Planck-Scale Effects on Nucleon Decay in Minimal SUSY SU(5)

Based on John Ellis, Jason L. Evans, Shihwen Hor, Natsumi Nagata, and Keith A. Olive, arXiv:2603.22418 [hep-ph].

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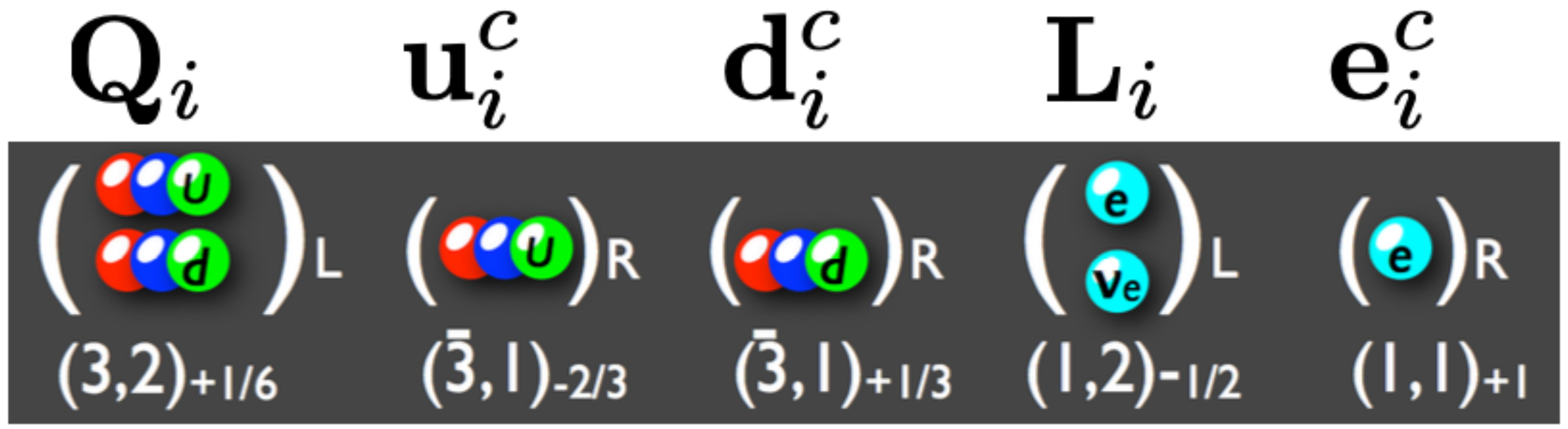
Outline

1. Introduction

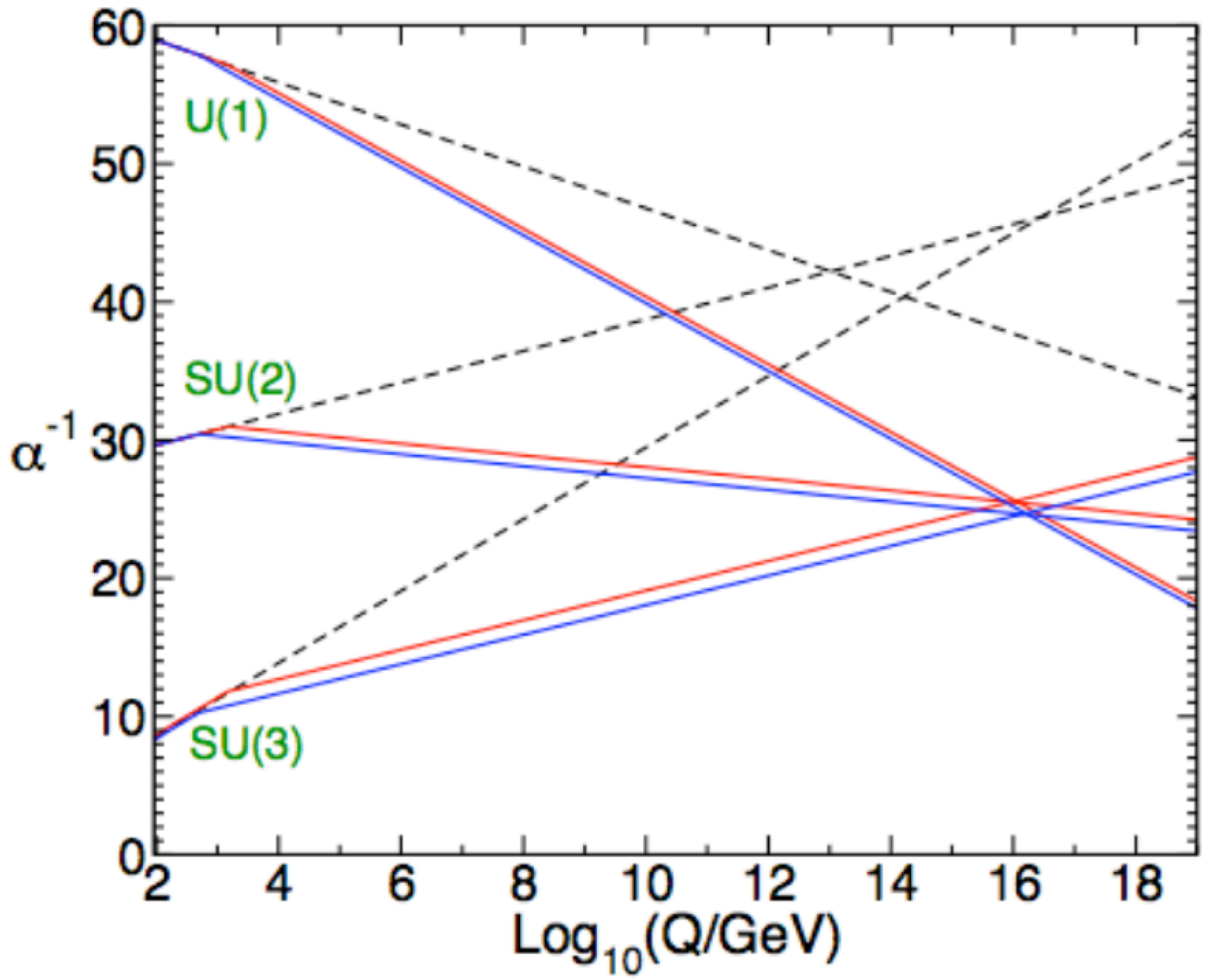
Minimal SUSY SU(5)

- $$\Psi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u^c_{i3} & -u^c_{i2} & u^1_i & d^1_i \\ -u^c_{i3} & 0 & u^c_{i1} & u^2_i & d^2_i \\ u^c_{i2} & -u^c_{i1} & 0 & u^3_i & d^3_i \\ -u^1_i & -u^2_i & -u^3_i & 0 & e^c_i \\ -d^1_i & -d^2_i & -d^3_i & -e^c_i & 0 \end{pmatrix}, \qquad \Phi_i = \begin{pmatrix} d^c_{i1} \\ d^c_{i2} \\ d^c_{i3} \\ e_i \\ -\nu_i \end{pmatrix}, \qquad l^c_i = \left(\nu^c_i\right)$$
- $SU(5) \to SU(3) \times SU(2) \times U(1)$
  - Broken by $\Sigma = 24$
  - $10 \to (\bar{3},1)_{-2/3} + (3,2)_{+1/6} + (1,1)_{+1}$
  - $\bar{5} \to (\bar{3},1)_{+1/3} + (1,2)_{-1/2}$
- Hypercharge



Minimal SUSY SU(5)

- ⋆ Unification of quarks and leptons
- ⋆ Coupling unification
  - ⋆ $g_1(M_{\rm GUT}) = g_2(M_{\rm GUT}) = g_3(M_{\rm GUT})$
- ⋆ Charge quantization
- ⋆ Anomaly cancelation
- ⋆ Proton decay

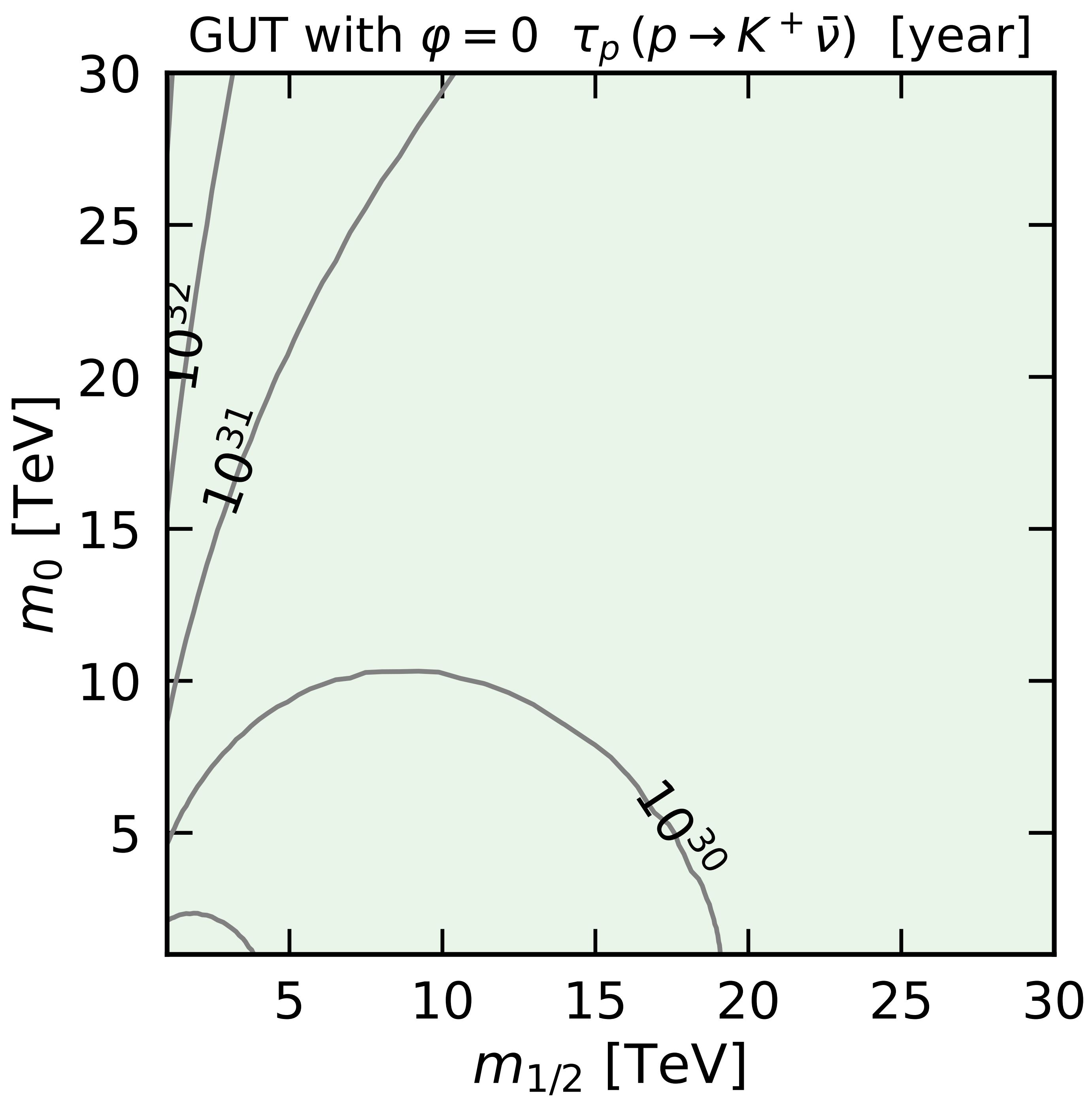


[S. P. Martin, A Supersymmetry primer. (1997)]

Proton decay

- Dimension-5 proton decay
  - $p \to K^+\bar{\nu}$ (mediated by triplet Higgs)
- Dimension-6 proton decay
  - $p \to \pi^0 e^+$ (mediated by SU(5) gauge boson)
- Without tuning, minimal SUSY SU(5) with $\mathcal{O}(10\ \mathrm{TeV})$ CMSSM is mostly ruled out.

$\lambda = \lambda' = 1\ ,\ \tan\beta = 4\ ,\ A_0/m_0 = 0\ .$



Decay Mode	Current [years]	HK sensitivity [years]
$p \to K^+\bar{\nu}$	6.6×10^{33} [37, 38]	3.2×10^{34} [2]
$p \to \pi^+\bar{\nu}$	3.5×10^{32} [39]	
$n \to \pi^0\bar{\nu}$	1.4×10^{33} [39]	
$p \to \pi^0 e^+$	2.4×10^{34} [40]	7.8×10^{34} [2]
$p \to \pi^0 \mu^+$	1.6×10^{34} [40]	7.7×10^{34} [2]
$p \to K^0 e^+$	1.0×10^{33} [41]	
$p \to K^0 \mu^+$	3.6×10^{33} [42]	

2. SUSY SU(5) with Planck-suppressed operators

The model

$$H = \begin{pmatrix} H_C^1 \\ H_C^2 \\ H_C^3 \\ H_u^+ \\ H_u^0 \end{pmatrix} , \qquad \bar{H} = \begin{pmatrix} \bar{H}_{C1} \\ \bar{H}_{C2} \\ \bar{H}_{C3} \\ H_d^- \\ -H_d^0 \end{pmatrix} ,$$

- ⋆ Superpotential of Higgs sector

$$W_{\text{eff}}^H = \mu_\Sigma \text{Tr}\left(\Sigma^2\right) + \frac{\lambda'}{6}\text{Tr}\left(\Sigma^3\right) + \frac{\kappa_1}{4M_P}\text{Tr}\left(\Sigma^4\right) + \frac{\kappa_2}{4M_P}\left(\text{Tr}\left(\Sigma^2\right)\right)^2 + \mu_H H\bar{H} + \lambda H\Sigma\bar{H}$$
$$+ \frac{c_1}{M_P}H\Sigma^2\bar{H} + \frac{c_2}{M_P}H\bar{H}\text{Tr}\left(\Sigma^2\right) + \frac{c_3}{M_P}(H\bar{H})^2 + \frac{c}{M_P}\text{Tr}\left(\Sigma\mathcal{W}\mathcal{W}\right) . \quad (1)$$

- ⋆ Kahler potential

$$\Delta K_{\text{eff}} = \frac{c_{\Sigma\Sigma}}{M_P}\text{Tr}(\Sigma^*\Sigma^2) + \frac{c_{\bar{H}\Sigma H}}{M_P}\bar{H}\Sigma^* H + \sum_{F=\Psi,\Phi,H,\bar{H}}\frac{c_{F\Sigma}}{M_P}F^*\Sigma F + \text{h.c.} \; . \quad (2)$$

- ⋆ Superpotential of Yukawa sector

$$\Psi \ni \{Q_i, \bar{U}_i, \bar{E}_i\} , \quad \Phi \ni \{\bar{D}_i, L_i\} ,$$

$$W_{\text{eff}}^{\Delta h} = (h_{\mathbf{10}})_{ij}\,\epsilon_{\alpha\beta\gamma\delta\zeta}\Psi_i^{\alpha\beta}\Psi_j^{\gamma\delta}H^\zeta + (h_{\bar{\mathbf{5}}})_{ij}\,\Psi_i^{\alpha\beta}\Phi_{j\alpha}\overline{H}_\beta$$
$$+ \frac{c_{\Delta h,1}^{ij}}{M_P}\Psi_i^{\alpha\beta}\Phi_{j\alpha}\Sigma^\gamma{}_\beta\overline{H}_\gamma + \frac{c_{\Delta h,2}^{ij}}{M_P}\Phi_{i\alpha}\Sigma^\alpha{}_\beta\Psi_j^{\beta\gamma}\overline{H}_\gamma$$
$$+ \frac{c_{\Delta h,3}^{ij}}{4M_P}\epsilon_{\alpha\beta\gamma\delta\zeta}\Psi_i^{\alpha\beta}\Psi_j^{\gamma\xi}\Sigma^\delta{}_\xi H^\zeta + \frac{c_{\Delta h,4}^{ij}}{4M_P}\epsilon_{\alpha\beta\gamma\delta\zeta}\Psi_i^{\alpha\beta}\Psi_j^{\gamma\delta}\Sigma^\zeta{}_\xi H^\xi . \quad (3)$$

The model

- The soft SUSY-breaking terms

$$\mathcal{L}_{\rm soft} = -\left(m^2_{\mathbf{10}}\right)_{ij}\widetilde{\psi}^*_i\widetilde{\psi}_j - \left(m^2_{\bar{\mathbf{5}}}\right)_{ij}\widetilde{\phi}^*_i\widetilde{\phi}_j - m^2_H|H|^2 - m^2_{\bar{H}}|\bar{H}|^2 - m^2_\Sigma \mathrm{Tr}(\Sigma^\dagger\Sigma)$$
$$-\Big[\frac{1}{2}M_5\widetilde{\lambda}^A\widetilde{\lambda}^A + A_{\mathbf{10}}(h_{\mathbf{10}})_{ij}\epsilon_{\alpha\beta\gamma\delta\zeta}\widetilde{\psi}^{\alpha\beta}_i\widetilde{\psi}^{\gamma\delta}_j H^\zeta + A_{\bar{\mathbf{5}}}(h_{\bar{\mathbf{5}}})_{ij}\widetilde{\psi}^{\alpha\beta}_i\widetilde{\phi}_{j\alpha}\bar{H}_\beta$$
$$+\mu_\Sigma B_\Sigma \mathrm{Tr}\left(\Sigma^2\right) + \frac{\lambda'}{6}A_{\lambda'}\mathrm{Tr}\left(\Sigma^3\right) + \frac{\kappa_1}{4M_P}\mathrm{Tr}A_1\left(\Sigma^4\right)$$
$$+\frac{\kappa_2}{4M_P}A_2\left(\mathrm{Tr}\left(\Sigma^2\right)\right)^2 + \mu_H B_H \bar{H}H + \lambda A_\lambda H\Sigma\bar{H} + \mathrm{h.c.}\Big],$$

- Symmetry breaking: SU(5) —> SU(3)xSU(2)xU(1)
  - $\langle\Sigma\rangle = \left(V + F_\Sigma\theta^2\right)\mathrm{diag}(2,2,2,-3,-3)$.

$$\kappa = 7\kappa_1 + 30\kappa_2\,, \qquad R = \frac{v_0}{M_P}\,,$$

$$v_0 = \frac{1}{4}\frac{\lambda' M_P \pm\sqrt{\lambda'^2M_P^2 - 32\kappa M_P\mu_\Sigma}}{\kappa}$$
$$\simeq \frac{4\mu_\Sigma}{\lambda'} + \frac{32\kappa\mu_\Sigma^2}{\lambda'^3M_P}\,, \quad \frac{1}{2}\frac{\lambda' M_P}{\kappa} - \frac{4\mu_\Sigma}{\lambda'} - \frac{32\kappa\mu_\Sigma^2}{\lambda'^3M_P}\,, \qquad (10)$$
$$v_1 = 2\frac{\lambda'(A_{\lambda'} - B_\Sigma) - 2\left(7\kappa_1(A_1 - B_\Sigma) + 30\kappa_2(A_2 - B_\Sigma)\right)R}{\left(\lambda' - 4\kappa R\right)^2}\,, \qquad (11)$$
$$v_2 = -4\frac{m_\Sigma^2}{v_0\left(\lambda' - 4\kappa R\right)^2} + 2\frac{\lambda' A_{\lambda'} - 4\left(7\kappa_1A_1 + 30\kappa_2A_2\right)R}{(\lambda' - 4\kappa R)^2}\frac{v_1}{v_0} - 2\frac{\lambda' - 7\kappa R}{\lambda' - 4\kappa R}\frac{v_1^2}{v_0}\,, \qquad (12)$$

Mass spectrum

- Masses for the adjoint components
  - $M_{\Sigma_3} = \frac{5}{2}\lambda' V - 20\frac{\kappa_1 V^2}{M_P}$,
  - $M_{\Sigma_8} = \frac{5}{2}\lambda' V + 5\frac{\kappa_1 V^2}{M_P}$,
  - $M_{\Sigma_1} = \frac{1}{2}\lambda' V - 2\frac{\kappa V^2}{M_P}$,
- Masses of gauge bosons and color triplet Higgs
  - $M_X = 5 g_5 V$,
  - $M_{H_C} = \mu_H + 2\lambda V + \frac{(4c_1 + 30c_2)}{M_P} V^2 = 5\lambda V - \frac{5c_1}{M_P} V^2$,

Matching conditions

- The gauge coupling matching conditions
  - $$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = -\frac{3}{10\pi^2}\ln\left(\frac{QM_{\Sigma_3}^{\frac{5}{2}}}{M_{H_C}M_{\Sigma_8}^{\frac{5}{2}}}\right) - \frac{96cV}{M_P}.$$
  - $$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{3}{4\pi^2}\ln\left(\frac{Q^6}{M_X^4 M_{\Sigma_3}M_{\Sigma_8}}\right),$$
  - $$\frac{5}{g_1^2(Q)} + \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{15}{2\pi^2}\ln\left(\frac{Q}{M_X}\right) + \frac{6}{g_5^2(Q)} - \frac{144cV}{M_P}.$$
- $M_G \equiv (M_X^4 M_{\Sigma_3} M_{\Sigma_8})^{1/6}$ is determined by gauge coupling
  - To determine V with $(g_5, \lambda, \lambda', \kappa_1)$

Yukawa sector

- MSSM Yukawa term

$$\begin{aligned} W_{\text{Yukawa}} = & f_{u_{ij}}(Q_i^a \cdot H_u)\overline{U}_{ja} - f_{d_{ij}}(Q_i^a \cdot H_d)\overline{D}_{ja} - f_{e_{ij}}\overline{E}_i(L_j \cdot H_d) \\ & - \frac{1}{2} f_{Q_iQ_j}(Q_i^a \cdot Q_j^b) H_C^c + f_{Q_iL_j}(Q_i^a \cdot L_j)\overline{H}_{Ca} \\ & + f_{U_iE_j}\overline{U}_{ia}\overline{E}_j H_C^a - f_{U_iD_j}\epsilon^{abc}\overline{U}_{ia}\overline{D}_{jb}\overline{H}_{Cc} \, . \end{aligned} \tag{37}$$

- Yukawa coupling matching

$$\begin{aligned} f_{u_{ij}} &= 4\,(h_{\mathbf{10}})_{ij} - 3c^{ij,S}_{\Delta h,4}R + \frac{1}{4}\left[3c^{ij,S}_{\Delta h,3} + 5c^{ij,A}_{\Delta h,3}\right] R \, , \\ f_{Q_iQ_j} &= 4\,(h_{\mathbf{10}})_{ij} + 4c^{ij,S}_{\Delta h,4}R - \frac{1}{4}c^{ij,S}_{\Delta h,3}R \, , \\ f_{U_iE_j} &= 4\,(h_{\mathbf{10}})_{ij} + 2c^{ij,S}_{\Delta h,4}R - \frac{1}{2}\left[c^{ij,S}_{\Delta h,3} + 5c^{ij,A}_{\Delta h,3}\right] R \, , \end{aligned}$$

$$\begin{aligned} \sqrt{2} f_{d_{ij}} &= (h_{\overline{\mathbf{5}}})_{ij} - 3c^{ij}_{\Delta h,1}R + 2c^{ij}_{\Delta h,2}R \, , \\ \sqrt{2} f_{e_{ij}} &= (h_{\overline{\mathbf{5}}})_{ij} - 3c^{ij}_{\Delta h,1}R - 3c^{ij}_{\Delta h,2}R \, , \\ \sqrt{2} f_{Q_iL_j} &= (h_{\overline{\mathbf{5}}})_{ij} + 2c^{ij}_{\Delta h,1}R - 3c^{ij}_{\Delta h,2}R \, , \\ \sqrt{2} f_{U_iD_j} &= (h_{\overline{\mathbf{5}}})_{ij} + 2c^{ij}_{\Delta h,1}R + 2c^{ij}_{\Delta h,2}R \, , \end{aligned}$$

- Lepton and down-type quark Yukawa splitting $\sqrt{2}\left(f_{d_{ij}} - f_{e_{ij}}\right) = 5c^{ij}_{\Delta h,2}R \, .$

3. Proton decay

Color Higgs Yukawa

- Fields $\Psi \ni \{Q_i, e^{-i\varphi_i}\bar{U}_i, V_{ij}\bar{E}_j\}$, $\Phi \ni \{\bar{D}_i, L_i\}$,
- Color Higgs Yukawa expressed in terms of MSSM Yukawa
- Up-type Yukawa
  - $f_{QQ,i} = f_{u,i} + 7(c_{\Delta h,4})_i R - (c_{\Delta h,3})_i R$,
  - $f_{UE,i} = f_{u,i} + 5(c_{\Delta h,4})_i R - \frac{5}{4}(c_{\Delta h,3})_i R$,

If we allow $(c_{\Delta h,3})_i$, $(c_{\Delta h,4})_i$ to be large, both $f_{QQ,i}$ and $f_{UE,i}$ are free parameters

- Lepton and down type Yukawa
  - $f_{QL,i} = f_{e,i} + \frac{5}{\sqrt{2}}(c_{\Delta h,1})_i R$,
  - $f_{UD,i} = f_{d,i} + \frac{5}{\sqrt{2}}(c_{\Delta h,1})_i R$.

$f_{QL,i}$ and $f_{UD,i}$ are related.

Full proton decay computation for every branches:
[N. Nagata. PhD thesis, Tokyo U., 2013.
http://doi.org/10.15083/00006623.]

Proton decay

- Dimension-5 proton decay $\mathscr{L}_5^{\text{eff}} = C_{5L}^{ijkl}\mathscr{O}_{ijkl}^{5L} + C_{5R}^{ijkl}\mathscr{O}_{ijkl}^{5R} + \text{h.c.}\,,$
  - $\mathscr{O}_{ijkl}^{5L} = \int d^2\theta\; \frac{1}{2}\epsilon_{abc}\epsilon_{mn}\epsilon_{pq}\; Q_i^{am}Q_j^{bn}Q_k^{cp}L_l^q\,,$
  - $\mathscr{O}_{ijkl}^{5R} = \int d^2\theta\; \epsilon^{abc}(\bar{U}_i)_a\bar{E}_j(\bar{U}_k)_b(\bar{D}_l)_c\,,$
- At the SUSY-breaking scale: wino-exchange process & higgsino-exchange process

$$C_i^{\widetilde{H}}(M_{\text{SUSY}}) = \frac{f_t f_\tau}{(4\pi)^2}C_{5R}^{*331i}(M_{\text{SUSY}})F(\mu, m_{\tilde{t}_R}^2, m_{\tilde{\tau}_R}^2)\,,$$

$$C_{jk}^{\widetilde{W}}(M_{\text{SUSY}}) = \frac{\alpha_2}{4\pi}C_{5L}^{jj1k}(M_{\text{SUSY}})\left[F(M_2, m_{\tilde{Q}_1}^2, m_{\tilde{Q}_j}^2) + F(M_2, m_{\tilde{Q}_j}^2, m_{\tilde{L}_k}^2)\right]\,,$$

$$\bar{C}_{jk}^{\widetilde{W}}(M_{\text{SUSY}}) = -\frac{3}{2}\frac{\alpha_2}{4\pi}C_{5L}^{jj1k}(M_{\text{SUSY}})\left[F(M_2, m_{\tilde{Q}_j}^2, m_{\tilde{Q}_j}^2) + F(M_2, m_{\tilde{Q}_1}^2, m_{\tilde{L}_k}^2)\right]\,,$$

- Wilson coefficients
  - $C_{5R}^{331i} = \frac{1}{M_{H_C}}(f_{UE})_3 V^{33}(V^*)^{1i}(f_{UD})_{i=1,2}\, e^{-i\varphi_1}\,,$
  - $C_{5L}^{jj1k} = \frac{1}{M_{H_C}}(f_{QQ})_{j=2,3}\, e^{i\varphi_j}(V^*)^{1k}(f_{QL})_{k=1,2,3}\,.$

$(f_{UE})_3$ **and** $(f_{QQ})_3$ **are big (top Yukawa)**

Wino-exchange process usually gives the dominant contribution

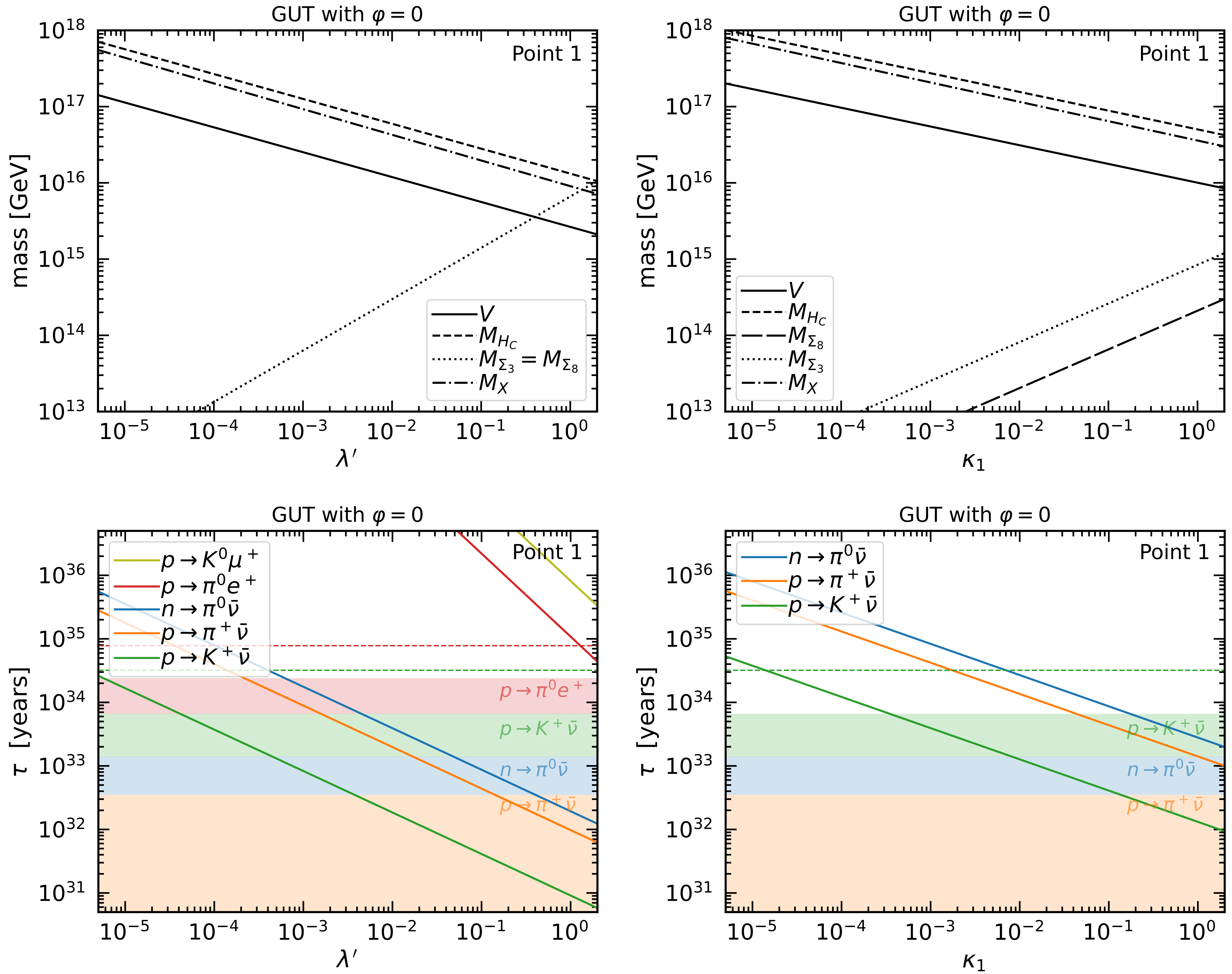
Suppression of f_{QL}

4. Results

Proton decay and SU(5) breaking

Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$A_0/m_0 = 0$	$\tan\beta = 4$
$\lambda = 1$	$\lambda' = 1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.818$	$M_{H_C} = 1.322$	$M_\Sigma = 0.661$	$M_X = 0.906$
Observables			
$\Omega_\chi h^2 = 0.096$	$m_h = 122.9$ GeV		

- Limit (i): $\lambda' \neq 0\,, \kappa_1 = 0$
  - $M_{\Sigma_3} \approx \frac{5}{2}\lambda' V\,,\; M_{\Sigma_8} \approx \frac{5}{2}\lambda' V$
  - $M_{H_C} = \lambda\left(\frac{2}{\lambda' g_5^2}\right)^{\frac{1}{3}} M_G$
- Limit (ii): $\lambda' = 0\,, \kappa_1 \neq 0$
  - $M_{\Sigma_3} \approx 20\frac{\kappa_1 V^2}{M_P}\,,\; M_{\Sigma_8} \approx 5\frac{\kappa_1 V^2}{M_P}$
  - $M_{H_C} = \lambda\left(\frac{5}{2g_5^2(\frac{\kappa_1}{M_P})}\right)^{\frac{1}{4}} M_G^{\frac{3}{4}}$



Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$A_0/m_0 = 0$	$\tan\beta = 4$
$\lambda = 1$	$\lambda' = 1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.818$	$M_{H_C} = 1.322$	$M_\Sigma = 0.661$	$M_X = 0.906$
Observables			
$\Omega_\chi h^2 = 0.096$	$m_h = 122.9$ GeV		

Yukawa sector in CMSSM

Decay mode: $p \to K^+\bar{\nu}$

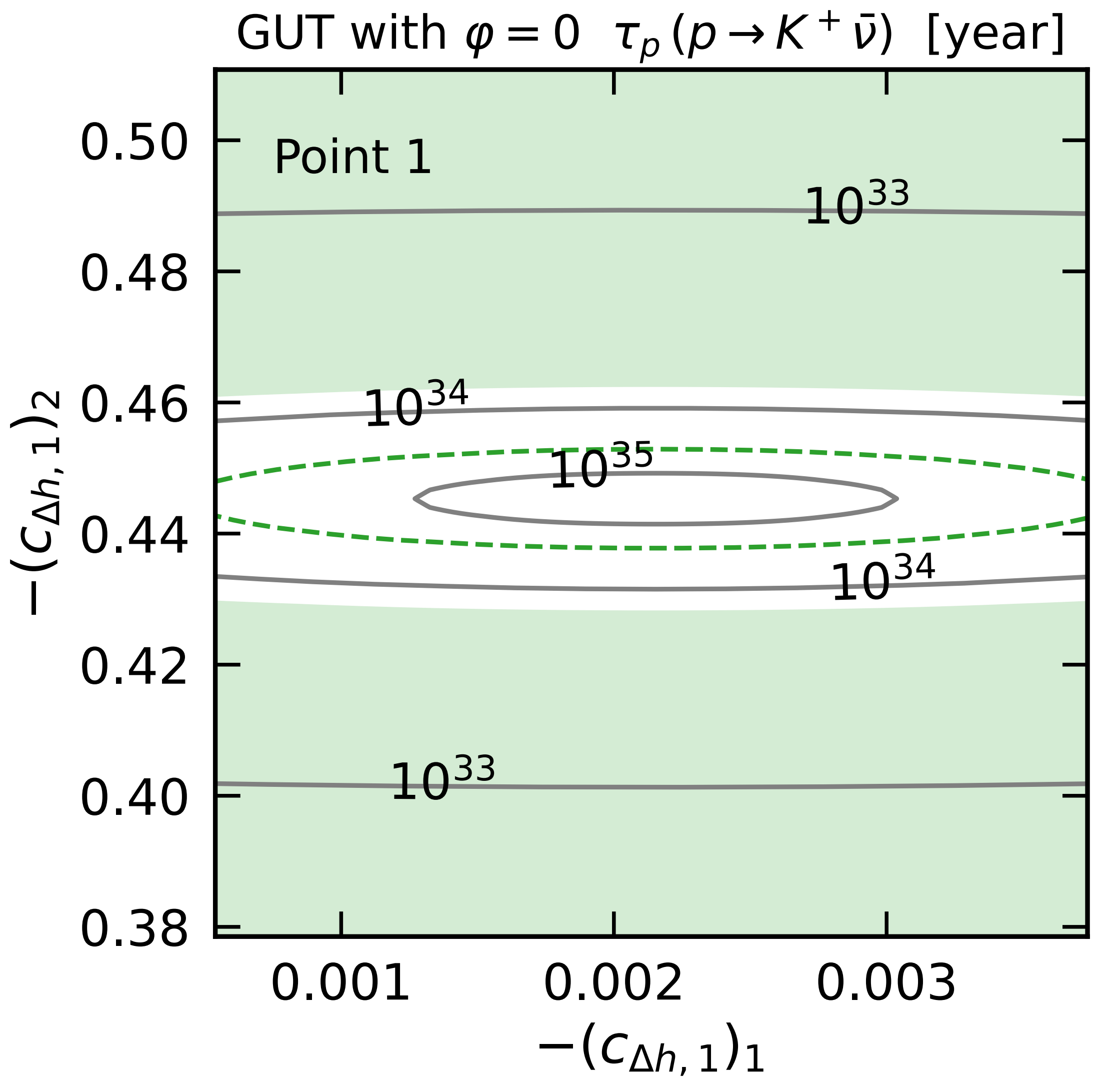
- ⋆ Wino exchange process
- ⋆ Higgsino exchange process

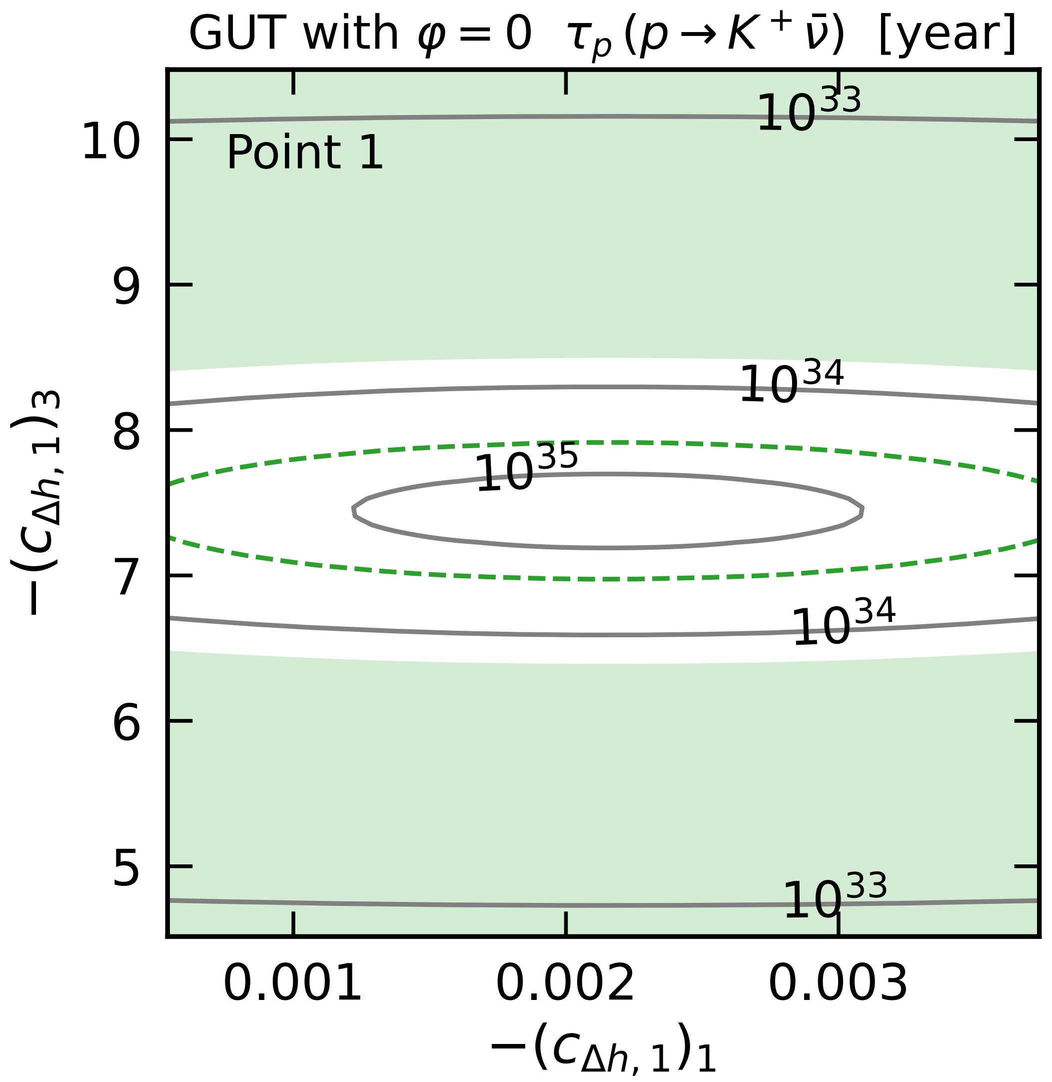
⋆ $$C_{5L}^{jj1k} = \frac{1}{M_{H_C}}(f_{QQ})_{j=2,3}e^{i\varphi_j}(V^*)^{1k}(f_{QL})_{k=1,2,3} \, .$$

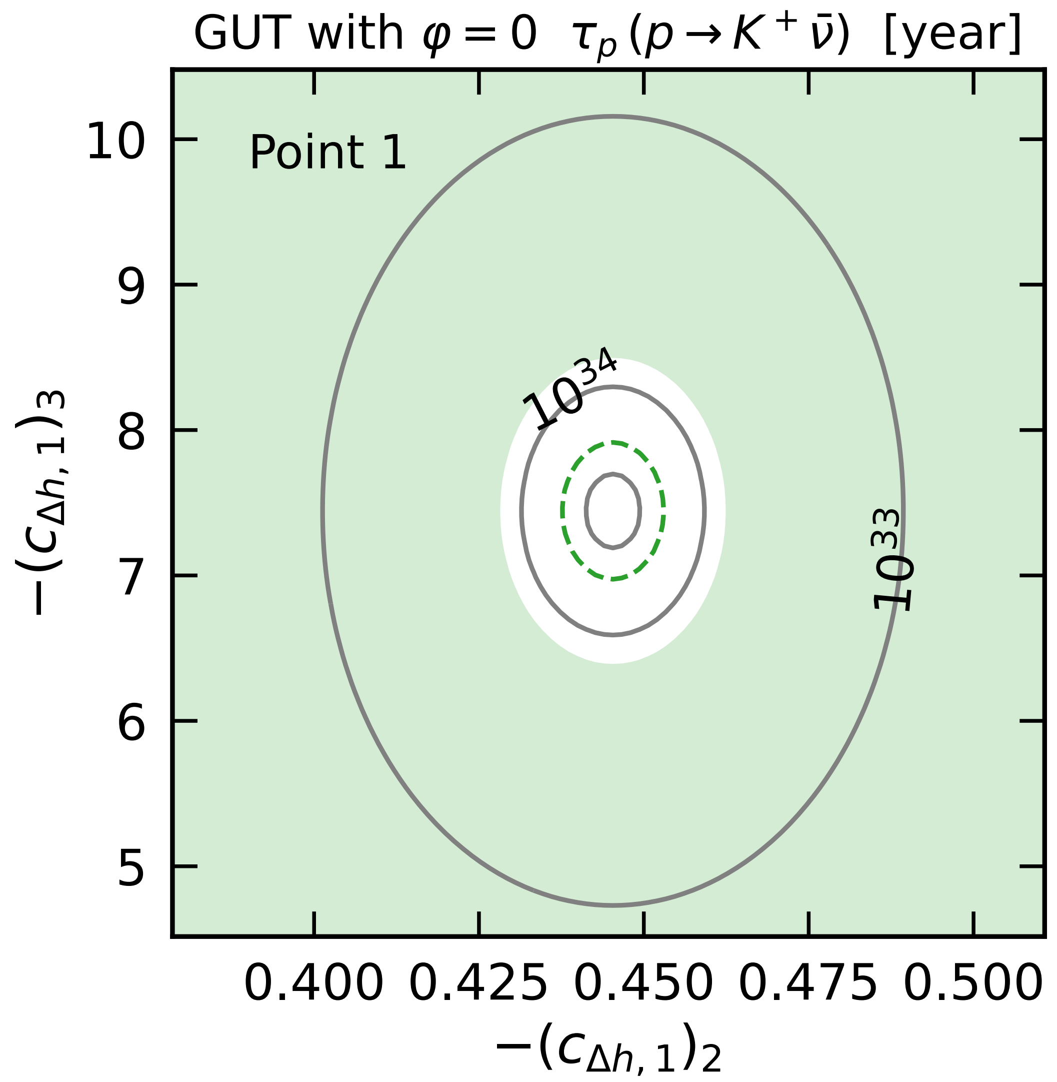
⋆ $$C_{5R}^{331i} = \frac{1}{M_{H_C}}(f_{UE})_3 V^{33}(V^*)^{1i}(f_{UD})_{i=1,2}e^{-i\varphi_1} \, ,$$

⋆ $$f_{QL,i} = f_{e,i} + \frac{5}{\sqrt{2}}(c_{\Delta h,1})_i R \, ,$$

⋆ $$f_{UD,i} = f_{d,i} + \frac{5}{\sqrt{2}}(c_{\Delta h,1})_i R \, .$$







Yukawa sector in CMSSM

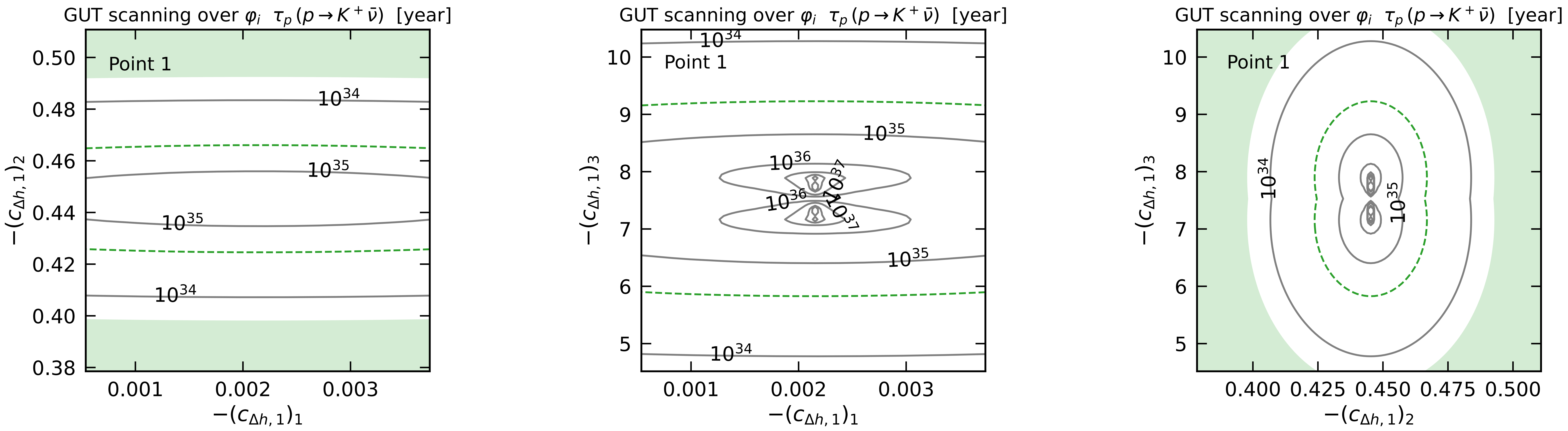
Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$A_0/m_0 = 0$	$\tan\beta = 4$
$\lambda = 1$	$\lambda' = 1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\mathrm{GUT}} = 0.818$	$M_{H_C} = 1.322$	$M_\Sigma = 0.661$	$M_X = 0.906$
Observables			
$\Omega_\chi h^2 = 0.096$	$m_h = 122.9$ GeV		

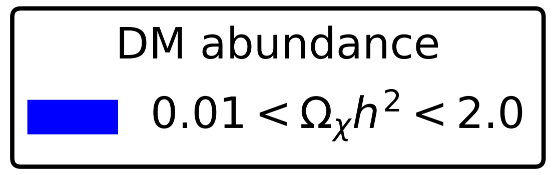
$$C_{5L}^{jj1k} = \frac{1}{M_{H_C}}(f_{QQ})_{j=2,3}\, e^{i\varphi_j}(V^*)^{1k}(f_{QL})_{k=1,2,3}\,, \quad C_{5R}^{331i} = \frac{1}{M_{H_C}}(f_{UE})_3 V^{33}(V^*)^{1i}(f_{UD})_{i=1,2}\, e^{-i\varphi_1},$$

$$\begin{aligned}\mathcal{L}(p\to K^+\bar{\nu}_i) =& C_{RL}(usd\nu_i)\left[\epsilon_{abc}(u_R^a s_R^b)(d_L^c \nu_i)\right] + C_{RL}(uds\nu_i)\left[\epsilon_{abc}(u_R^a d_R^b)(s_L^c \nu_i)\right] \\ &+ C_{LL}(usd\nu_i)\left[\epsilon_{abc}(u_L^a s_L^b)(d_L^c \nu_i)\right] + C_{LL}(uds\nu_i)\left[\epsilon_{abc}(u_L^a d_L^b)(s_L^c \nu_i)\right]\,.\end{aligned}$$

$$C_{RL}(usd\nu_\tau) = -V_{td}C_2^{\widetilde{H}}(m_Z)$$

$$C_{RL}(uds\nu_\tau) = -V_{ts}C_1^{\widetilde{H}}(m_Z)$$



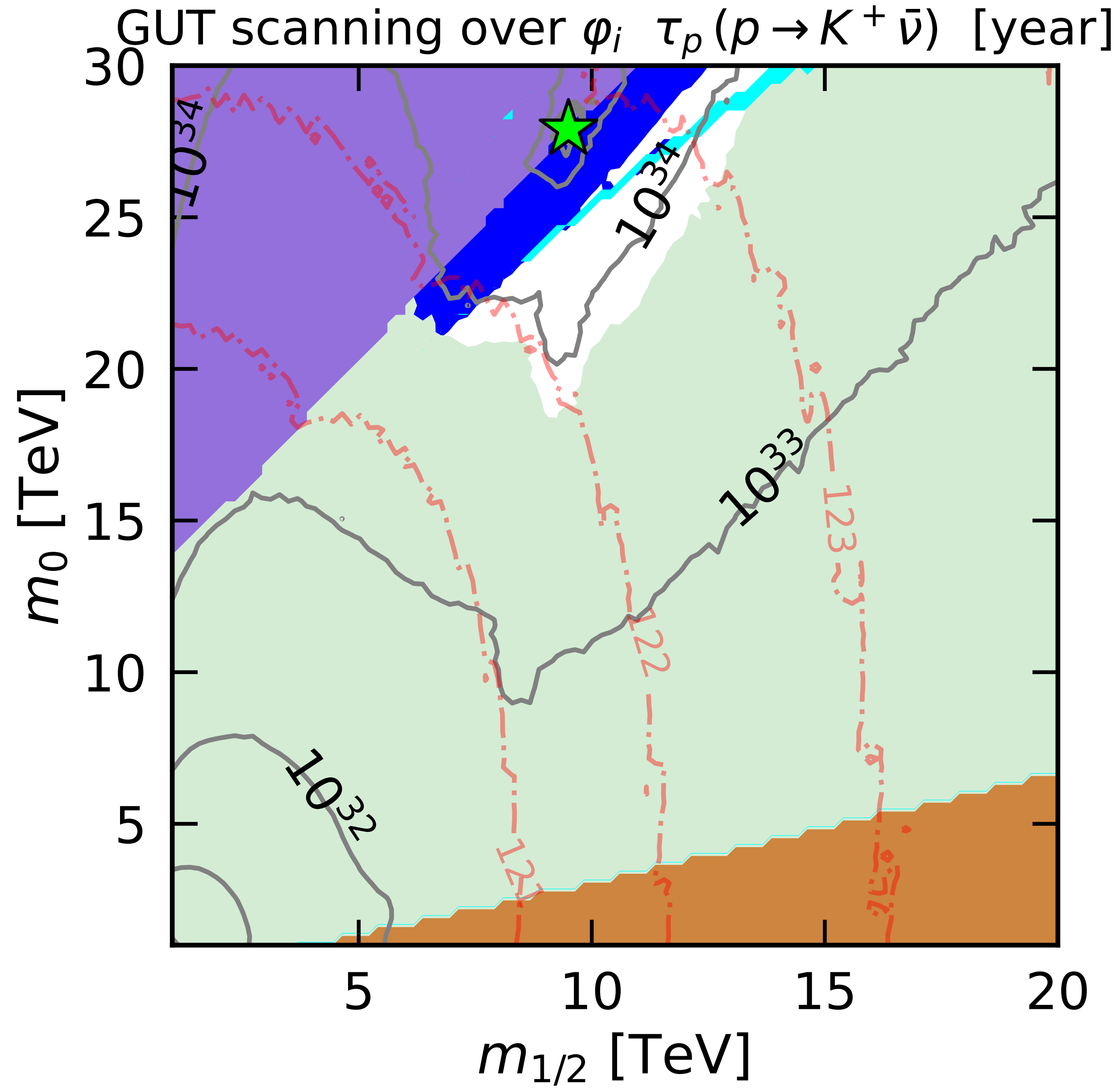


Yukawa sector in CMSSM

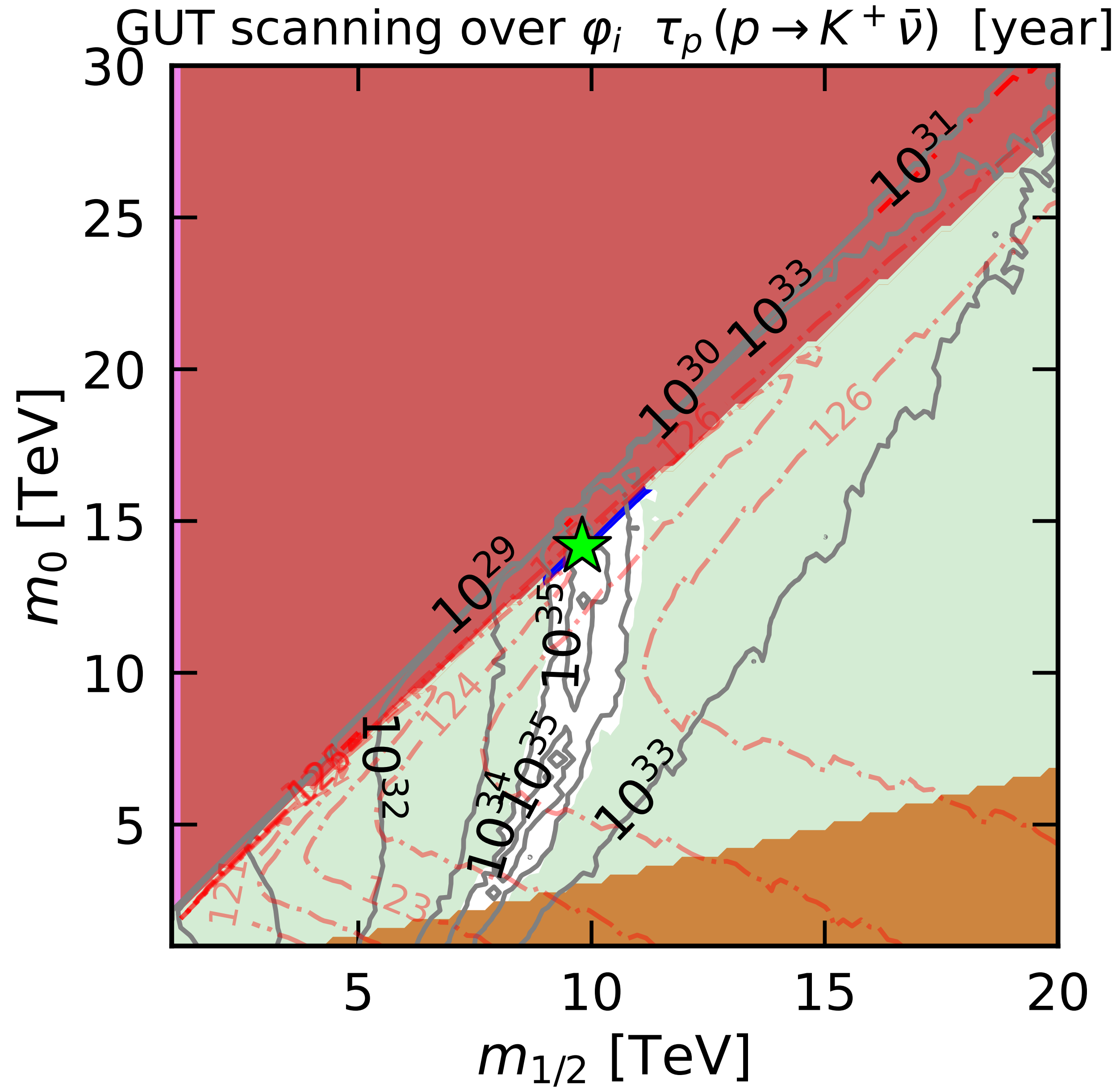
Inputs			
$m_{1/2}=9.5$ TeV	$m_0=27.9$ TeV	$A_0/m_0=0$	$\tan\beta=4$
$\lambda=1$	$\lambda'=1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT}=0.818$	$M_{H_C}=1.322$	$M_\Sigma=0.661$	$M_X=0.906$
$V=0.264$	$g_5=0.685$	$c=0.1365$	
Observables			
$\Omega_\chi h^2=0.096$	$m_h=122.9$ GeV		

Inputs			
$m_{1/2}=9.8$ TeV	$m_0=14.15$ TeV	$A_0/m_0=3$	$\tan\beta=5$
$\lambda=1$	$\lambda'=1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT}=0.685$	$M_{H_C}=1.257$	$M_\Sigma=0.628$	$M_X=0.862$
$V=0.251$	$g_5=0.686$	$c=-0.481$	
Observables			
$\Omega_\chi h^2=0.099$	$m_h=124.3$ GeV		

$$\lambda=\lambda'=1\ ,\ \tan\beta=4\ ,\ A_0/m_0=0\ .$$

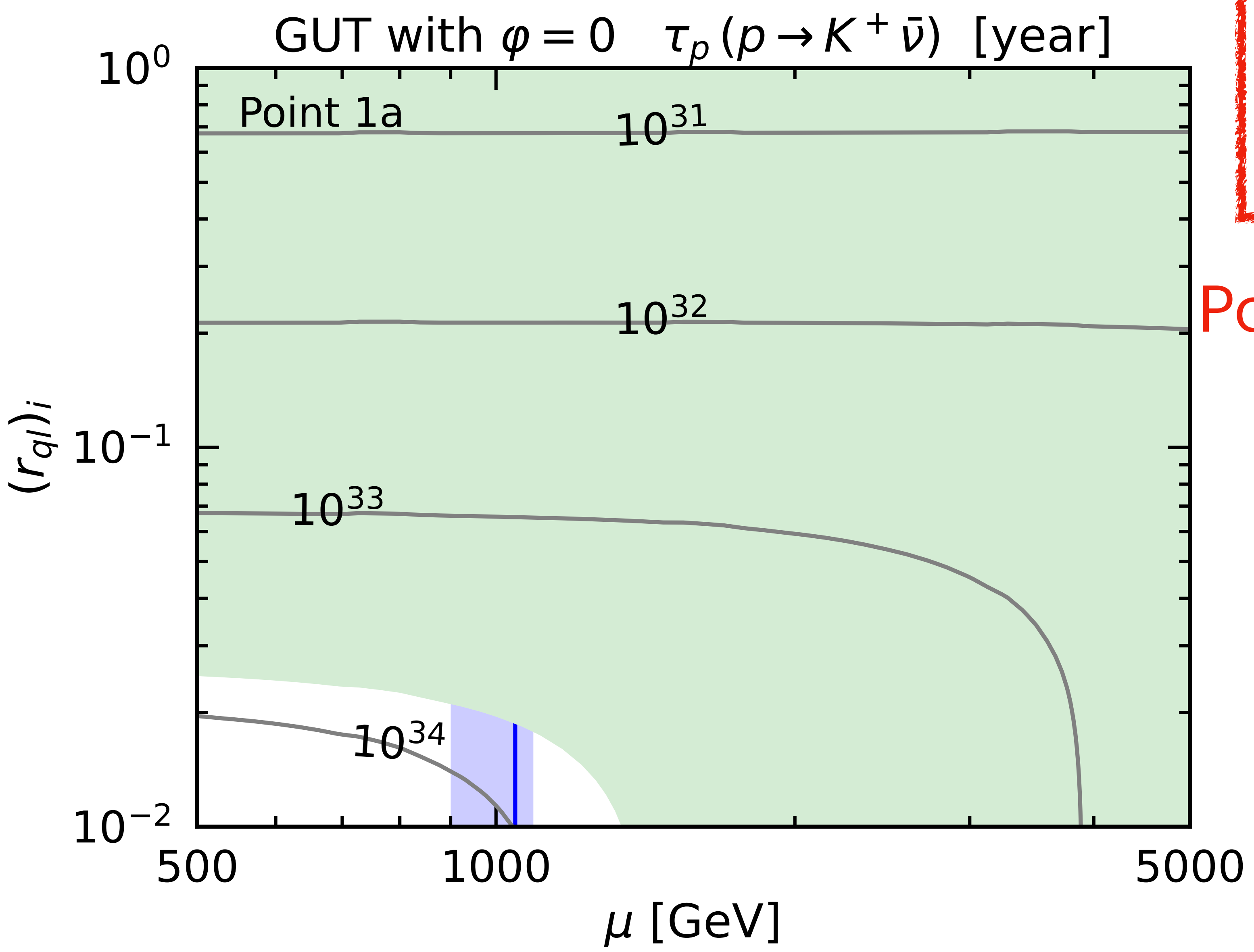


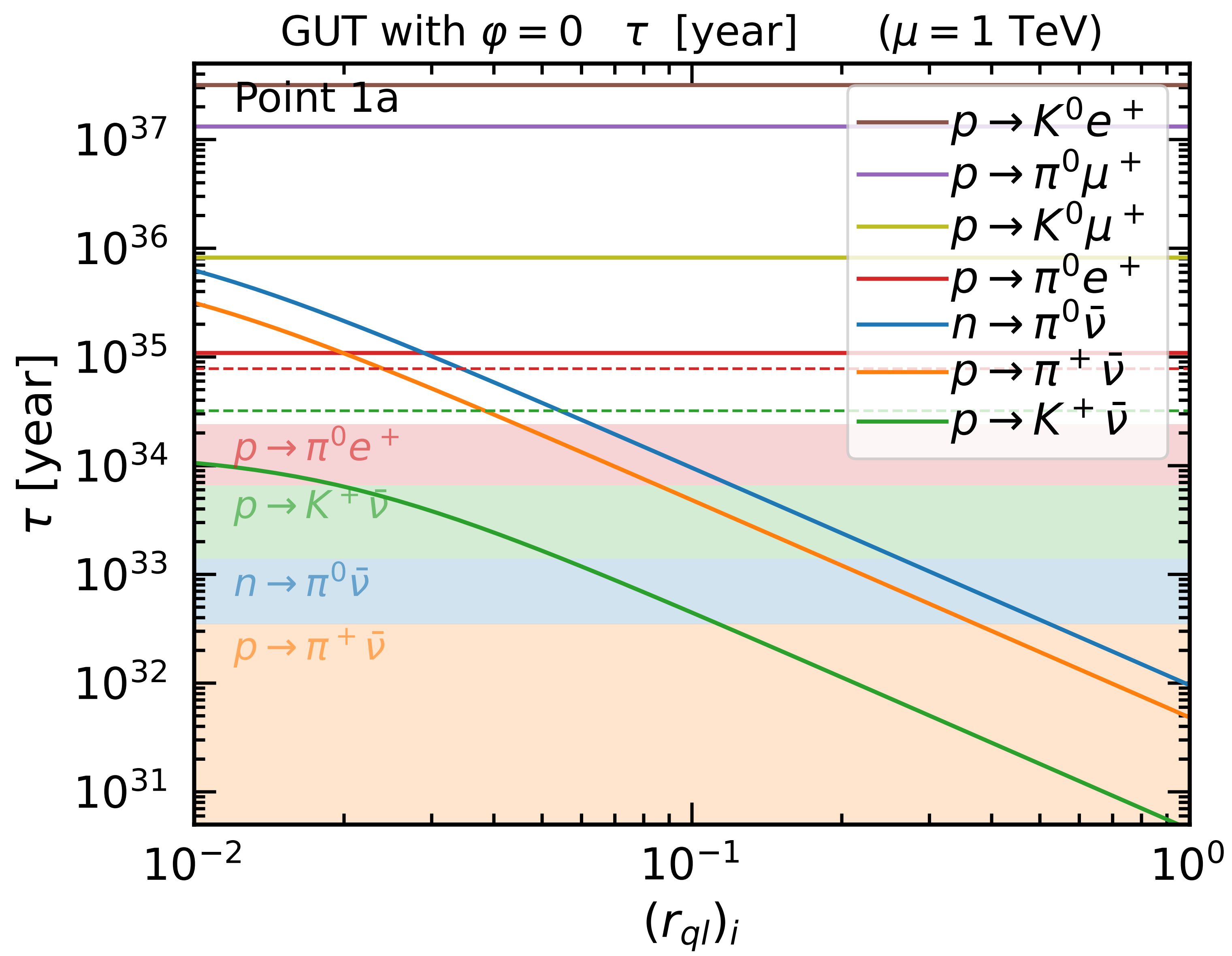
$$\lambda=\lambda'=1\ ,\ \tan\beta=5\ ,\ A_0/m_0=3\ .$$



$$f_{QL,i} = (r_{ql})_i f_{e,i}$$

NUHM





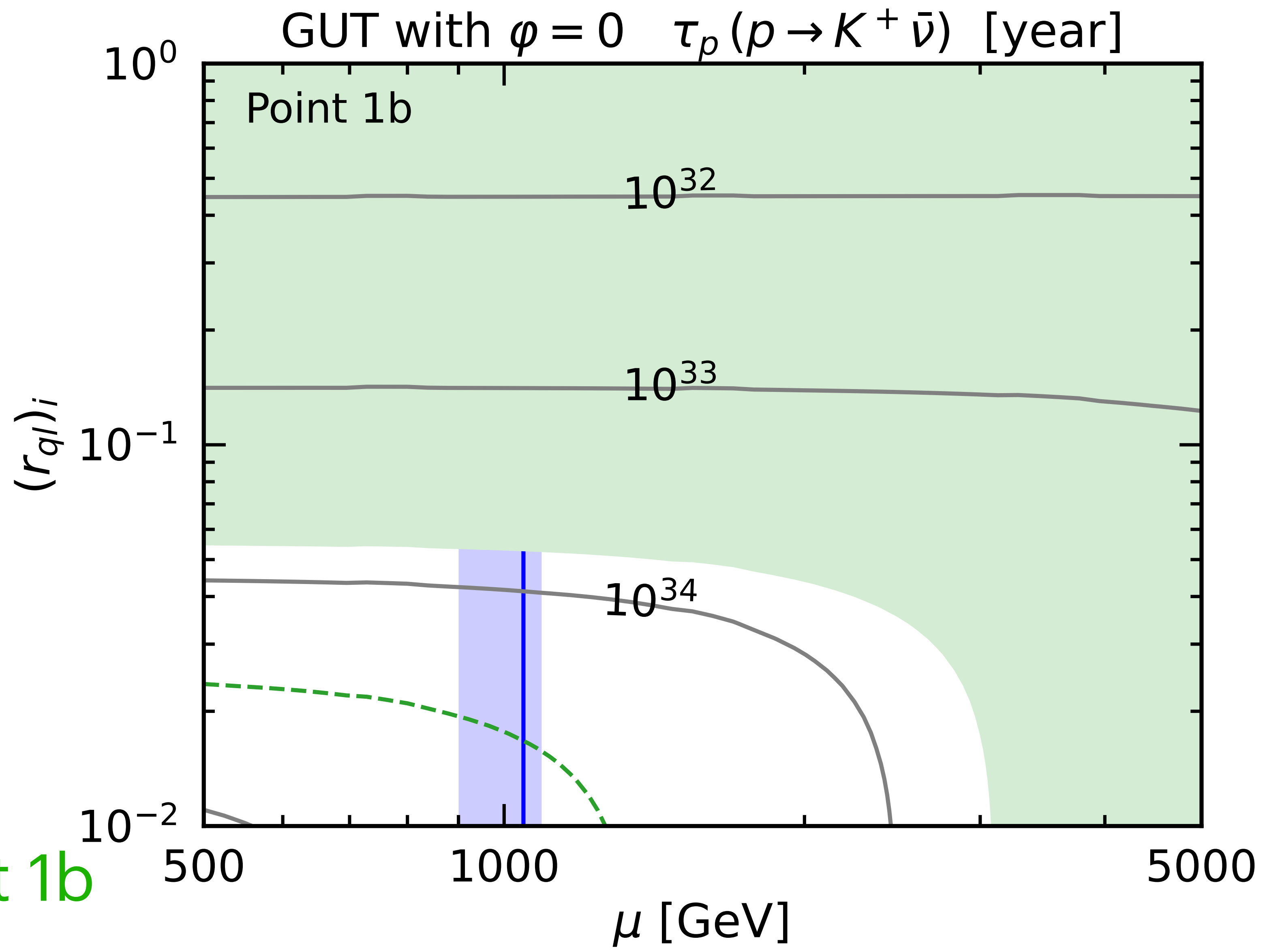
Point 1a

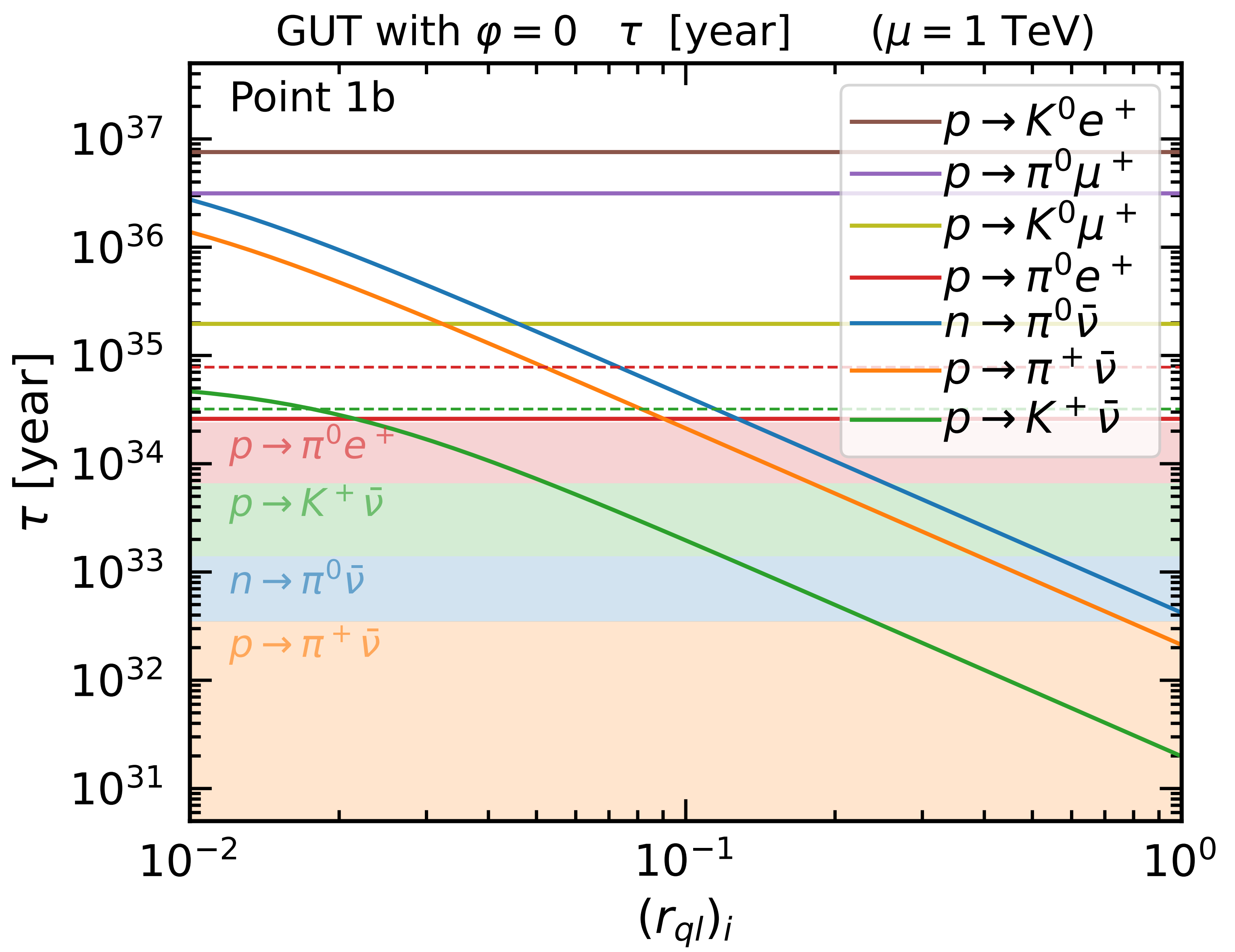
Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$m_A = 27.9$ TeV	$A_0/m_0 = 0$
$\mu = 1$ TeV	$\tan\beta = 6$	$\lambda = 1$	$\lambda' = 1$
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.810$	$M_{H_C} = 1.324$	$M_\Sigma = 0.662$	$M_X = 0.907$
$V = 0.265$	$g_5 = 0.685$	$c = -1.23 \times 10^{-6}$	

Point 1b

Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$m_A = 27.9$ TeV	$A_0/m_0 = 0$
$\mu = 1$ TeV	$\tan\beta = 6$	$\lambda = 3$	$\lambda' = 3$
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.810$	$M_{H_C} = 2.776$	$M_\Sigma = 1.388$	$M_X = 0.626$
$V = 0.185$	$g_5 = 0.677$	$c = -1.76 \times 10^{-6}$	

MSSM parameters (masses in units of TeV)			
$m_\chi = 1.060$	$m_{\tilde{t}_1} = 22.1$	$m_{\tilde{g}} = 19.40$	$m_{\chi_2} = 1.061$
$m_A = 27.90$	$\mu = 1.0$	$m_{\tilde{\ell}_L} = 28.4$	$m_{\tilde{\ell}_R} = 28.1$
$m_{\tilde{\tau}_1} = 28.0$	$m_{\tilde{q}_L} = 31.2$	$m_{\tilde{d}_R} = 30.9$	$m_{\tilde{t}_2} = 27.3$
$A_t = 18.75$	$A_b = 27.2$	$B = -131$	
Observables			
$\Omega_\chi h^2 = 0.110$	$m_h = 125.8$ GeV		





6. Summary

Summary

- SUSY SU(5) GUT with dimension-5 Planck-suppressed operators —> mass spectrum and proton decays
- Higgs sector
  - Mass splitting of M_{Σ_3} and M_{Σ_8}
- Yukawa sector
  - Color Higgs Yukawa deviation form the MSSM Yukawa $(c_{\Delta h,1})_i$, $(c_{\Delta h,2})_i$, $(c_{\Delta h,3})_i$, $(c_{\Delta h,4})_i$
- CMSSM & NUHM
- Hyper-Kamiokande, JUNO, and DUNE

Backup slides

Proton decay

$$\mathcal{L}(p \to K^+\bar{\nu}_i) = C_{RL}(usd\nu_i)[\epsilon_{abc}(u_R^a s_R^b)(d_L^c \nu_i)] + C_{RL}(uds\nu_i)[\epsilon_{abc}(u_R^a d_R^b)(s_L^c \nu_i)]$$
$$+ C_{LL}(usd\nu_i)[\epsilon_{abc}(u_L^a s_L^b)(d_L^c \nu_i)] + C_{LL}(uds\nu_i)[\epsilon_{abc}(u_L^a d_L^b)(s_L^c \nu_i)],$$

$$C_{RL}(usd\nu_\tau; m_t) = -V_{td} C_2^{\tilde{H}}(m_t),$$
$$C_{RL}(uds\nu_\tau; m_t) = -V_{ts} C_1^{\tilde{H}}(m_t),$$
$$C_{LL}(usd\nu_k; m_t) = \sum_{j=2,3} V_{j1} V_{j2} C_{jk}^{\tilde{W}}(m_t),$$
$$C_{LL}(uds\nu_k; m_t) = \sum_{j=2,3} V_{j1} V_{j2} C_{jk}^{\tilde{W}}(m_t).$$

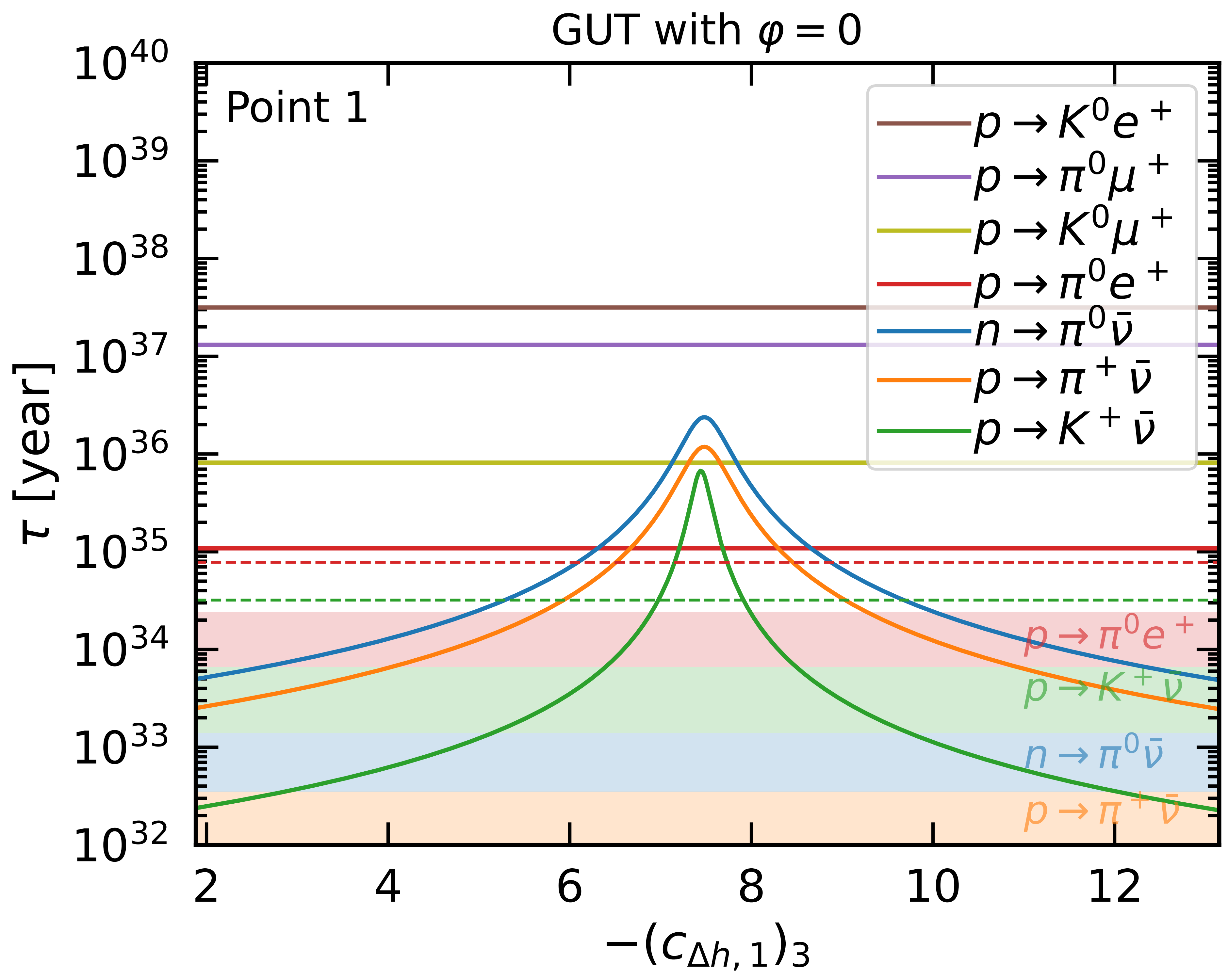
Benchmark point parameters

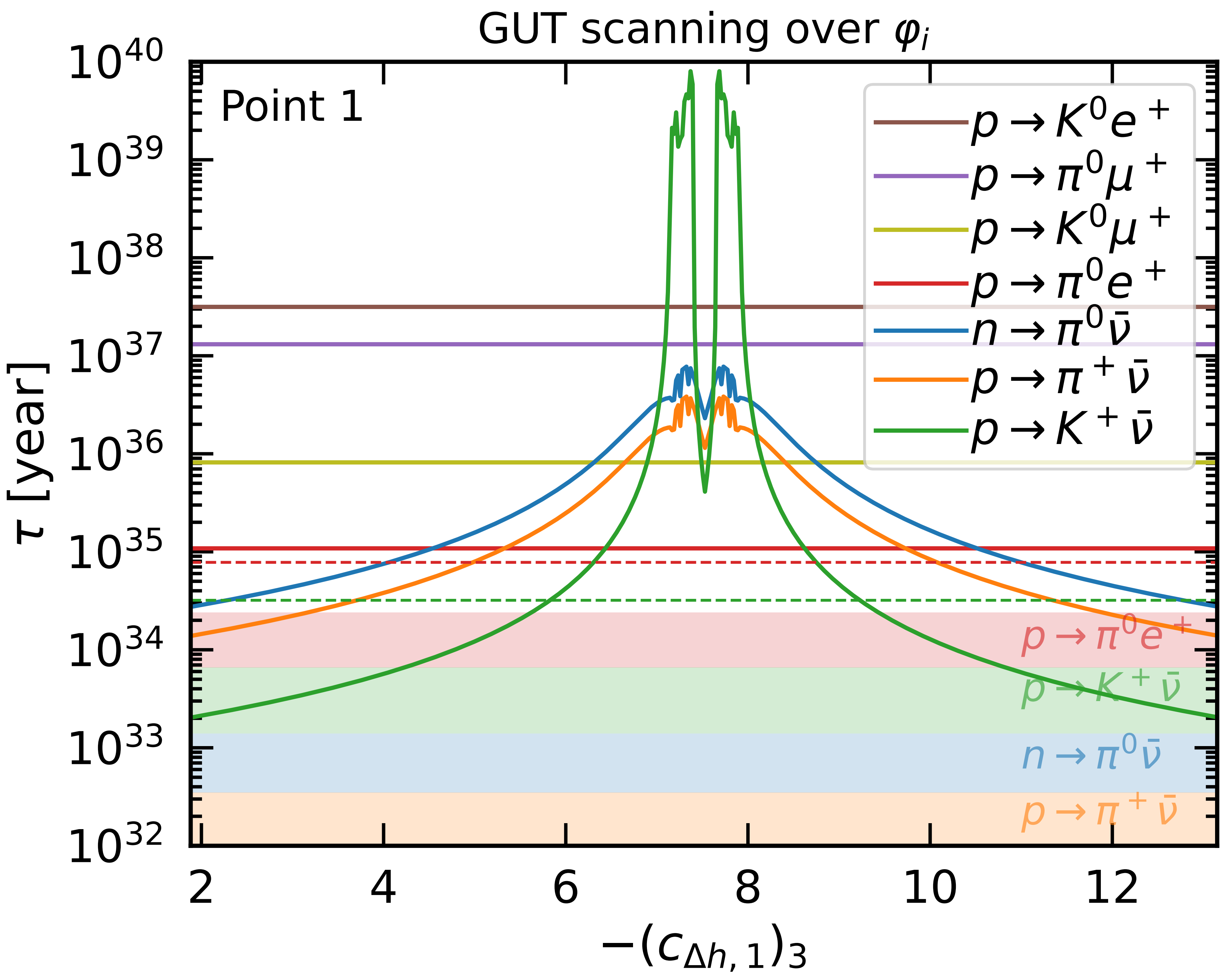
Inputs			
$m_{1/2} = 9.5$ TeV	$m_0 = 27.9$ TeV	$A_0/m_0 = 0$	$\tan\beta = 4$
$\lambda = 1$	$\lambda' = 1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.818$	$M_{H_C} = 1.322$	$M_\Sigma = 0.661$	$M_X = 0.906$
$V = 0.264$	$g_5 = 0.685$	$c = 0.1365$	
MSSM parameters (masses in units of TeV)			
$m_\chi = 0.987$	$m_{\tilde{t}_1} = 21.3$	$m_{\tilde{g}} = 19.40$	$m_{\chi_2} = 0.988$
$m_A = 28.85$	$\mu = 0.938$	$m_{\tilde{\ell}_L} = 28.4$	$m_{\tilde{\ell}_R} = 28.0$
$m_{\tilde{\tau}_1} = 28.0$	$m_{\tilde{q}_L} = 31.2$	$m_{\tilde{d}_R} = 30.8$	$m_{\tilde{t}_2} = 27.0$
$A_t = 18.45$	$A_b = 27.2$	$B = -218$	
Observables			
$\Omega_\chi h^2 = 0.096$	$m_h = 122.9$ GeV		

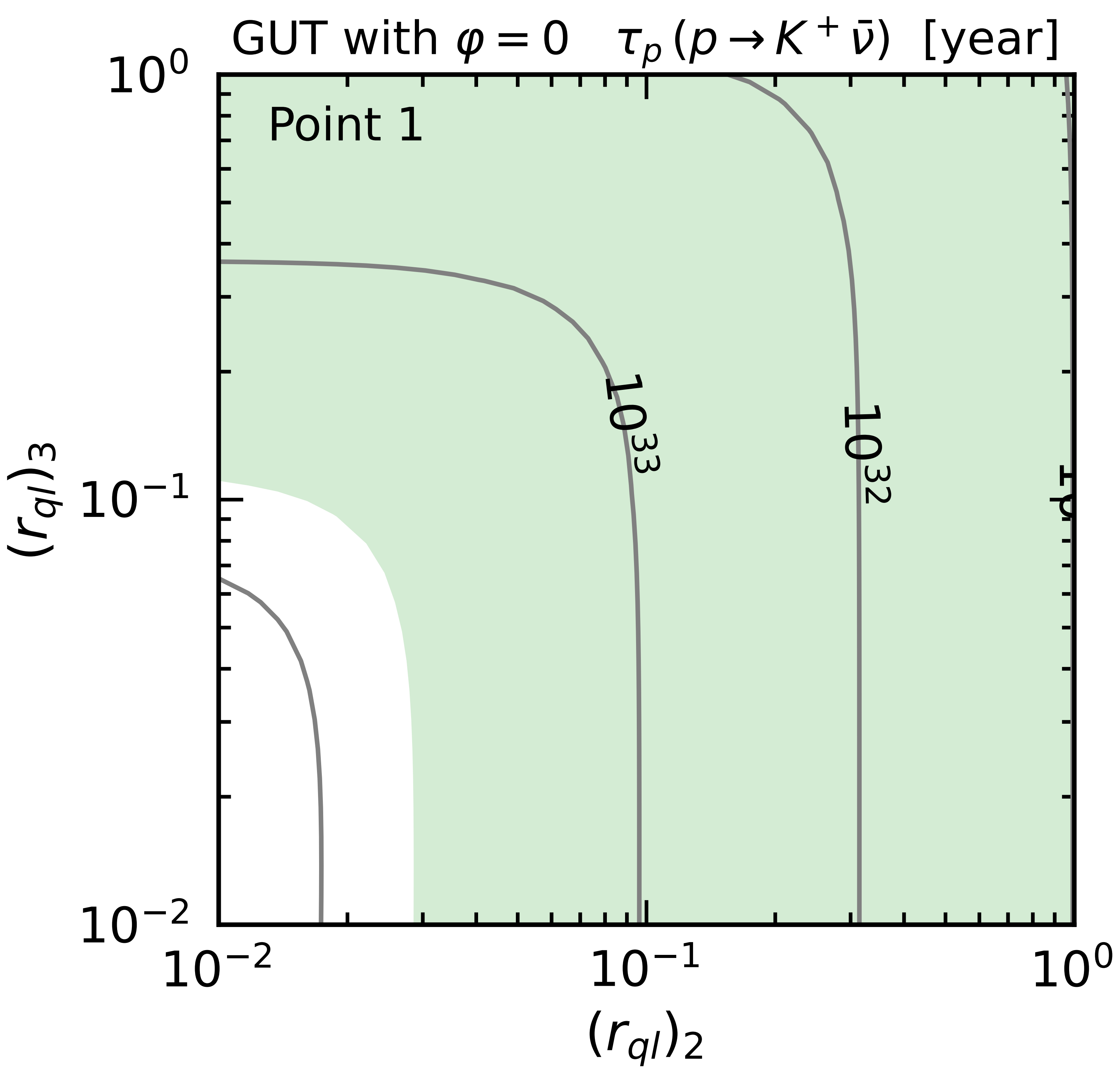
Inputs			
$m_{1/2} = 9.8$ TeV	$m_0 = 14.15$ TeV	$A_0/m_0 = 3$	$\tan\beta = 5$
$\lambda = 1$	$\lambda' = 1$		
GUT-scale parameters (masses in units of 10^{16} GeV)			
$M_{\rm GUT} = 0.685$	$M_{H_C} = 1.257$	$M_\Sigma = 0.628$	$M_X = 0.862$
$V = 0.251$	$g_5 = 0.686$	$c = -0.481$	
MSSM parameters (masses in units of TeV)			
$m_\chi = 4.78$	$m_{\tilde{t}_1} = 4.84$	$m_{\tilde{g}} = 19.15$	$m_{\chi_2} = 4.84$
$m_A = 24.21$	$\mu = 18.87$	$m_{\tilde{\ell}_L} = 15.35$	$m_{\tilde{\ell}_R} = 14.56$
$m_{\tilde{\tau}_1} = 14.44$	$m_{\tilde{q}_L} = 20.9$	$m_{\tilde{d}_R} = 20.3$	$m_{\tilde{t}_2} = 15.78$
$A_t = 32.5$	$A_b = 65.6$	$B = -11.43$	
Observables			
$\Omega_\chi h^2 = 0.099$	$m_h = 124.3$ GeV		

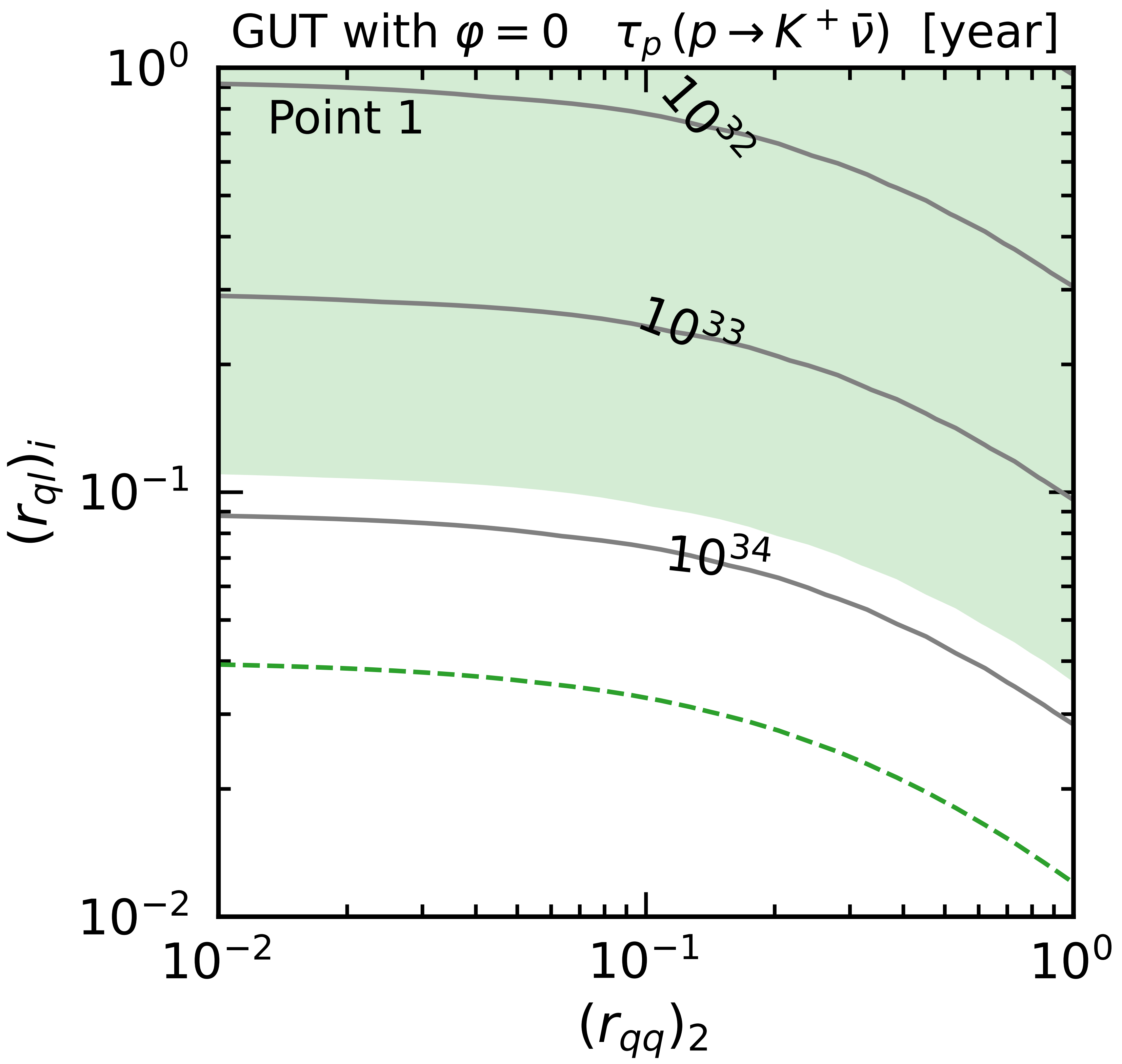
CMSSM

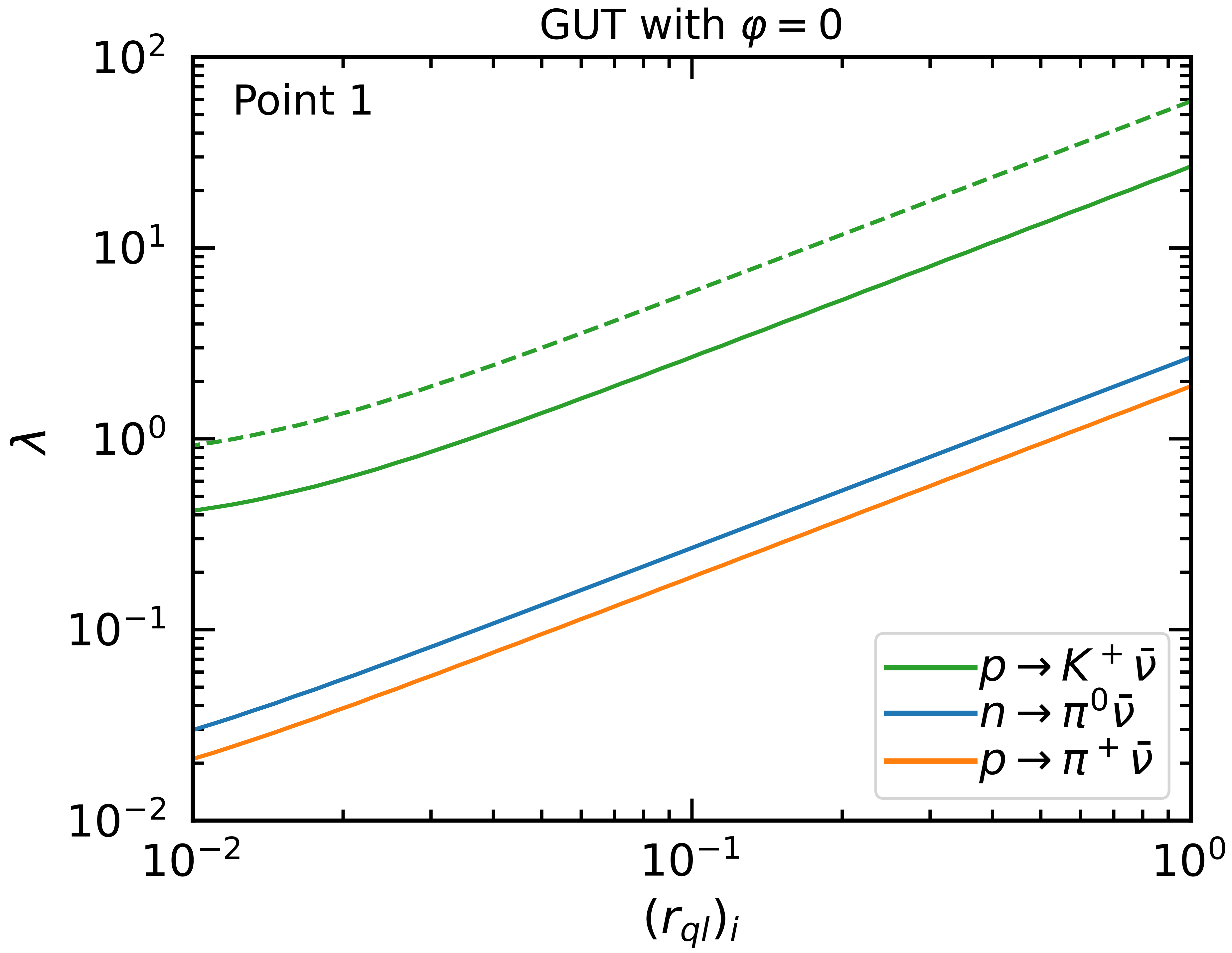
- The phases φ_i —> the cancellation among higgsino exchange and wino exchange processes

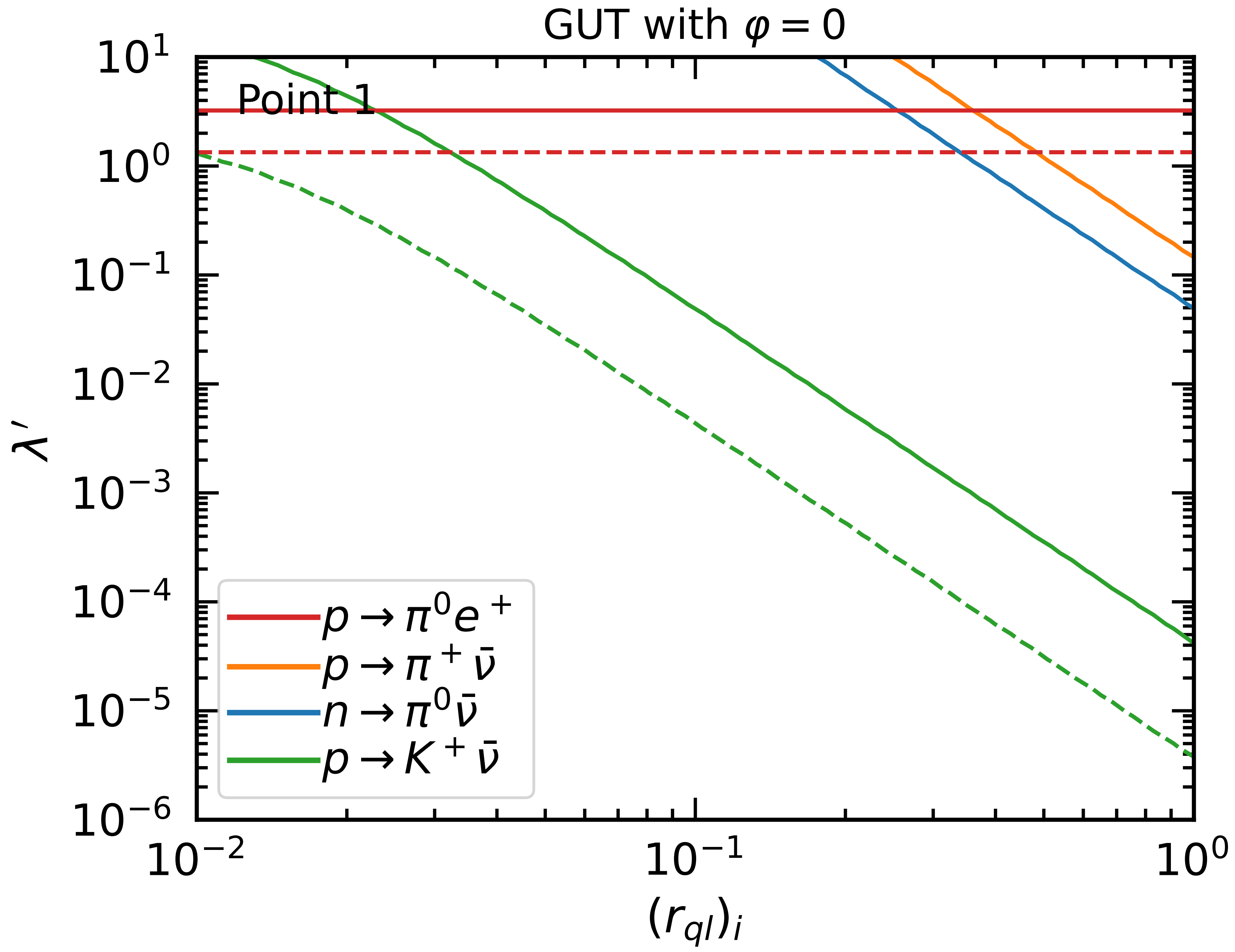





GUT with $\varphi = 0$ $\tau_p\,(p \to K^+\bar{\nu})$ [year]
Point 1
10^{33}
10^{32}
$(r_{ql})_3$
$(r_{ql})_2$
10^{-2}
10^{-1}
10^{0}


GUT with $\varphi = 0$ $\tau_p\,(p \to K^+\bar{\nu})$ [year]
Point 1
10^{32}
10^{33}
10^{34}
$(r_{ql})_i$
$(r_{qq})_2$
10^{-2}
10^{-1}
10^{0}


GUT with $\varphi = 0$
Point 1
λ
$(r_{ql})_i$
$p \to K^+ \bar{\nu}$
$n \to \pi^0 \bar{\nu}$
$p \to \pi^+ \bar{\nu}$


GUT with $\varphi = 0$
Point 1
λ'
$(r_{ql})_i$
$p \to \pi^0 e^+$
$p \to \pi^+ \bar{\nu}$
$n \to \pi^0 \bar{\nu}$
$p \to K^+ \bar{\nu}$