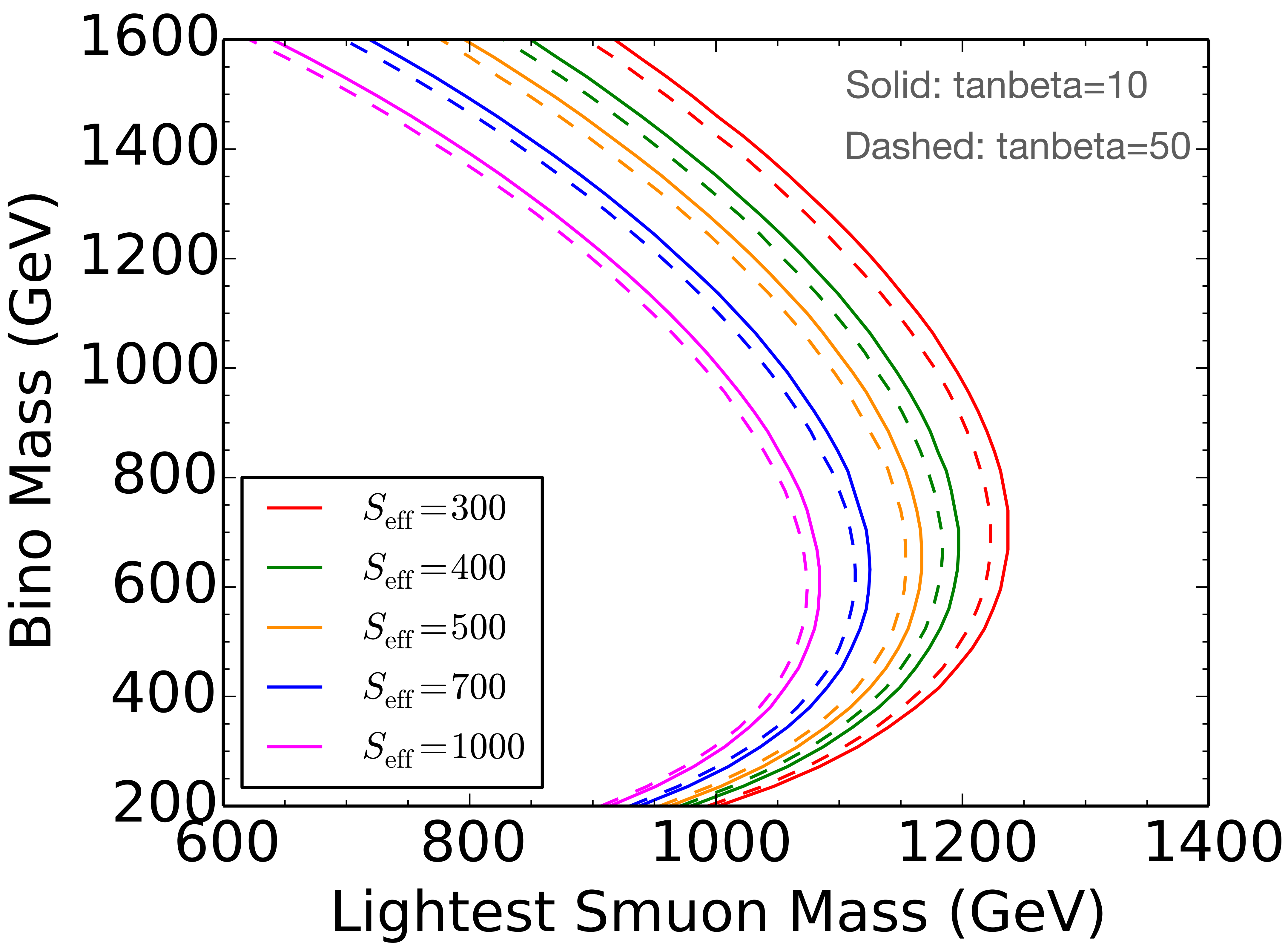
(We also include the SUSY correction to the muon Yukawa coupling)

[P. von Weitershausen, M. Schafer, H. Stockinger-Kim, D. Stockinger, ’10]

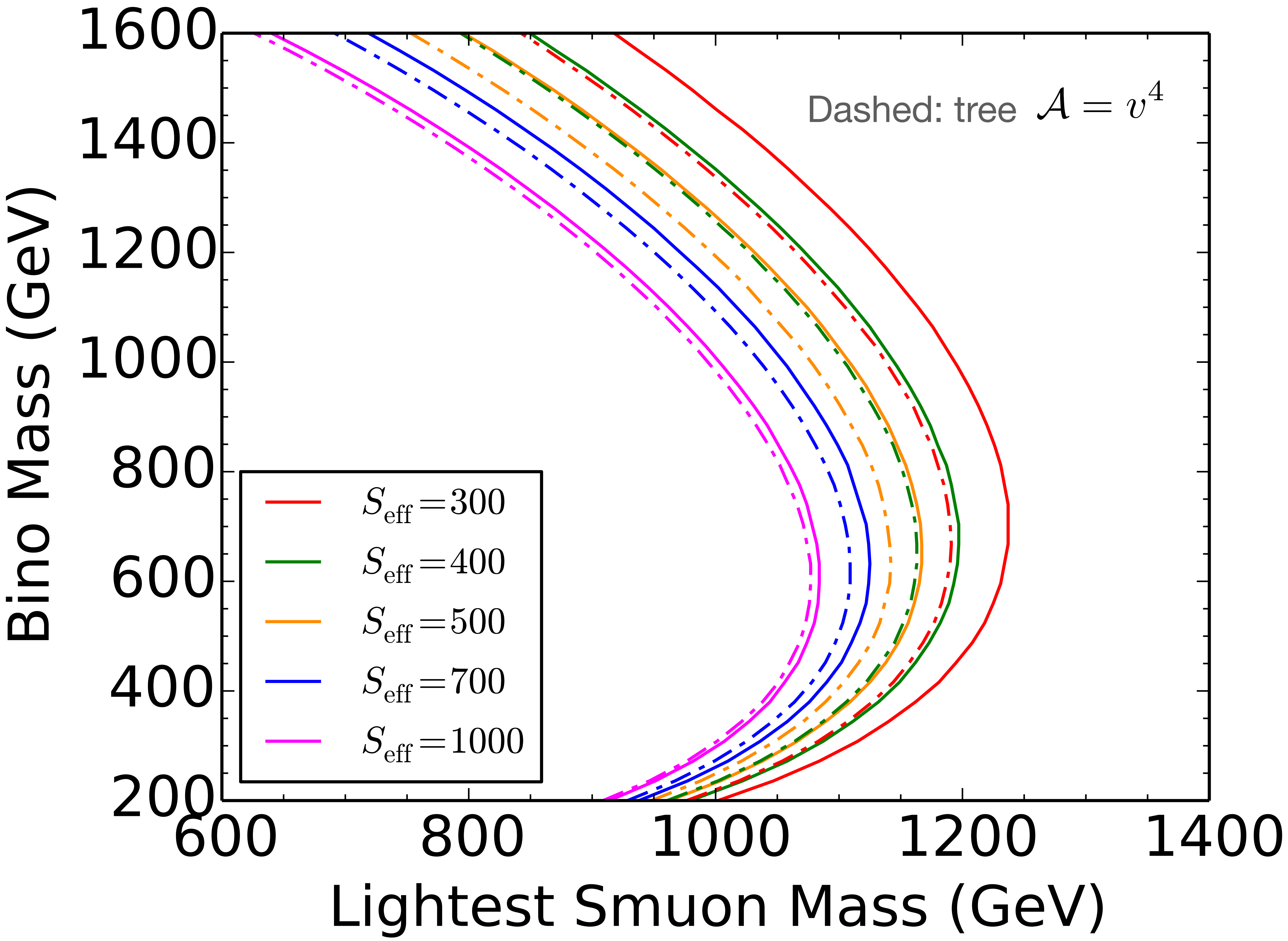
Bubble nucleation rate

$$S_{\text{eff}} \equiv -\ln\left(\frac{\gamma}{1\ \text{GeV}^4}\right)$$

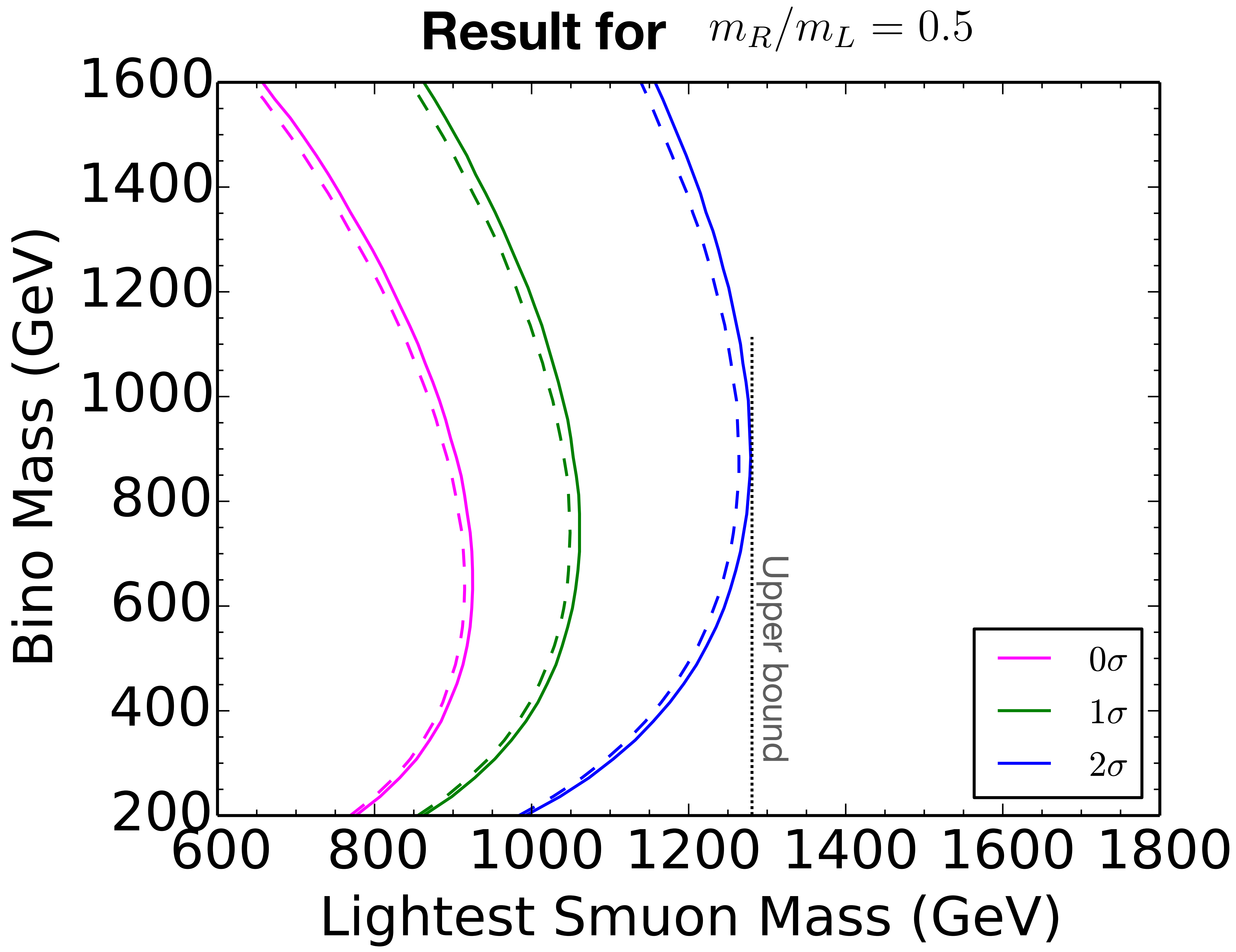
Contours of the decay rate

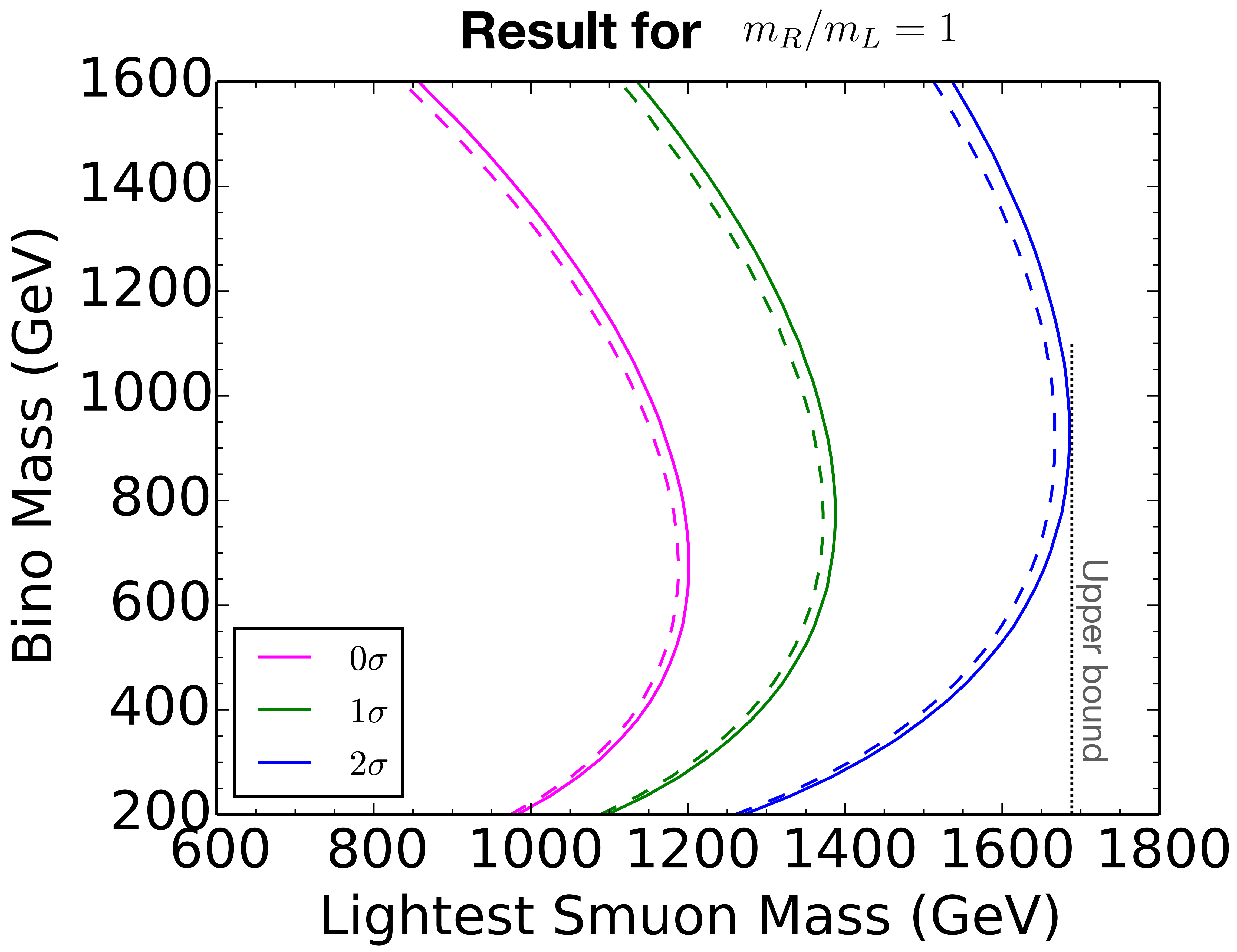


Tree vs one-loop

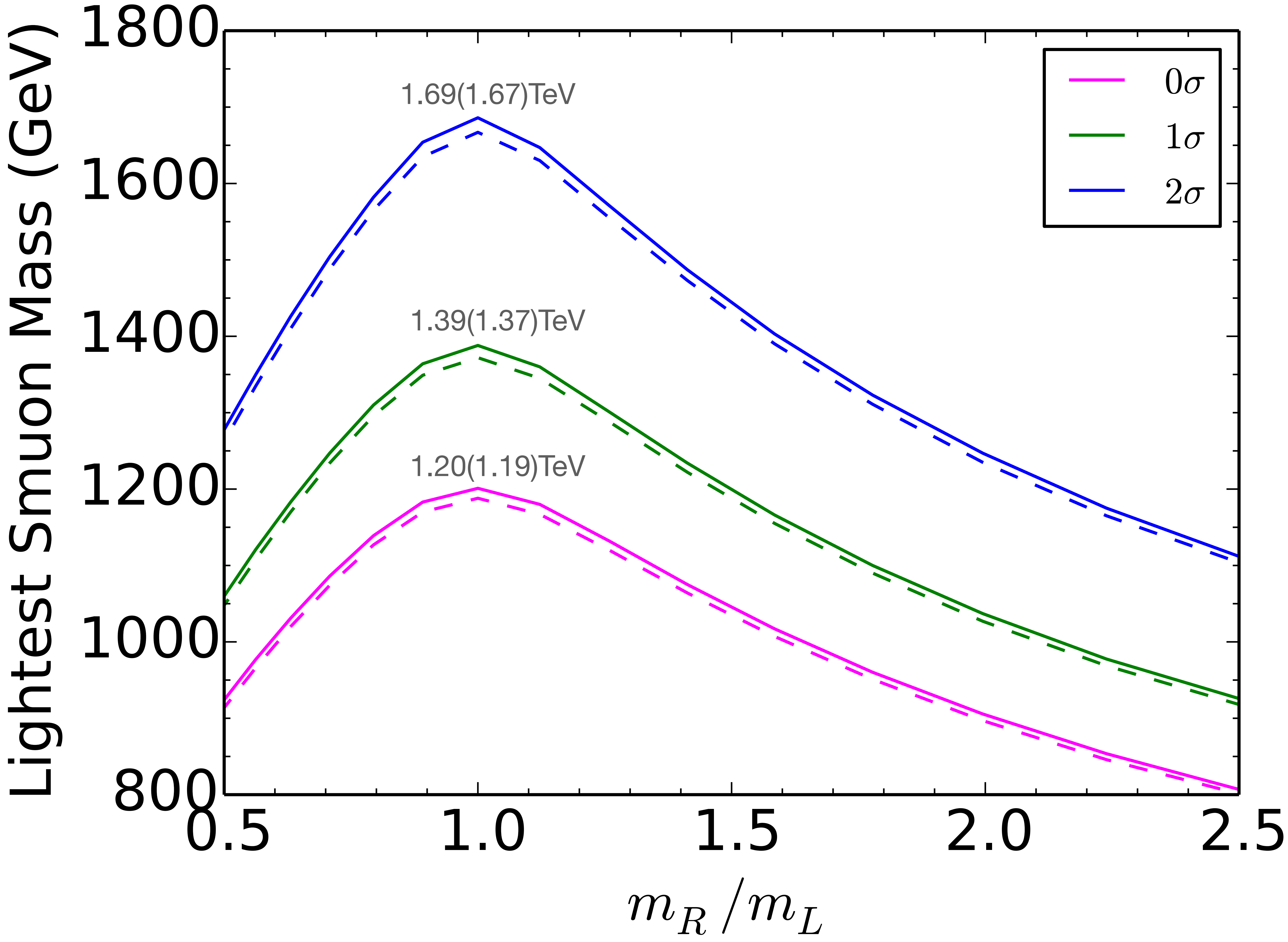


Vacuum stability





Upper bound on the smuon mass



Summary

- We calculated the upper bound on the smuon mass assuming the Bino-smuon diagram explains the observed muon g-2 discrepancy
- To explain the anomaly with heavier smuons, we need a large tri-linear coupling, which make the electroweak vacuum unstable
- We used the state-of-the-art technique to calculate the decay rate at the one-loop level, which results in O(10GeV) difference from the tree level analysis
- We obtained a precise upper bound on the smuon mass; 1.20, 1.39, 1.69 TeV for 0, 1, 2 sigma (tanbeta=10)
- When the staus are also light, they give a severer constraint, which will be discussed in our next paper