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A low scale Flavon model
with
a Z_N flavor symmetry

Junichiro Kawamura (Ohio State University)

email: kawamura.14_AT_osu.edu

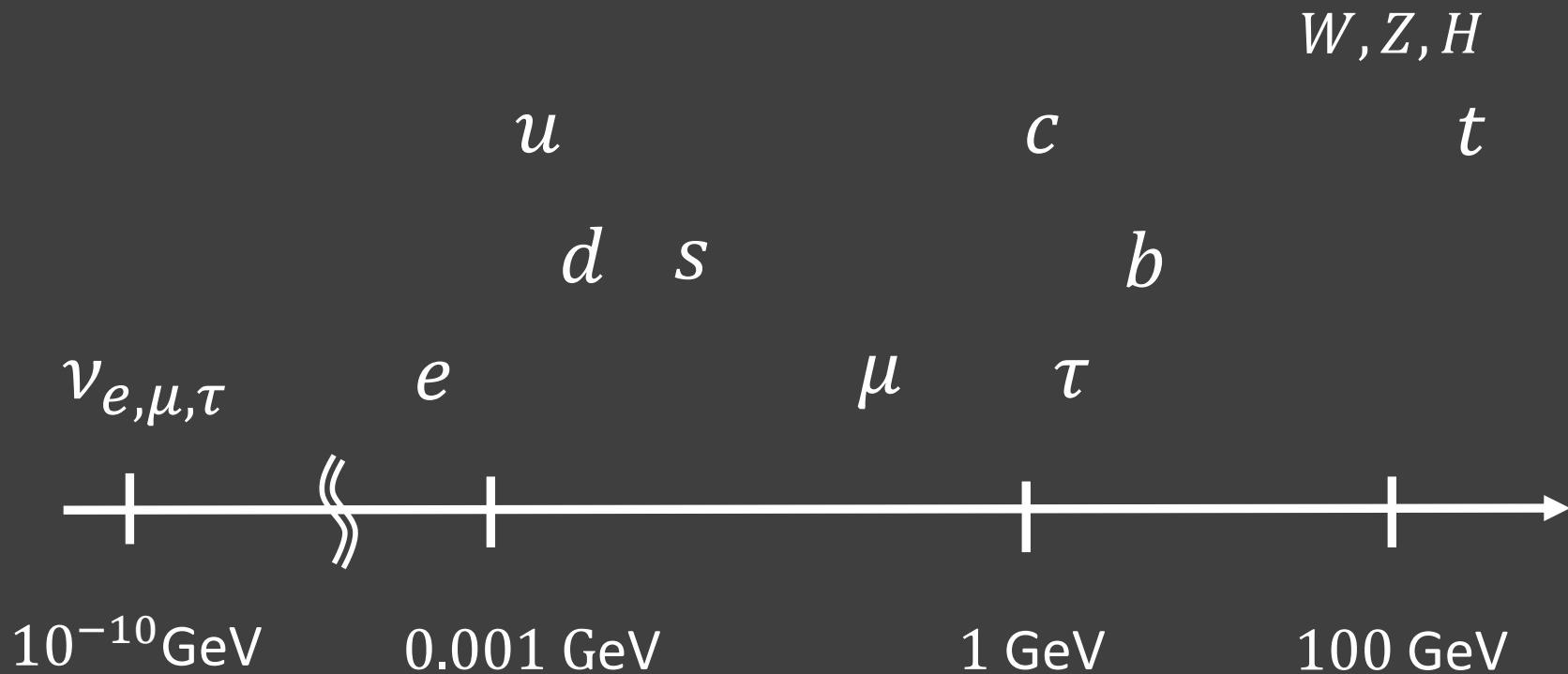
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in collaboration with

Tetsutaro Higaki (Keio Univ., Japan)

Fermion Mass Hierarchy

➤ Standard Model (SM)



Why so hierarchical ?

Froggatt-Nielsen Mechanism

'79 Froggatt, Nielsen

- Introduce “flavon” S

$$c_{ij}^f \left(\frac{S}{\Lambda} \right)^{n_{ij}^f} H \bar{f}_i f_j \quad \longrightarrow \quad Y_{ij}^f = c_{ij}^f \left(\frac{\langle S \rangle}{\Lambda} \right)^{n_{ij}^f} \equiv c_{ij} \epsilon^{n_{ij}^f}$$

$c_{ij}^f \sim \mathcal{O}(1)$, Λ : cutoff scale $\epsilon \ll 1$

- Flavor symmetry $U(1)_F$

- Flavon S is a gauge singlet, but charged under $U(1)_F$
- Power n_{ij}^f is determined by $U(1)_F$ charge: $n_{ij}^f \cdot n_S + n_i^f + n_j^f = 0$
- $U(1)_F$ can be replaced to abelian discrete symmetry Z_N^F

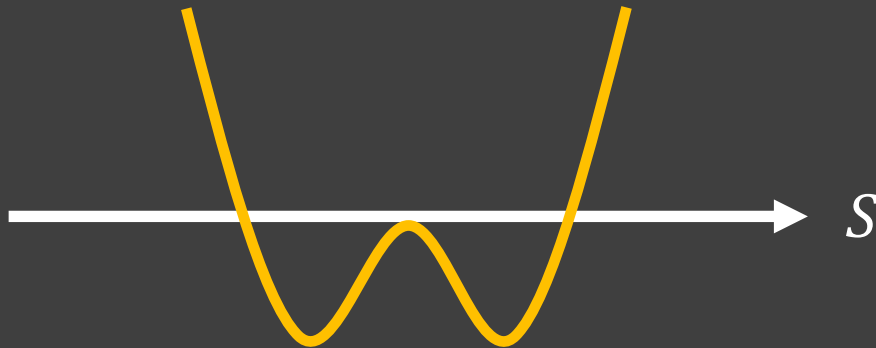
What's flavon ?

➤ Flavon Lagrangian

$$\mathcal{L}_{flavon} = \partial^\mu S^* \partial_\mu S - V(S, H) + c_{ij}^f \left(\frac{S}{\Lambda} \right)^{n_{ij}^f} H \bar{f}_i f_j + \dots$$

- We know Yukawa couplings to SM fermions
- We do **NOT** know a flavon potential

➤ Flavon potential ?



$$\begin{aligned} \langle S \rangle &\neq 0 \\ \langle S \rangle / \Lambda &\sim \epsilon \quad \text{for FN} \end{aligned}$$

Flavon Hierarchy problem

➤ Scalar potential

$$V = -m_H^2 |H|^2 + \frac{\lambda_H}{2} |H|^4 - m_S^2 |S|^2 + \frac{\lambda_S}{2} |S|^4 + \lambda_{SH} |S|^2 |H|^2 + \dots$$

λ_{SH} can **NOT** be forbidden by symmetry

$$V(H) = (-m_H^2 + \lambda_{SH} \langle S \rangle^2) |H|^2 + \frac{\lambda_H}{2} |H|^4$$

$$\rightarrow \lambda_H \langle H \rangle^2 \sim m_H^2 - \lambda_{SH} \langle S \rangle^2 \sim \mathcal{O}(100^2 \text{ GeV}^2)$$

Fine-tuning problem arises if $\langle S \rangle \gg 100 \text{ GeV}$

Low-scale flavon model

➤ Low scale flavon

- Flavon VEV $\langle S \rangle \sim 100 \text{ GeV}$
- Cut-off scale Λ is TeV-PeV scale for FN mechanism

➤ Supersymmetry (SUSY)

- Good solution to gauge hierarchy problem
- Good framework to control scalar potential
- Holomorphy allows smaller discrete symmetry

Low-scale flavon model

- Superpotential with Z_N symmetry

$$W = \frac{S^N}{\Lambda^{N-3}} + \frac{S^m}{\Lambda^{m-1}} H_u H_d + \sum_f \left(\frac{S}{\Lambda} \right)^{n_{ij}^f} H_f \bar{f}_i f_j$$

- Z_N symmetry allows to have **self-coupling of flavon**
- $\langle S \rangle$ also generates Higgsino \tilde{H} mass term * NMSSM-like solution
- Higgsino is a good candidate for dark matter (DM)

07' Cirelli, Strumia, Tamburini

$$m_{\tilde{H}} \sim \frac{\langle S \rangle^m}{\Lambda^{m-1}} \rightarrow$$

- Higgsino is EW doublet DM
- Mass is given by flavon VEV

Low-scale flavon model

➤ Minimal possibility: Z_4 symmetry

$$Z_N \text{ symmetry} \rightarrow \left(\frac{\langle S \rangle}{\Lambda} \right)^{N-1} \sim \frac{m_u}{m_t} \sim 7.5 \times 10^{-6}$$

- $N = 4$ may be the minimal possibility
- $\epsilon = \langle S \rangle / \Lambda \sim 0.02$ can explain the mass/mixing hierarchies

➤ Fermion Mass

$$(m_u, m_c, m_t) \sim (\epsilon^3, \epsilon, 1)$$

$$(m_d, m_s, m_b) \sim \epsilon^k (\epsilon^2, \epsilon, 1)$$

$$(m_e, m_\mu, m_\tau) \sim \epsilon^k (\epsilon^2, 1, 1)$$

➤ CKM mixing

$$V_{CKM} \sim \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

* Cabibbo angle ~ 0.2 treated as $\mathcal{O}(1)$

Z_4 charge assignment

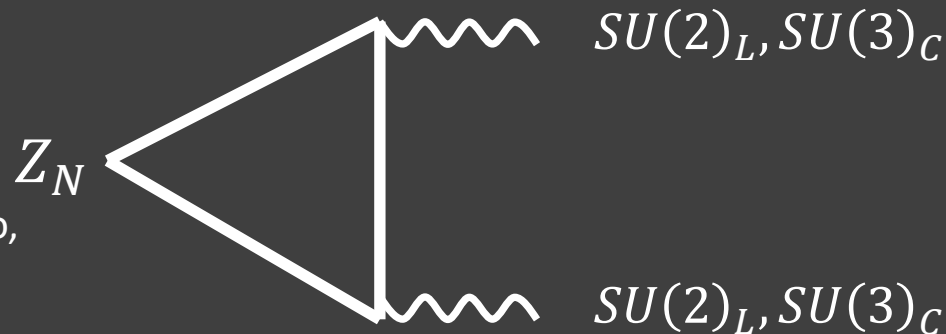
➤ Yukawa hierarchy

$$k = 0, 1 \text{ for } \tan \beta \sim 50, 1$$

$$Y_u \sim \begin{pmatrix} \epsilon^3 & \epsilon^3 & \epsilon^2 \\ \epsilon & \epsilon & 1 \\ \epsilon & \epsilon & 1 \end{pmatrix}, \quad Y_d \sim \epsilon^k \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon & \epsilon & 1 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

➤ Anomaly cancellation

- Z_N charges are mostly determined from the Yukawa hierarchy
- Mixed anomaly with $SU(3)_C \times SU(2)_L$ should vanish



08' Araki, Kobayashi, Kubo,
Ramos-Sanchez, Ratz,
Vaudrevange

Z_4 charge assignment

➤ Yukawa hierarchy and anomaly cancellation:

$$(1) \tan\beta = \langle H_u \rangle / \langle H_d \rangle \sim 50,$$

$$W = \frac{S^4}{\Lambda} + SH_u H_d + W_{\text{Yukawa}}$$

➔ Higgsino mass $m_{\tilde{H}} \sim \langle S \rangle$

$$(2) \tan\beta \sim 1,$$

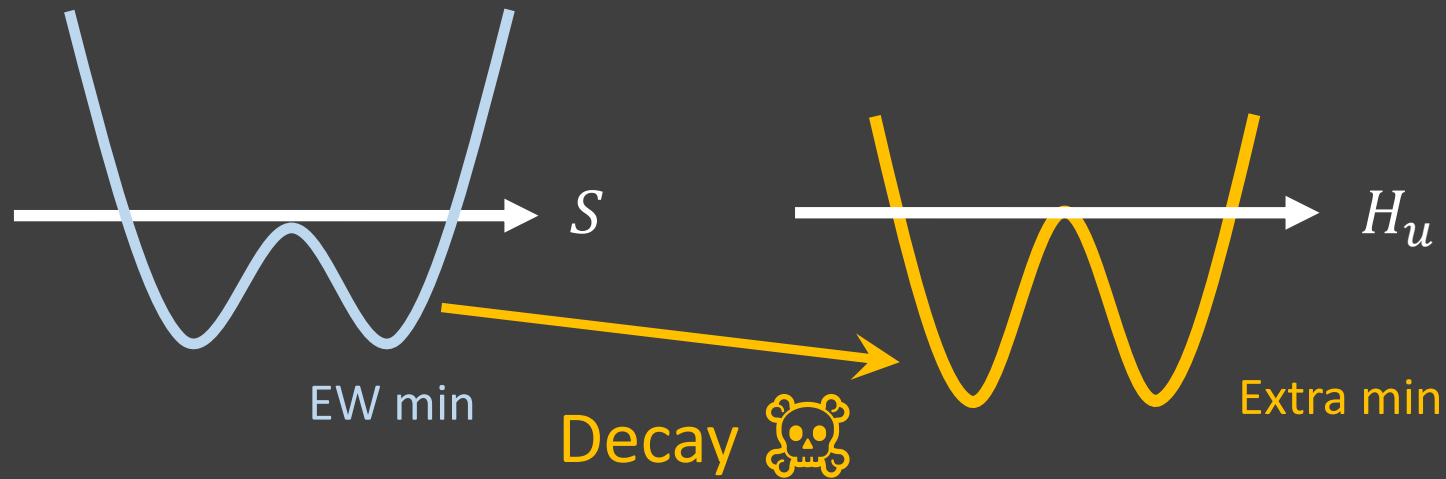
$$\epsilon = \frac{\langle S \rangle}{\Lambda} \sim 0.02$$

$$W = \frac{S^4}{\Lambda} + \frac{S^2}{\Lambda} H_u H_d + W_{\text{Yukawa}}$$

➔ Higgsino mass $m_{\tilde{H}} \sim \epsilon \langle S \rangle$

Higgs-flavon potential

- Higgs potential : $V = V_F + V_D + V_{soft}$



- Stabilize EW minimum
 - constraints on charges of Higgs fields
 - is achieved only in Case (2): Higgsino mass $\sim \epsilon \langle S \rangle$

Model Summary

➤ Superpotential with Z_4 flavor symmetry

$$W = \frac{S^4}{\Lambda} + \frac{S^2}{\Lambda} H_u H_d + \left(\frac{S}{\Lambda} \right)^{n_f^{ij}} H_f \bar{f}_i f_j + \frac{1}{2} M_{Maj}^{ij} N_i N_j$$

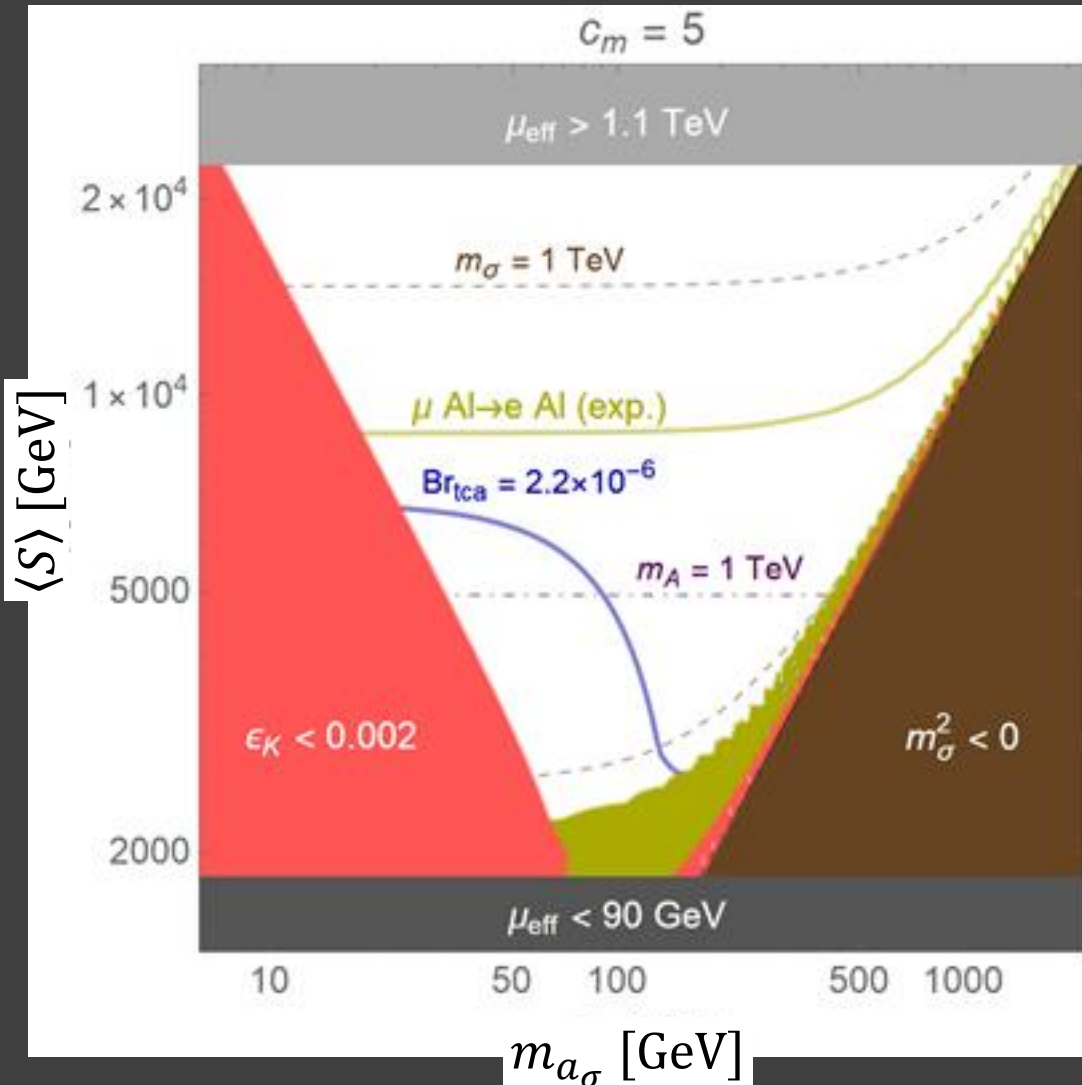
- Fermion mass/mixing is explained without anomaly
- Stable EW vacuum is realized only in the above superpotential
- Higgsino DM mass is given by $\epsilon \langle S \rangle$

➤ We set $n_N = 2$ for see-saw mechanism

$$m_\nu \sim \epsilon^6 \frac{\langle H_u \rangle^2}{M_{Maj}} \quad \longrightarrow \quad M_{Maj} \sim 1 \text{ PeV can explain neutrino mass} \\ \sim \Lambda ?$$

Phenomenology

09' Tsumura, Velasco-Sevilla
16' Bauer, Schell, Plehn



$$S = \langle S \rangle + \frac{1}{\sqrt{2}} (\sigma + i a_\sigma)$$

white region is allowed

$90 \text{ GeV} < \text{Higgsino} < 1.1 \text{ TeV}$

ϵ_K excludes light flavon region

top decay is detectable

$\mu \rightarrow e$ conversion is promising

DeeMe, COMET, Mu2e

Summary

$\langle S \rangle + Z_N + \text{SUSY @ TeV-PeV}$



Fermion Mass

Fermion Mixing

Neutrino Mass

EW minimum

Flavon VEV $\langle S \rangle$

Higgsino DM

Flavon Hierarchy

Gauge Hierarchy

Little Hierarchy

Thank you

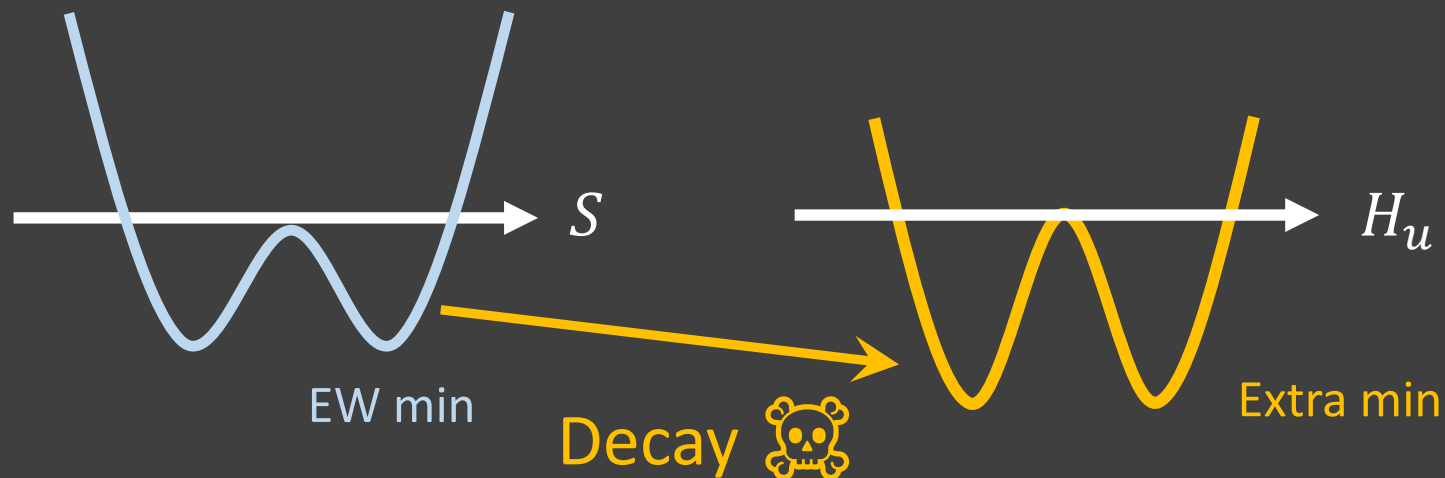
Higgs potential

➤ Higgs potential : $V = V_F + V_D + V_{soft}$

$$V_F = \left| \frac{S^3}{\Lambda} - \frac{S^m}{\Lambda^{m-1}} H_u H_d \right|^2 + (|H_u|^2 + |H_d|^2) \left| \frac{S^m}{\Lambda^{m-1}} \right|^2$$

$$V_D = \frac{g^2}{2} |H_u|^4 + \frac{g^2}{2} |H_d|^4 - g^2 |H_u|^2 |H_d|^2$$

$$V_{soft} = m_S^2 |S|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + \left(A_S \frac{S^4}{\Lambda} - A_H \frac{S^m}{\Lambda^{m-1}} H_u H_d + h.c. \right)$$



Stability of EW minimum

- Depth of EW minimum is almost the minimum of

$$V_S = m_S^2 |S|^2 + \left| \frac{S^{N-1}}{\Lambda^{N-3}} \right|^2 + A_S \frac{S^N}{\Lambda^N} + h.c.$$

$$\rightarrow V_{EW} \sim \langle V_S \rangle \sim -\epsilon^2 \langle S \rangle^4 \quad \epsilon = \frac{\langle S \rangle}{\Lambda}$$

- Another minimum may appear in H_u direction

$$V_{H_u} = -m_{\tilde{H}}^2 |H_u|^2 + \frac{g^2}{2} |H_u|^4 \quad -m_{H_u}^2 \sim -m_{\tilde{H}}^2: \text{Higgsino mass}$$

EW condition

$$\rightarrow \langle V_{H_u} \rangle \sim -m_{\tilde{H}}^4 / g^2$$

In case (1): $m_{\tilde{H}} \sim \langle S \rangle \rightarrow \langle V_{H_u} \rangle \sim -\langle S \rangle^4 \ll -\epsilon^2 \langle S \rangle^4 \sim V_{EW}$

Unstable

Stability of EW minimum

- Depth of EW minimum is almost the minimum of

$$V_S = m_S^2 |S|^2 + \left| \frac{S^{N-1}}{\Lambda^{N-3}} \right|^2 + A_S \frac{S^N}{\Lambda^N} + h.c.$$

$$\rightarrow V_{EW} \sim \langle V_S \rangle \sim -\epsilon^2 \langle S \rangle^4 \quad \epsilon = \frac{\langle S \rangle}{\Lambda}$$

- Another minimum may appear in H_u direction

$$V_{H_u} = -m_{\tilde{H}}^2 |H_u|^2 + \frac{g^2}{2} |H_u|^4 \quad -m_{H_u}^2 \sim -m_{\tilde{H}}^2: \text{Higgsino mass}$$

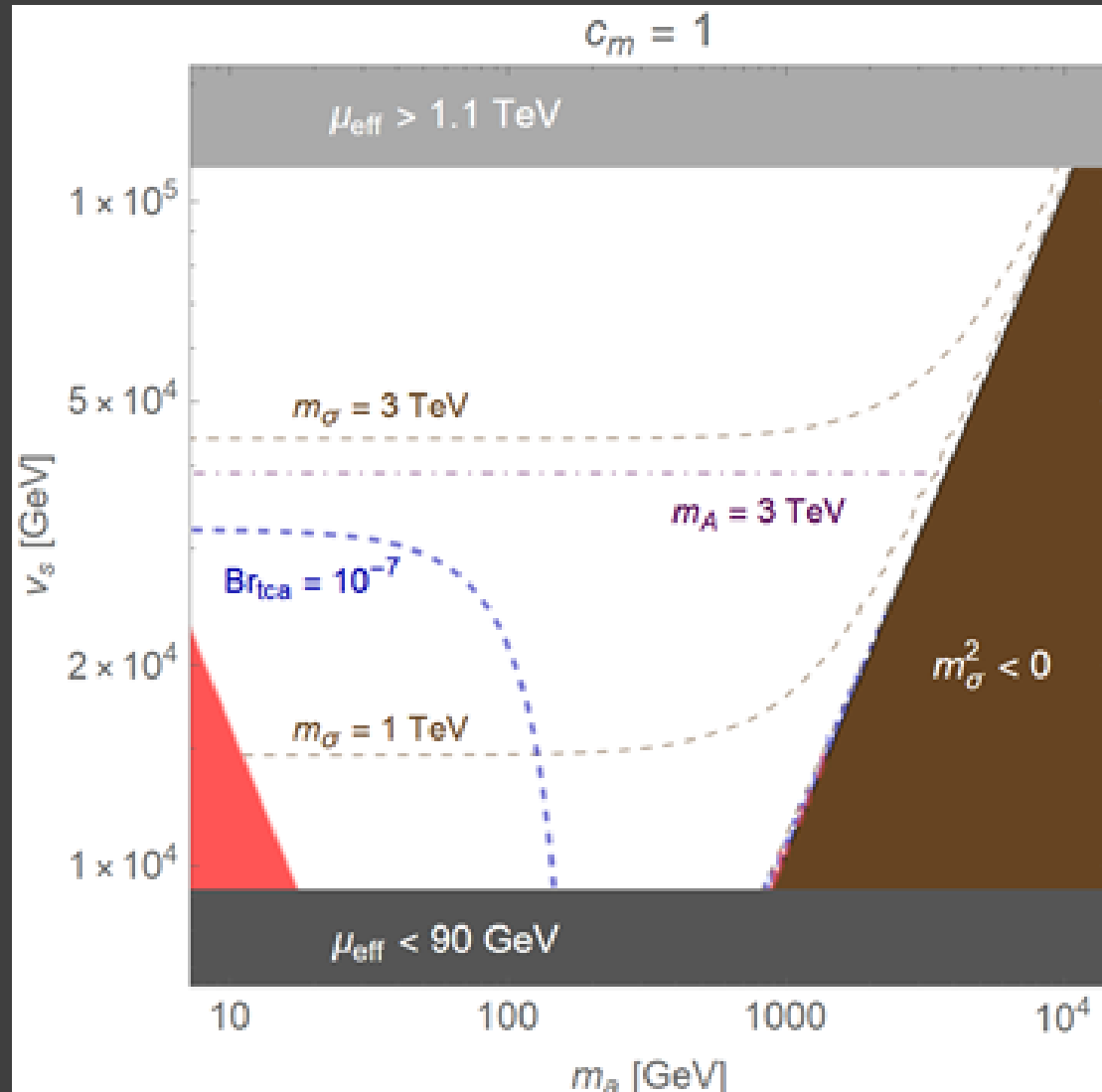
EW condition

$$\rightarrow \langle V_{H_u} \rangle \sim -m_{\tilde{H}}^4 / g^2$$

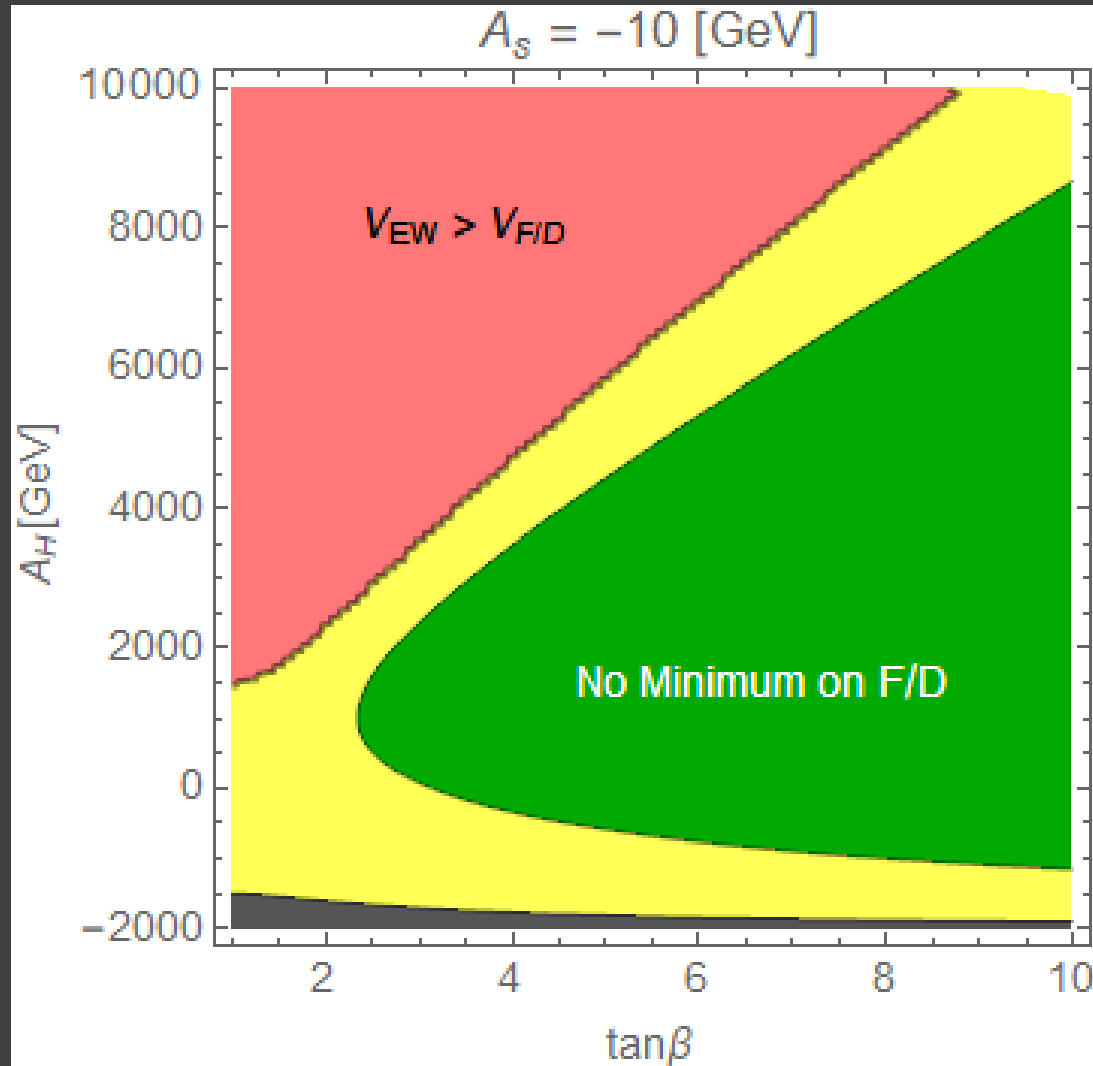
In case (2): $m_{\tilde{H}} \sim \epsilon \langle S \rangle \rightarrow \langle V_{H_u} \rangle \sim -\epsilon^4 \langle S \rangle^4 \gg -\epsilon^2 \langle S \rangle^4 \sim V_{EW}$

Stable

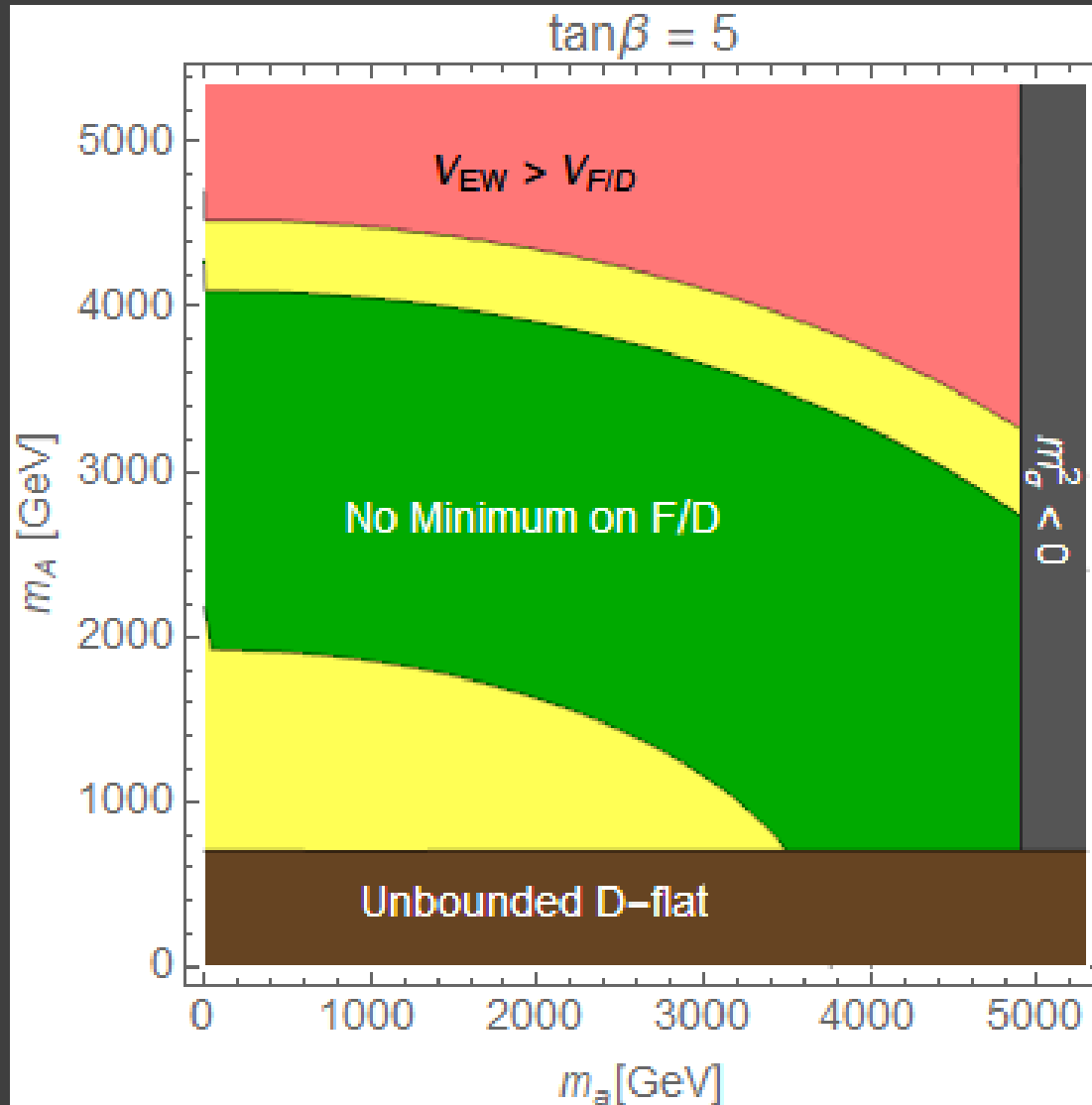
Pessimistic case



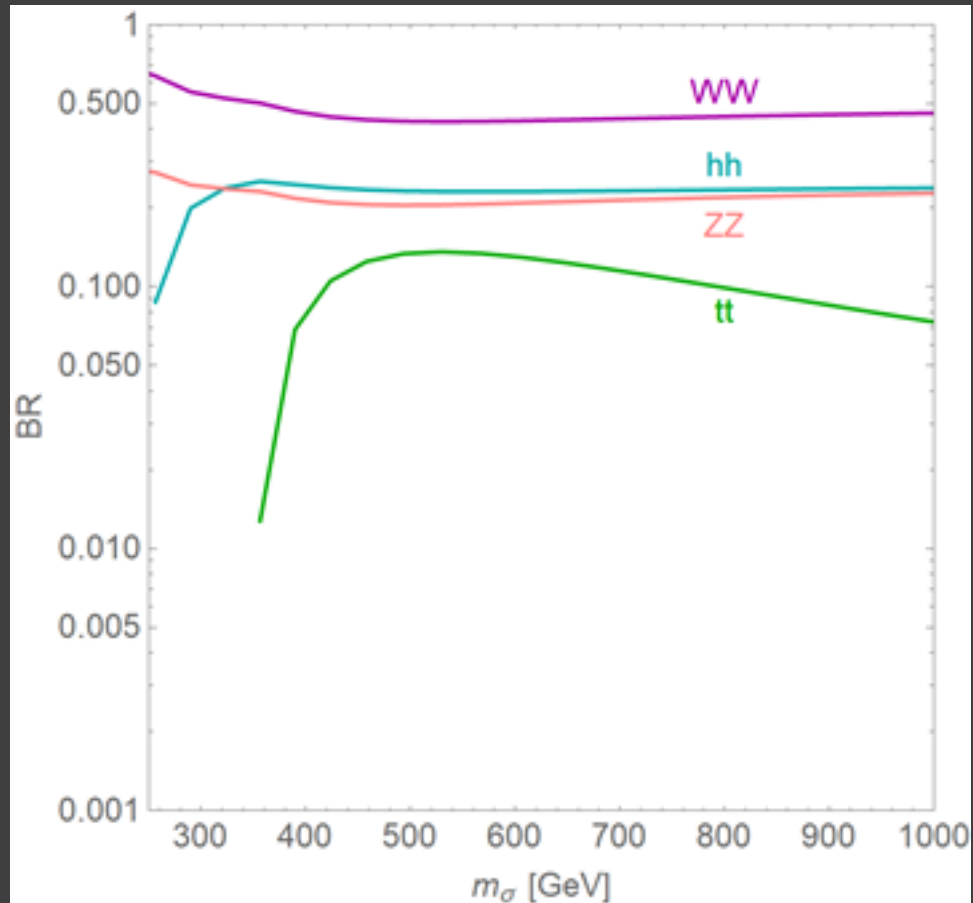
F/D flat direction



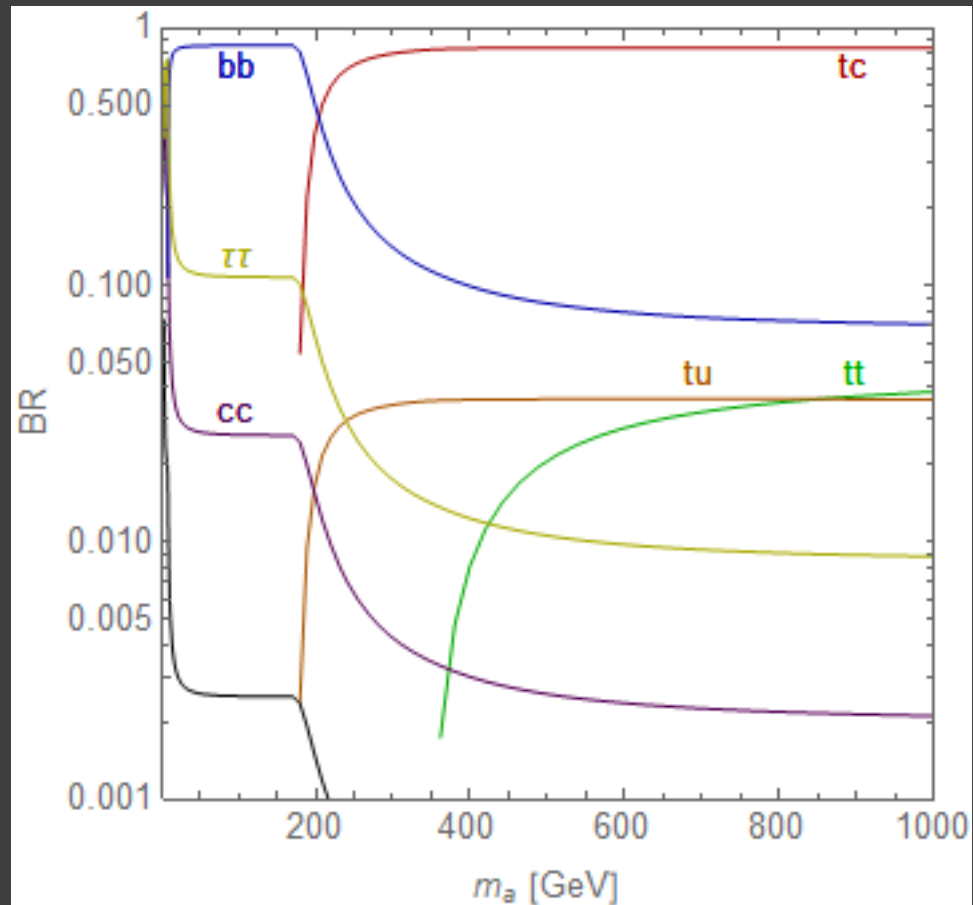
F/D flat direction



CP even Higgs decay



CP odd Higgs decay



Froggatt-Nielsen Mechanism

➤ Example of Z_4^F : all fermions

$$Y_u \sim \begin{pmatrix} \epsilon^3 & \epsilon^3 & \epsilon^2 \\ \epsilon & \epsilon & 1 \\ \epsilon & \epsilon & 1 \end{pmatrix}, \quad Y_d \sim \epsilon^k \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon & \epsilon & 1 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

$$Y_e \sim \epsilon^k \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \quad Y_\nu \sim \epsilon^p \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$(m_u, m_c, m_t) \sim (\epsilon^3, \epsilon, 1)$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

➔ $(m_d, m_s, m_b) \sim \epsilon^k (\epsilon^2, \epsilon, 1)$

$$(m_e, m_\mu, m_\tau) \sim \epsilon^k (\epsilon^2, 1, 1)$$

$$V_{PMNS} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Froggatt-Nielsen Mechanism

➤ Example of Z_4^F : strange/bottom quark

Charge: $n_S = 1$, $n_H = 0$, $(n_{Q_2}, n_{Q_3}) = (3, 0)$, $(n_{D_2}, n_{D_3}) = (3, 3)$

$$\begin{array}{cccc}
 \frac{S}{\Lambda} H \bar{Q}_3 D_3 & + \frac{S^2}{\Lambda^2} H \bar{Q}_3 D_2 & + \frac{S^2}{\Lambda^2} H \bar{Q}_2 D_3 & + \frac{S^3}{\Lambda} H \bar{Q}_2 D_2 \\
 +1 & +3 & +2 & +6 & +1 & +3 & +2 & +6 \\
 = +4 & & = +8 & & = +4 & & = +8 &
 \end{array}$$

$$\sim H \begin{pmatrix} \bar{Q}_2 & \bar{Q}_3 \end{pmatrix} \begin{pmatrix} \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon \end{pmatrix} \begin{pmatrix} D_2 \\ D_3 \end{pmatrix} \quad \epsilon \sim \frac{\langle S \rangle}{\Lambda} \sim 0.02$$

$$\begin{array}{l}
 \rightarrow m_b \sim \epsilon^1 \langle H \rangle \sim 4 \text{ GeV} \\
 m_s \sim \epsilon^2 \langle H \rangle \sim 80 \text{ MeV}
 \end{array}
 \quad U_{DL} \sim \begin{pmatrix} 1 & \epsilon \\ \epsilon & 1 \end{pmatrix}$$