PIKIMO8@Cinncinati

A low scale Flavon model with a Z_N flavor symmetry

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in collaboration with

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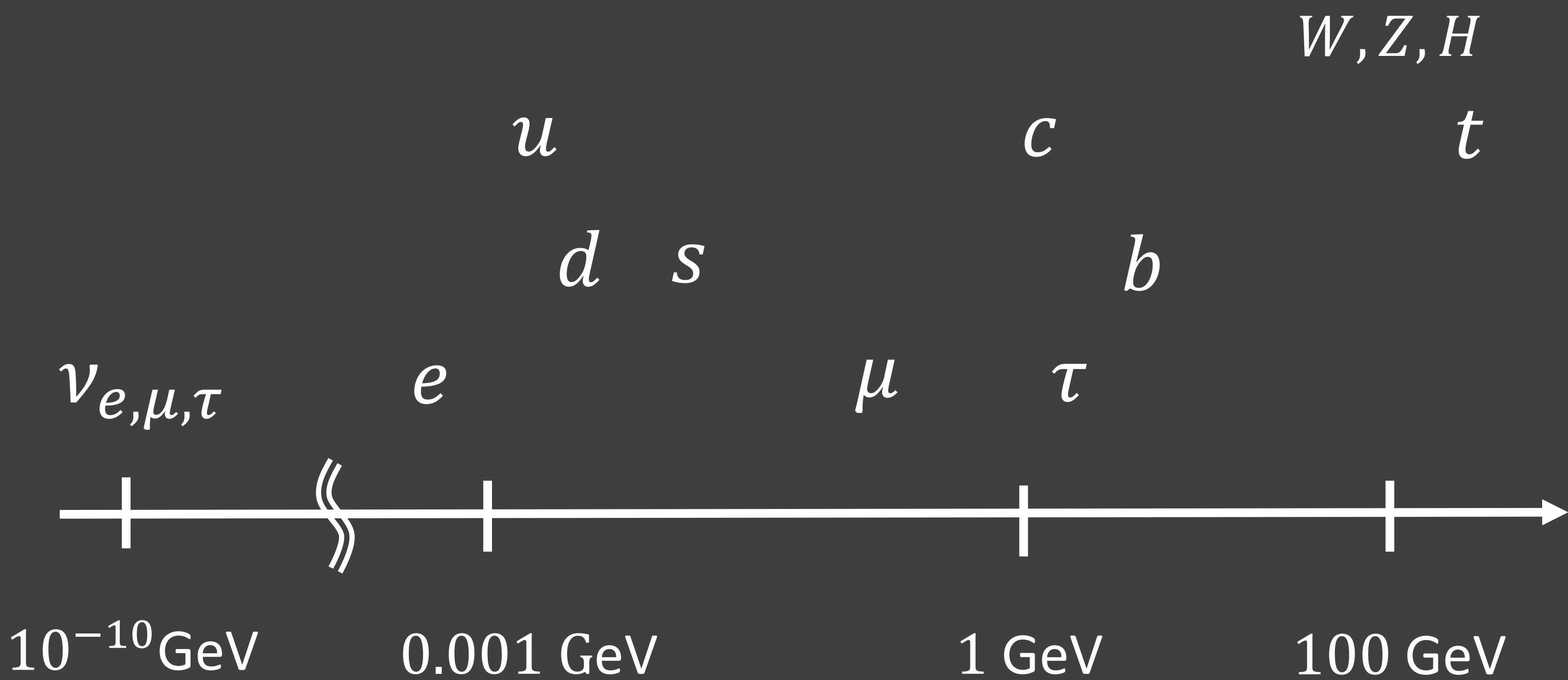
Outline

1. **Introduction**
2. A low scale flavon model
3. Phenomenology
4. Summary

Fermion Mass Hierarchy

- Standard Model (SM)



Why so hierarchical ?

Froggatt-Nielsen Mechanism

'79 Froggatt, Nielsen

- Introduce "flavon" S

$$c_{ij}^{f}\left(\frac{S}{\Lambda}\right)^{n_{ij}^{f}} H\,\overline{f}_{i}\,f_{j} \quad \rightarrow \quad Y_{ij}^{f}=c_{ij}^{f}\left(\frac{\langle S\rangle}{\Lambda}\right)^{n_{ij}^{f}} \equiv c_{ij}\,\epsilon^{n_{ij}^{f}}$$

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

$\epsilon \ll 1$

- Flavor symmetry $U(1)_{\mathrm{F}}$

  - 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

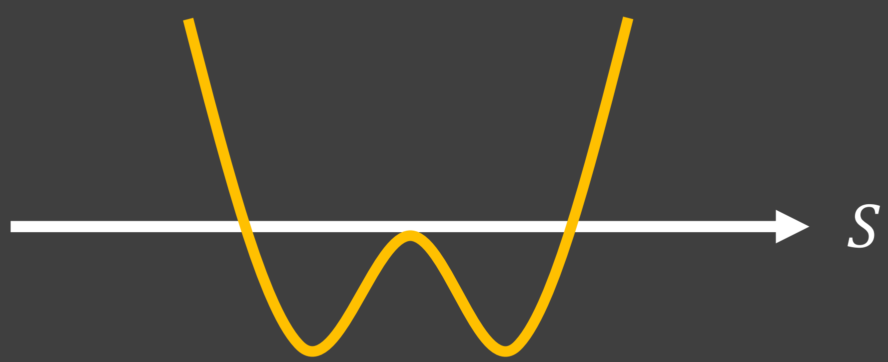
What's flavon ?

- Flavon Lagrangian

$$\mathcal{L}_{flavon} = \partial^\mu S^* \partial_\mu S - V(S,H) + c^f_{ij}\left(\frac{S}{\Lambda}\right)^{n^f_{ij}} H\,\overline{f}_i\, f_j + \cdots$$

  - We know the Yukawa coupling to SM fermions
  - We do NOT know the flavon potential

- Flavon potential ?



$\langle S \rangle \neq 0$

$\langle S \rangle / \Lambda \sim \epsilon$

for FN

Flavon Hierarchy problem

- Scalar potential

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

λ_{SH} can NOT be forbidden by symmetry

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

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

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

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Low-scale flavon model

- Low scale flavon
  - Flavon VEV $\langle S \rangle \sim 100$ 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

Ex) Higgs potential

$$V_D = \frac{g^2}{4}(|H_u|^2 - |H_d|^2)^2 \rightarrow$$

- $m_h \sim 125$ GeV
- Positive quartic coupling

Low-scale flavon model

- Superpotential with Z_N symmetry

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

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

07' Cirelli, Strumia, Tamburini

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

- 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

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

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

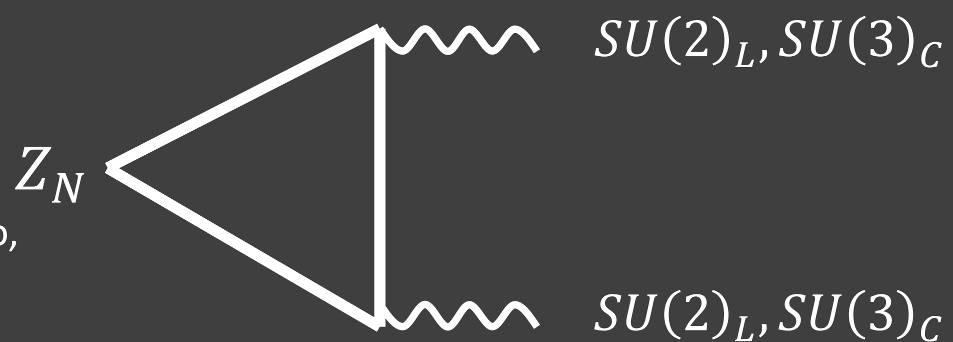
Z_4 charge assignment

- Yukawa hierarchy

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

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

- 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) When $\tan\beta = \langle H_u \rangle / \langle H_d \rangle \sim 50$,

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

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

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

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

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

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

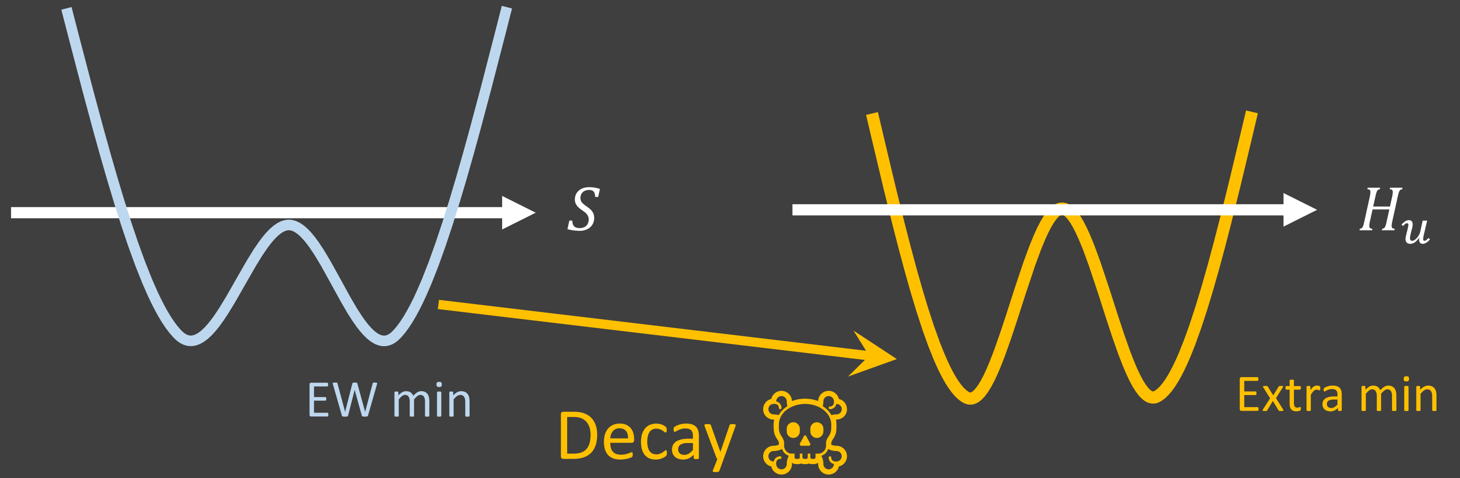
Higgs potential

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

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

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

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



Stability of EW minimum

- Depth of EW minimum is almost the minimum of

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

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

- Another minimum may appear in H_u direction

$$V_{H_u} = -m_{\tilde{H}}^2\,|H_u|^2 + \frac{g^2}{2}|H_u|^4 \qquad -m_{H_u}^2 \sim -m_{\tilde{H}}^2$$

: Higgsino mass

EW condition

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

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

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

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

- Another minimum may appear in H_u direction

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

EW condition

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

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

Model Summary

- Superpotential with Z_4 flavor symmetry

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

  - 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

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

$\sim \Lambda\,?$

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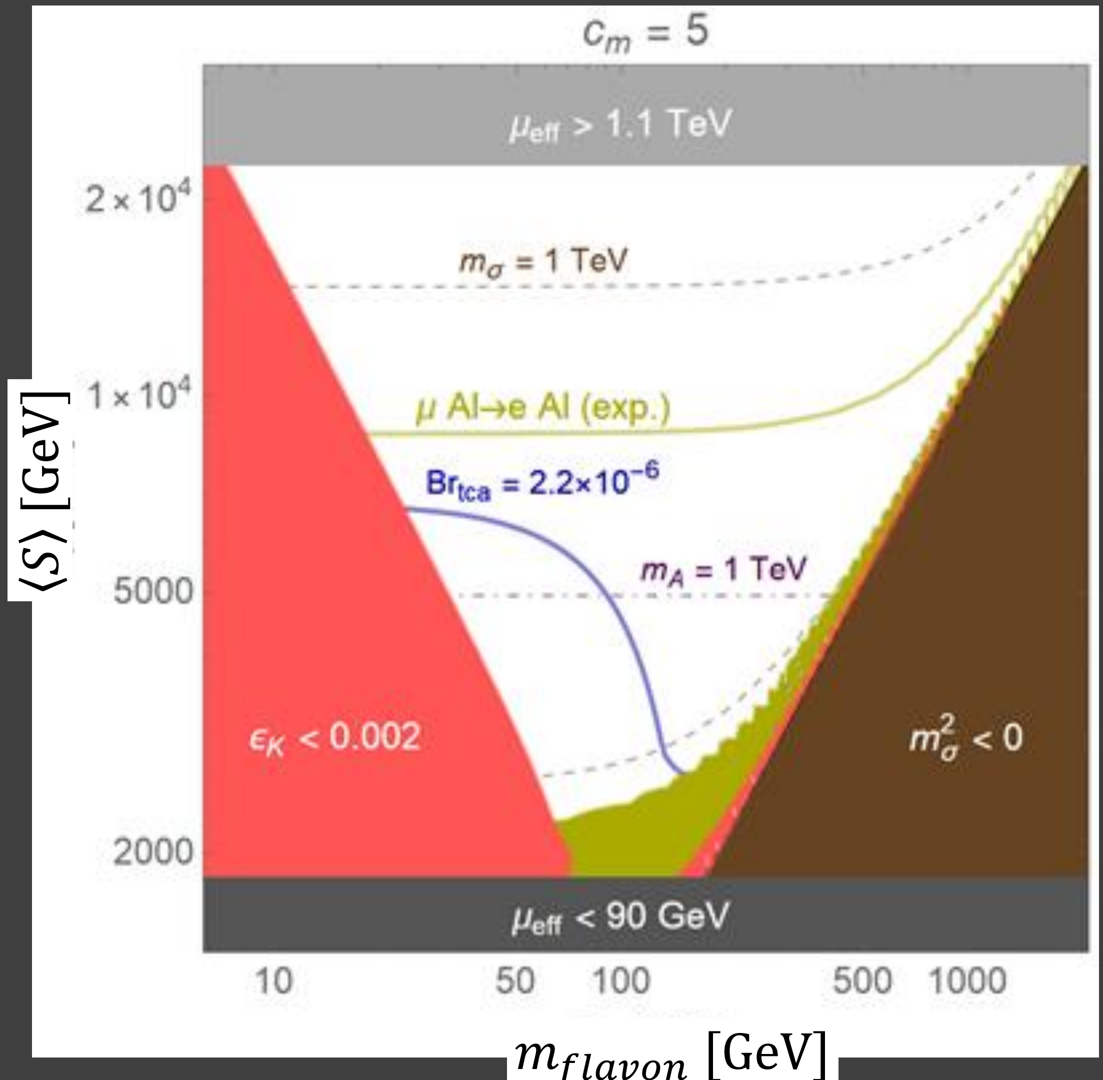
Phenomenology

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



white region is allowed

90 GeV < Higgsino < 1.1 TeV

ϵ_K excludes light flavon region

top decay is detectable

$\mu \to e$ conversion is promising

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

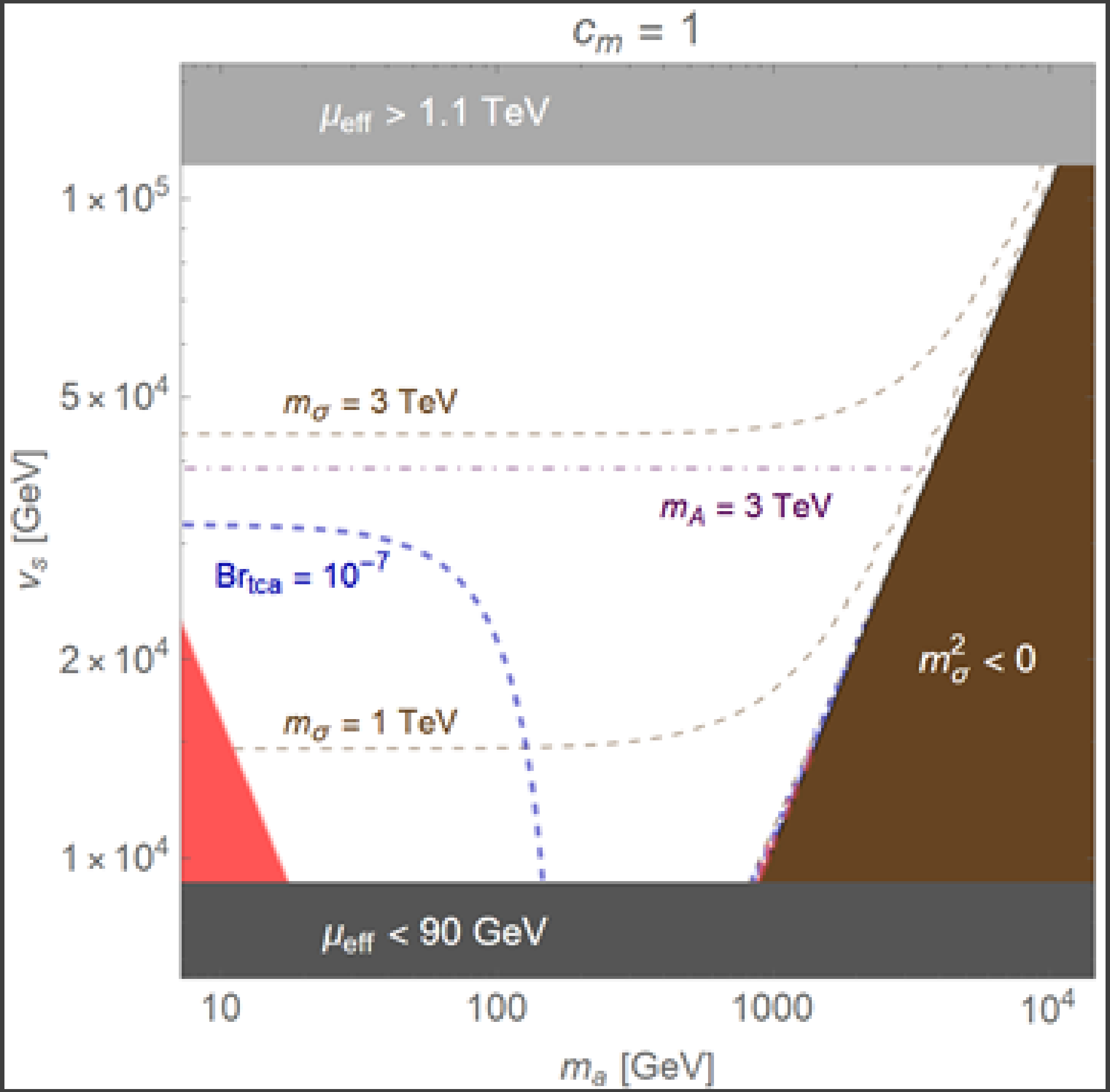
Flavon Hierarchy

Gauge Hierarchy

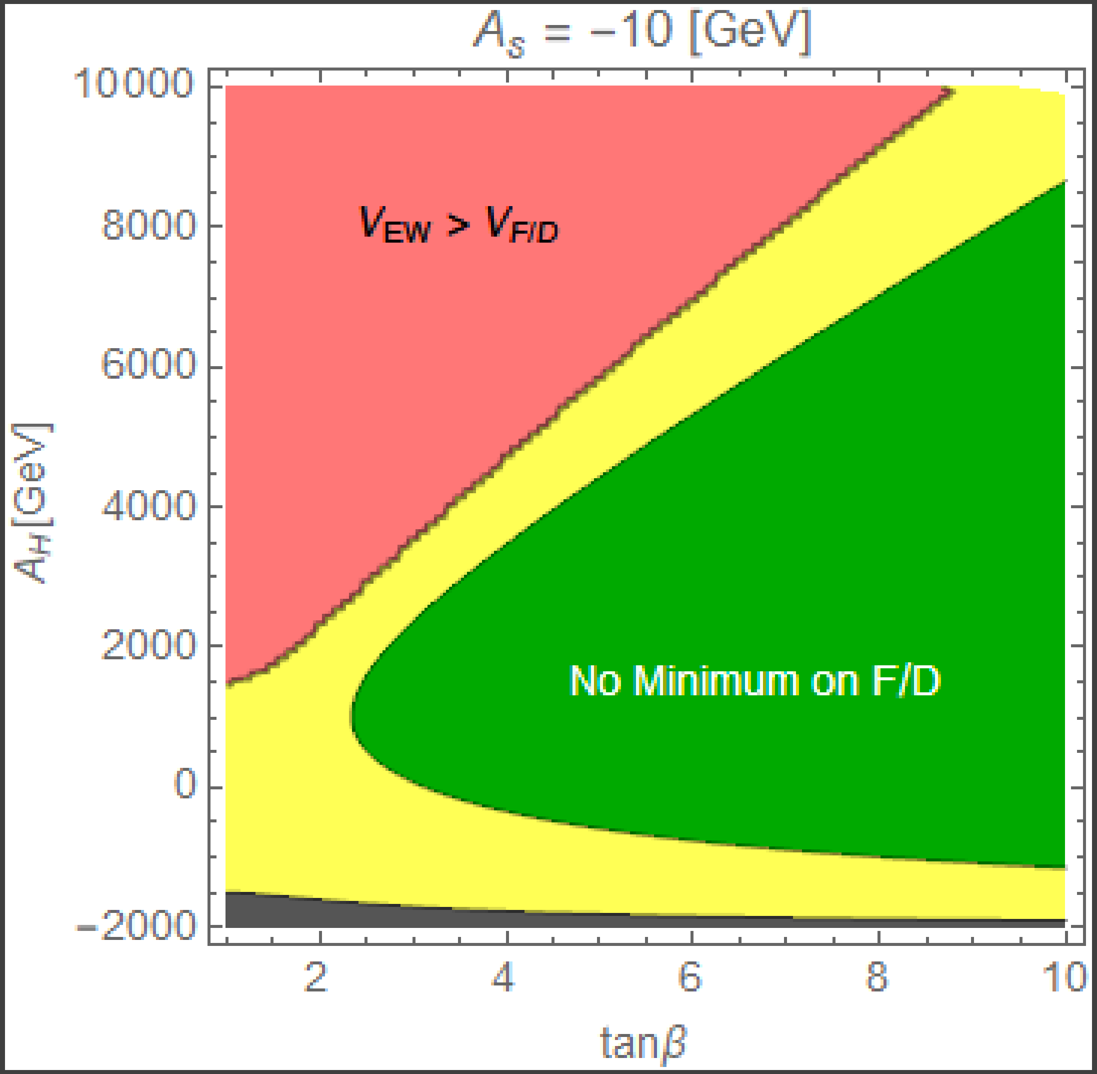
Little Hierarchy

Thank you

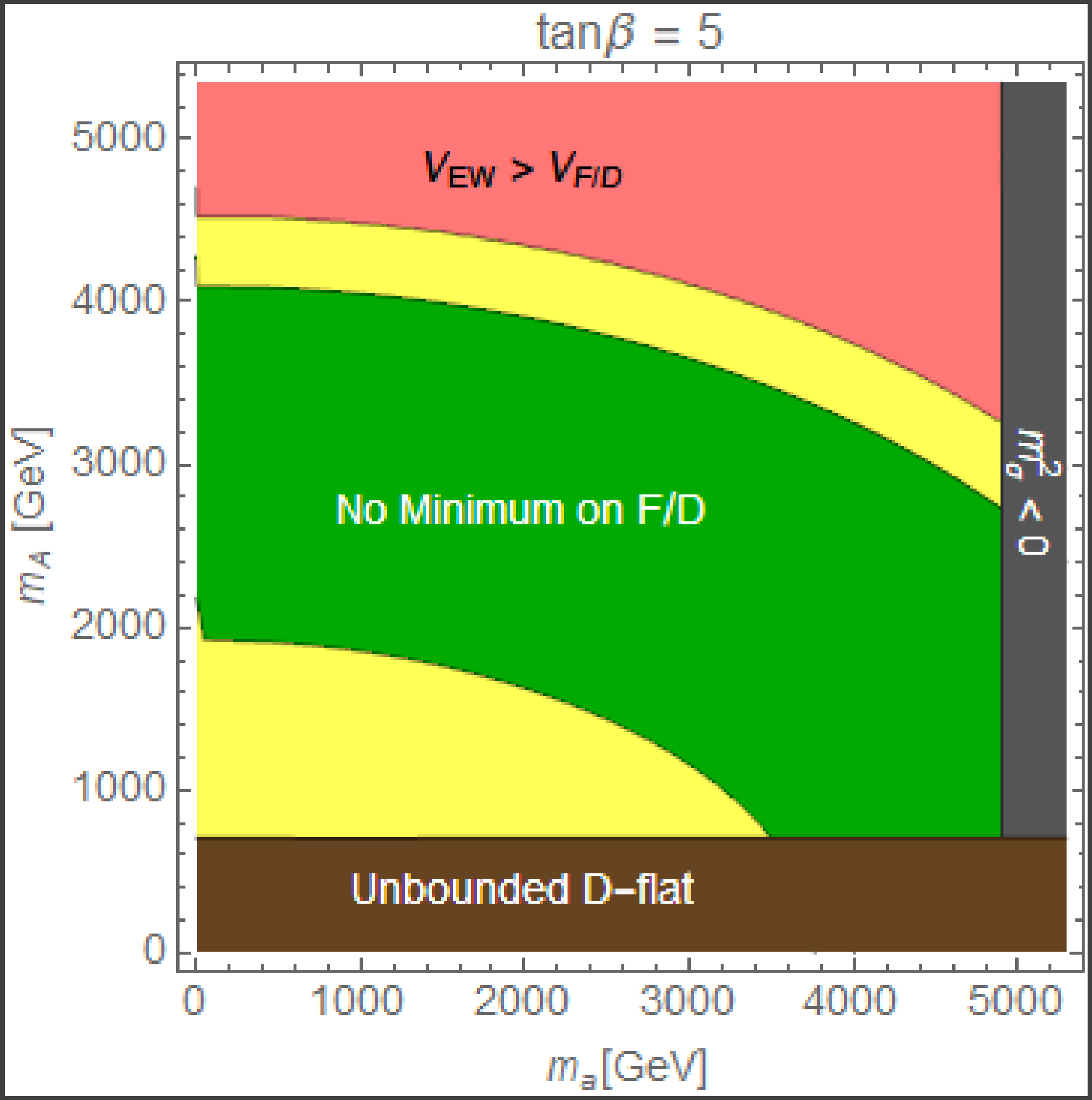
Pessimistic case



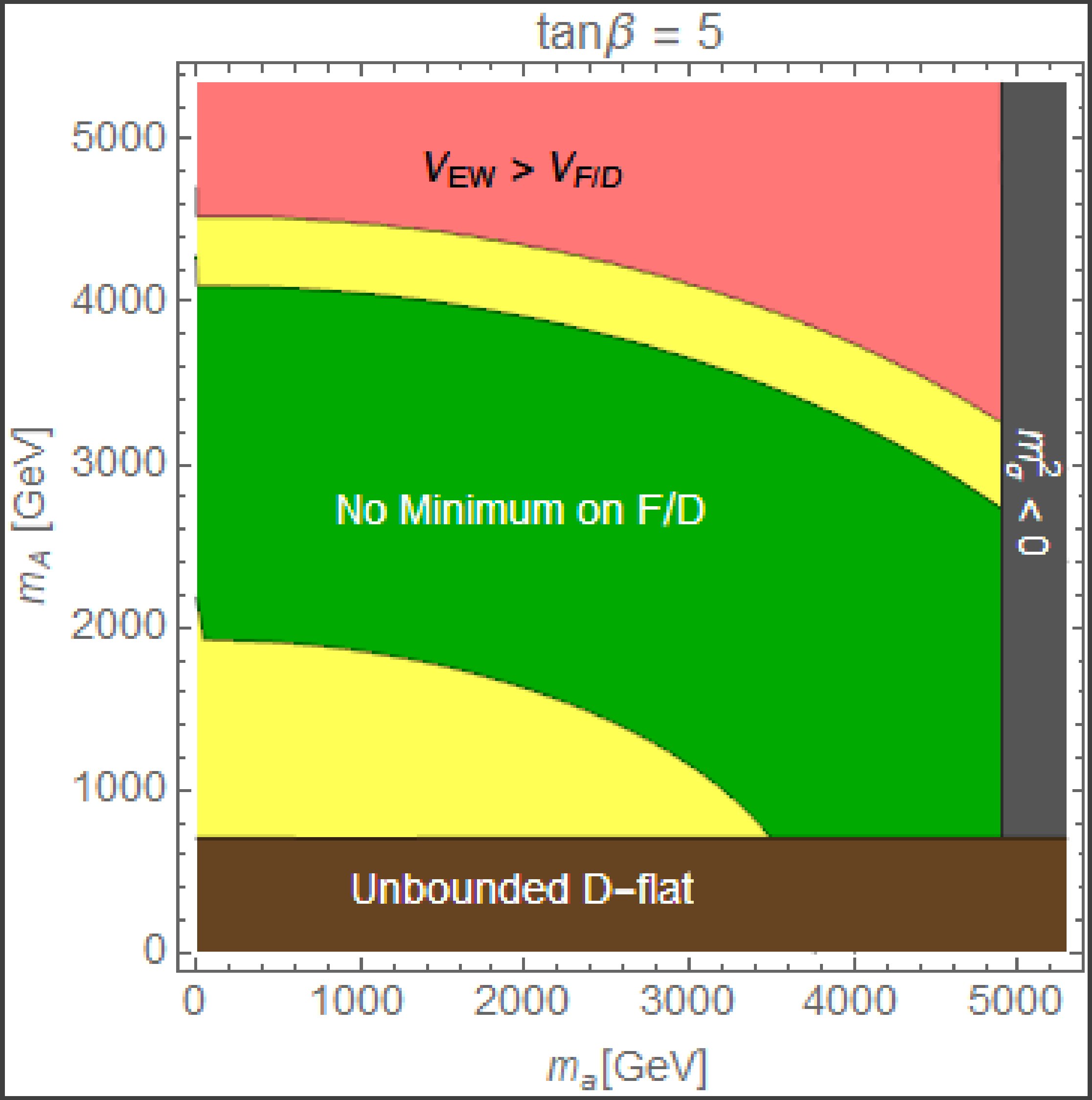
F/D flat direction



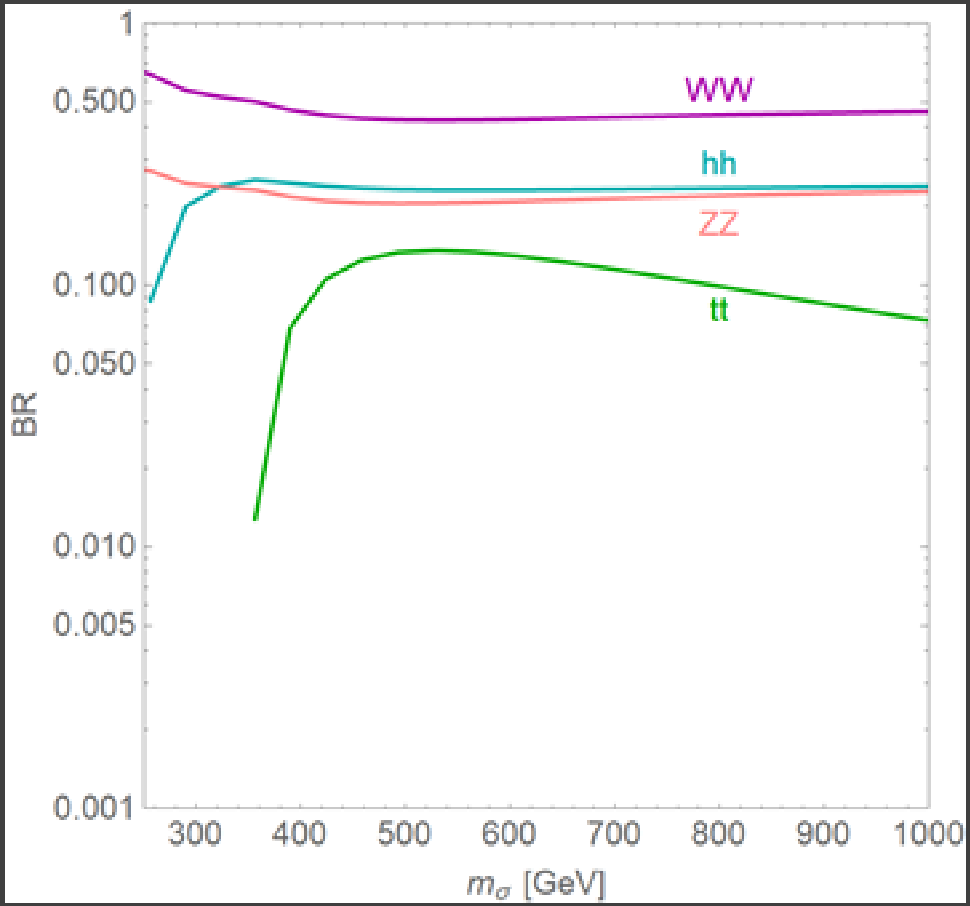
F/D flat direction



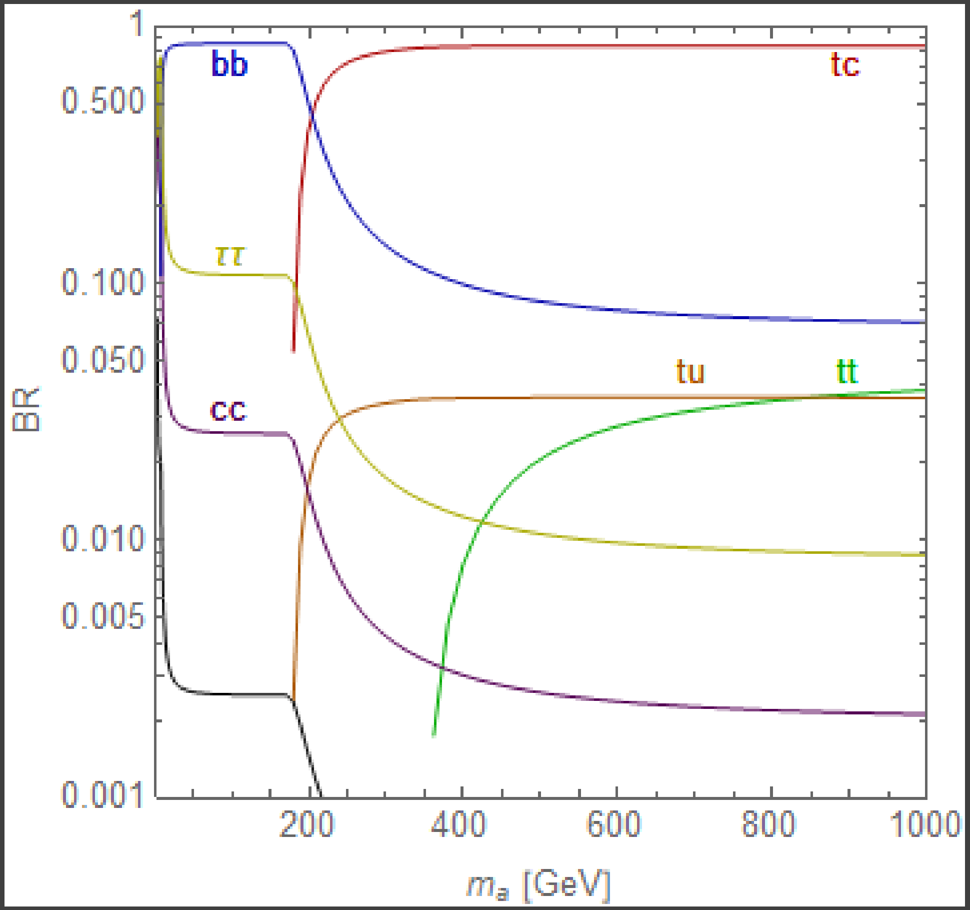
F/D flat direction



CP even Higgs decay



CP odd Higgs decay



Froggatt-Nielsen Mechanism

- Example of Z_4^F: all fermions

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

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

$$\rightarrow \quad \begin{aligned} (m_u, m_c, m_t) &\sim (\epsilon^3, \epsilon, 1) \\ (m_d, m_s, m_b) &\sim \epsilon^k \, (\epsilon^2, \epsilon, 1) \\ (m_e, m_\mu, m_\tau) &\sim \epsilon^k \, (\epsilon^2, 1, 1) \end{aligned}$$

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

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

Froggatt-Nielsen Mechanism

- Example of Z_4^F: strange/bottom quark

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

$$\frac{S}{\Lambda} H\, \overline{Q}_3\, D_3 + \frac{S^2}{\Lambda^2} H\, \overline{Q}_3\, D_2 + \frac{S^2}{\Lambda^2} H\, \overline{Q}_2\, D_3 + \frac{S^3}{\Lambda} H\, \overline{Q}_2\, D_2$$

$+1$ $+3$ $+2$ $+6$ $+1$ $+3$ $+2$ $+6$

$= +4$ $= +8$ $= +4$ $= +8$

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

$\rightarrow$

$m_b \sim \epsilon^1 \langle H \rangle \sim 4$ GeV

$m_s \sim \epsilon^2 \langle H \rangle \sim 80$ MeV

$$U_{D_L} \sim \begin{pmatrix} 1 & \epsilon \\ \epsilon & 1 \end{pmatrix}$$