Flavorful Composite Higgs Models

based on arXiv:2104.11719 and 2106.XXXXX

Yi Chung

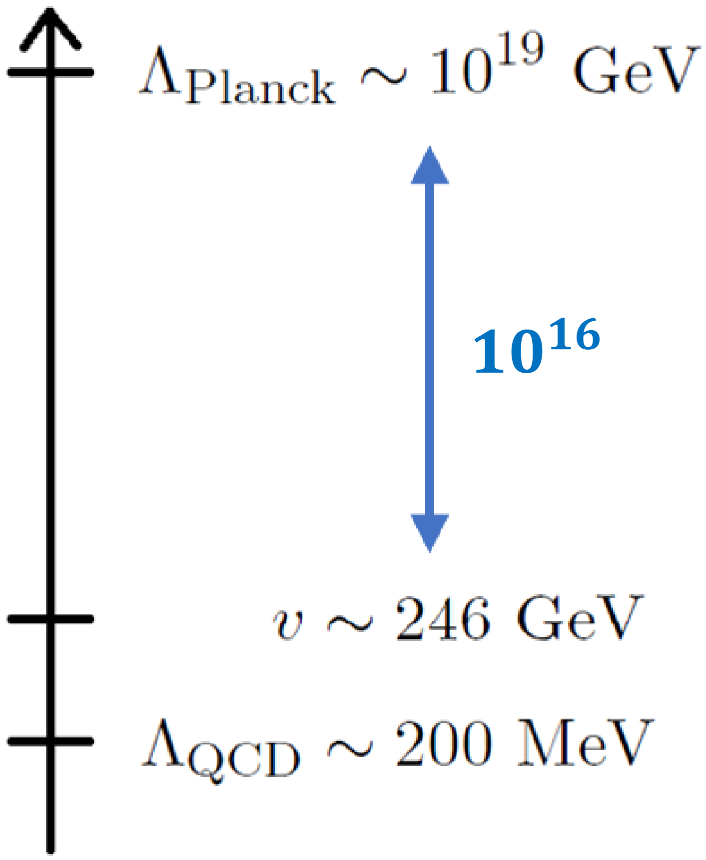
QMAP, Department of Physics, UC Davis

Phenomenology Symposium, May 25, 2021

University of Pittsburgh

Two Hierarchies in the Standard Model

- Scalar - hierarchy problem



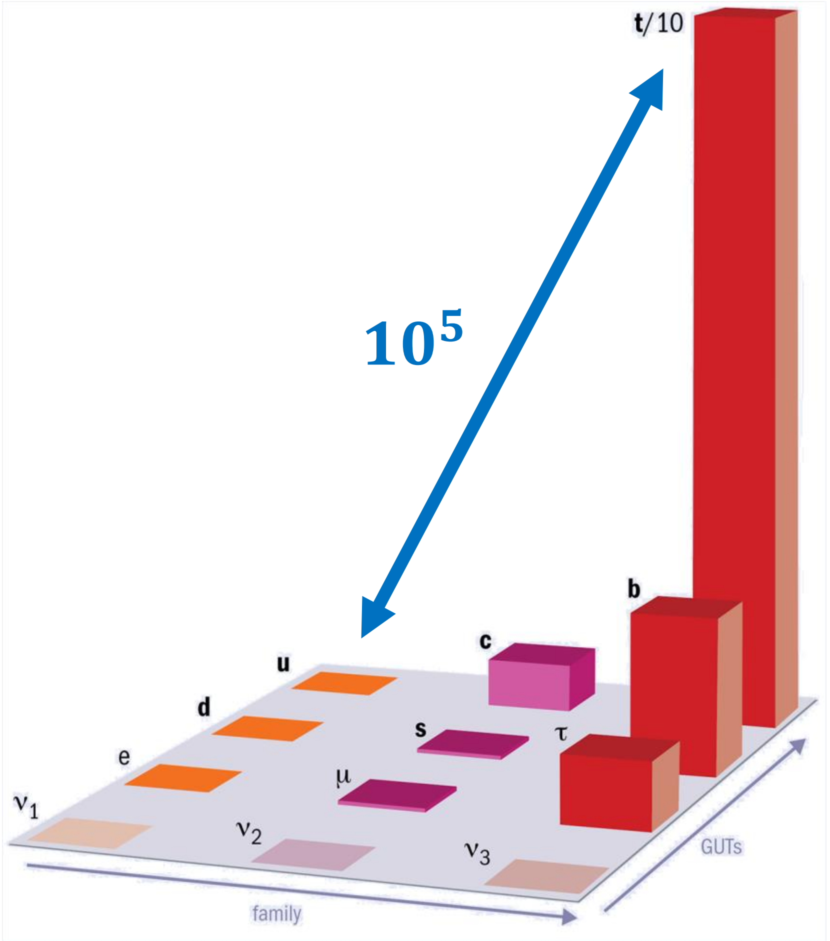
$\Lambda_{\text{Planck}} \sim 10^{19}$ GeV

10^{16}

$v \sim 246$ GeV

$\Lambda_{\text{QCD}} \sim 200$ MeV

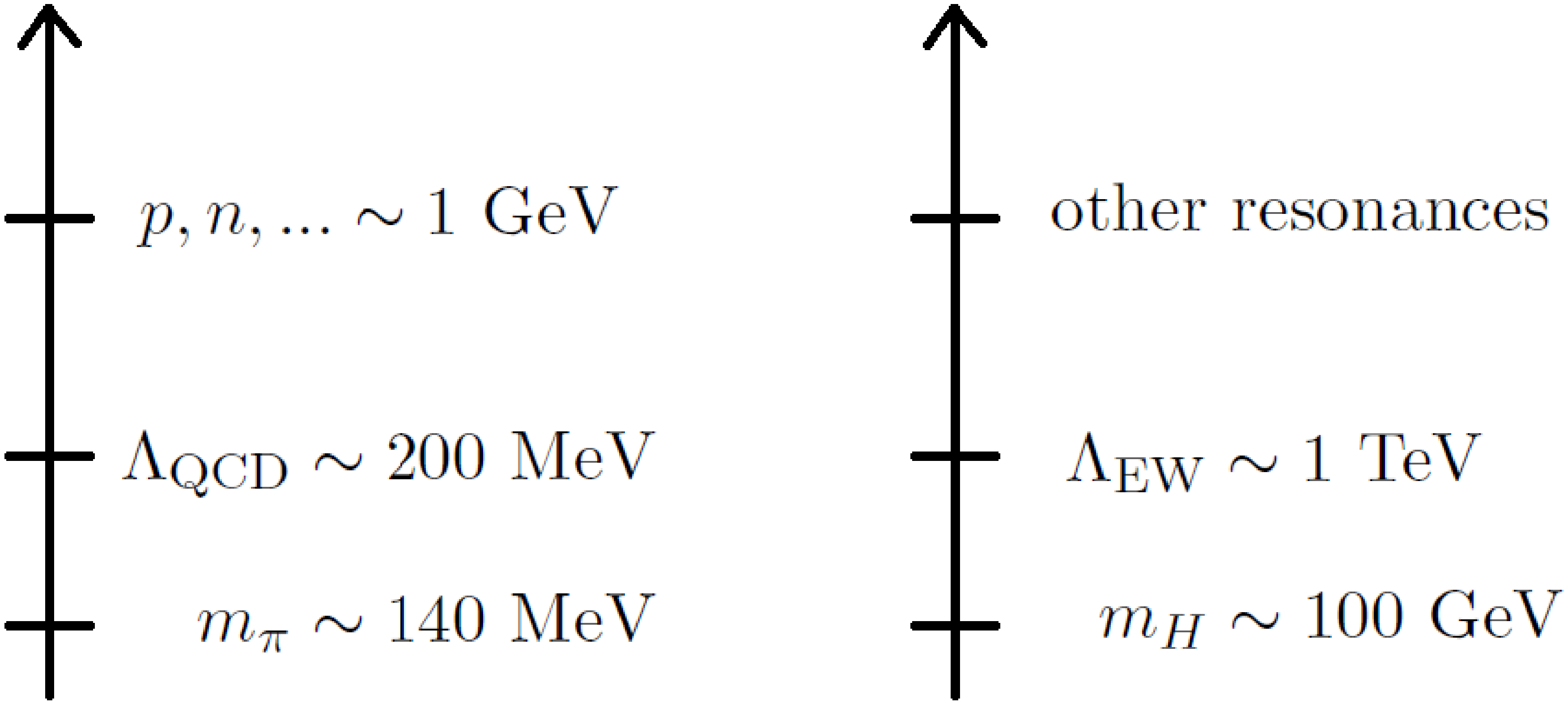
- Fermion - flavor puzzle



10^5

Higgs as pseudo-Nambu-Goldstone bosons

Light pions in QCD ↔ Light Higgs in EW



$p, n, \ldots \sim 1\ \mathrm{GeV}$

$\Lambda_{\mathrm{QCD}} \sim 200\ \mathrm{MeV}$

$m_\pi \sim 140\ \mathrm{MeV}$

other resonances

$\Lambda_{\mathrm{EW}} \sim 1\ \mathrm{TeV}$

$m_H \sim 100\ \mathrm{GeV}$

Composite Higgs Models

- Chiral symmetry breaking in Λ_{QCD}

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

which gives three massless NG bosons, i.e. pions!!

However, the symmetry is broken by EM interactions and quark masses, and we get massive pions.

- (Some global) symmetry breaking in Λ_{EW}

$$\mathcal{G} \rightarrow \mathcal{H} \ni SU(2)_L \times U(1)_Y$$

which gives (at least) four NG bosons as **Higgs doublet!!**

The symmetry can be broken by different interactions (usually by electroweak interaction and Yukawa interaction) and give us the nontrivial Higgs potential.

Partial Compositeness

Composite pNGBs can couple to SM particles through the mixing between SM particles and composite resonances with the same quantum number.

Elementary Sector
$\psi_{L/R}, A_\mu$
SM particles (w/o Higgs)

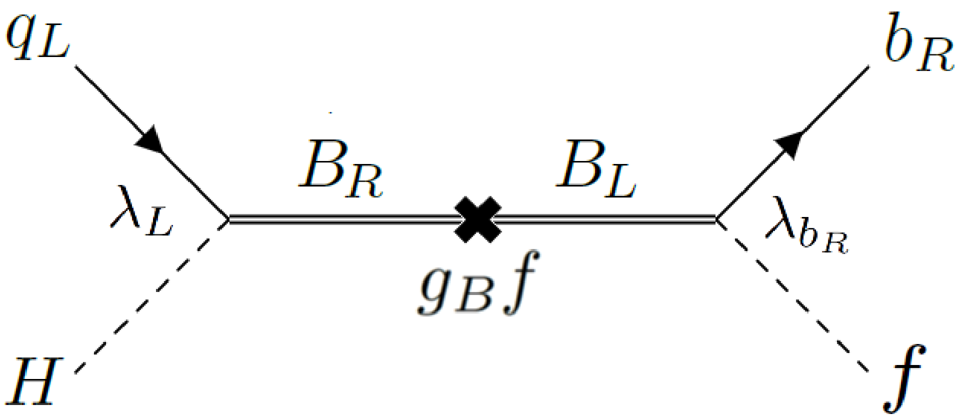
$\mathcal{L}_{mix} = \lambda \bar{\psi} \mathcal{O}_\psi + g A_\mu J^\mu$

Composite Sector
$H, \mathcal{O}_{L/R}, J_\mu$
composite resonances

The SM particles are the mixture of elementary state and composite state.

Ex: bottom Yukawa coupling

$$\mathcal{L} = \lambda_L \bar{q}_L O_R + \lambda_{b_R} \bar{b}_R O_L \implies$$



$$\sim \frac{\lambda_L \lambda_{b_R}}{g_B}$$

yichung@ucdavis.edu

The Froggatt-Nielsen (FN) mechanism

Assume an abelian $\boldsymbol{U(1)_F}$ **flavor symmetry**, where different SM fermions carry different flavor charges, so the SM Yukawa couplings can not be generated directly.

The low-energy effective Yukawa coupling terms require the insertion of additional $U(1)_F$ charged **scalar fields – flavon s** , as

$$\mathcal{L}_{\text{Yukawa}} = y_{ij} \left(\frac{s}{\Lambda_F} \right)^{a_{ij}} \bar{q}_{L,i} H q_{R,j}$$

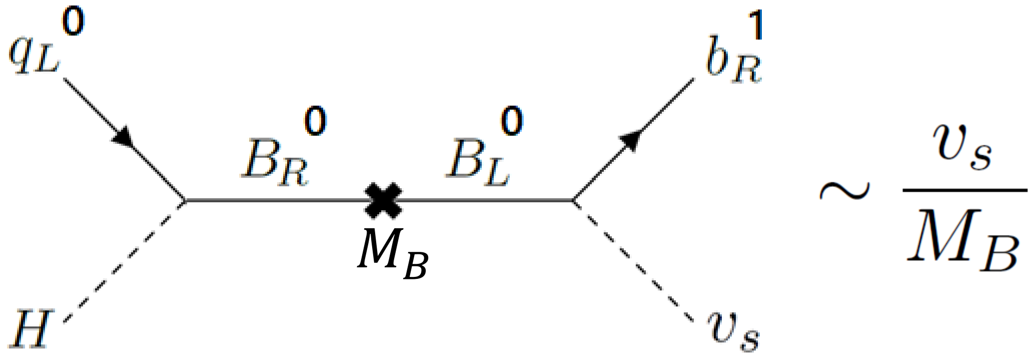
The coupling can be understood as integrating out **the heavy vector-like fermion** B

Flavon field gets a VEV which carries charge

— *flavor breaking vacuum* v_s

Vector-like fermions get masses w/o charges

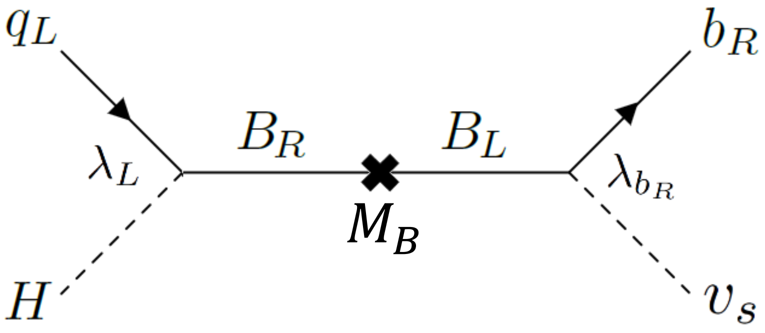
— *flavor conserving mass* M_B



Similarity between two mechanisms

Froggatt-Nielsen mechanism

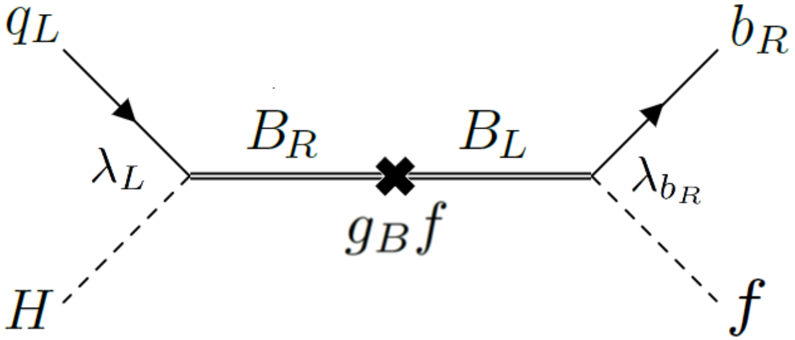
- $U(1)_F$ flavor symmetry
- scalar flavon s with VEV v_s
- vector-like fermion B



- A small parameter $\varepsilon = v_s / M_B$
  - — *flavor breaking vacuum* v_s
  - — *flavor conserving mass* M_B

CHM with Partial Compositeness

- $\mathcal{G} \rightarrow \mathcal{H}$ global symmetry breaking
- pseudo-Nambu-Goldstone bosons
- composite resonances (baryon)



- Questions
  - — *where is the* $U(1)_F$ *flavor symmetry?*
  - — *how to get the other scale?*

Two ways to embed the flavor symmetry

Symmetry breaking in CHMs: $full\ group\ \boldsymbol{\mathcal{G}} \rightarrow unbroken\ subgroup\ \boldsymbol{\mathcal{H}}$

1) $U(1)_F \subset \boldsymbol{\mathcal{H}}$

- The flavon field arises as pNGB of global symmetry breaking
- $U(1)_F$ is subsequently broken by the VEV of the flavon field
- Analogy to EWSB: $\sim$Composite Higgs

2) $U(1)_F \subset \boldsymbol{\mathcal{G}}$ but not $\boldsymbol{\mathcal{H}}$

- Only the pNGB of broken $U(1)_F$ (no scalar flavon)
- $U(1)_F$ is broken by strong dynamics directly
- Analogy to EWSB: $\sim$Technicolor

$U(1)_F \subset \mathcal{H} : SU(6)/Sp(6)$ CHM

Nonlinear Sigma model Σ as an anti-symmetric tensor representation

$$\langle \Sigma \rangle = f \begin{pmatrix} 0 & -\mathbb{I}_{3\times 3} \\ \mathbb{I}_{3\times 3} & 0 \end{pmatrix} \qquad U(1)_F : \frac{1}{2} \begin{pmatrix} \mathbb{I}_{2\times 2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\mathbb{I}_{2\times 2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \subset Sp(6)$$

The coset SU(6)/Sp(6) contains 14 pNGBs, including a real triplet ϕ_a, a real singlet η, a complex singlet s (as the flavon field), and two Higgs (complex) doublets H_1 and H_2

$$\pi_a X_a = \begin{pmatrix} \frac{\phi_a}{\sqrt{2}}\sigma^a - \frac{\eta}{\sqrt{6}}\mathbf{1} & H_2 & \boxed{\epsilon s} & H_1 \\ H_2^\dagger & \frac{2\eta}{\sqrt{6}} & -H_1^T & 0 \\ \epsilon^T s^* & -H_1^* & \frac{\phi_a}{\sqrt{2}}\sigma^{a*} - \frac{\eta}{\sqrt{6}}\mathbf{1} & H_2^* \\ H_1^\dagger & 0 & H_2^T & \frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

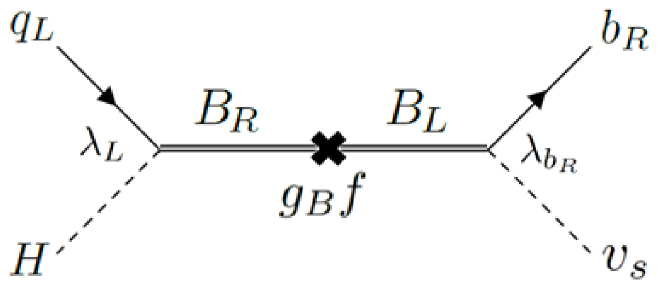
The complex singlet is SM singlet but carries flavor charge 1

The flavon field s can acquire a VEV $\langle s \rangle = v_s$

— *flavor breaking vacuum v_s*

— *flavor conserving mass $M \sim gf$*

$\Rightarrow$



$\sim \frac{v_s}{f}$

$U(1)_F \subset \mathcal{G} : SU(4)/Sp(4)$ CHM

Nonlinear Sigma model Σ as an anti-symmetric tensor representation

$$\langle \Sigma \rangle = f \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix} \qquad U(1)_F : \frac{1}{2} \begin{pmatrix} \mathbb{I}_{2\times 2} & 0 \\ 0 & -\mathbb{I}_{2\times 2} \end{pmatrix} \subset SU(4)$$

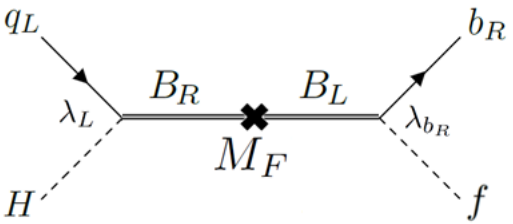
The coset SU(4)/Sp(4) contains 5 pNGBs, including a real singlet a and Higgs doublet H

$$\pi_a X_a = \begin{pmatrix} \frac{ia}{\sqrt{2}} \mathbb{I}_{2\times 2} & (\tilde{H} \;\; H) \\ -(\tilde{H} \;\; H)^\dagger & \boxed{-\frac{ia}{\sqrt{2}} \mathbb{I}_{2\times 2}} \end{pmatrix} \longrightarrow$$

The real singlet is the pNGB of broken $U(1)_F$ flavor symmetry

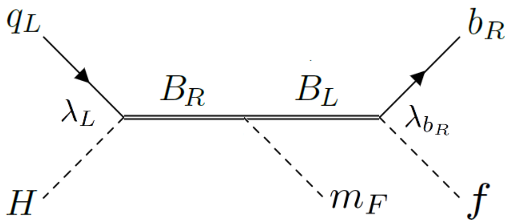
We still need a flavor conserving vacuum to generate the hierarchy, ex: technifermion mass

(1) Large *flavor conserving mass* M_F



$$\sim \frac{f}{M_F}$$

(2) Small *flavor conserving mass* m_F

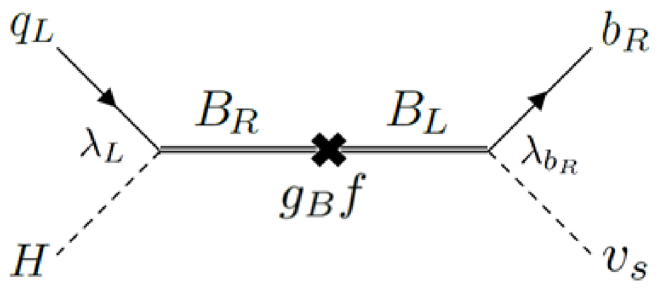


$$\sim \frac{m_F}{f}$$

Comparison between two examples

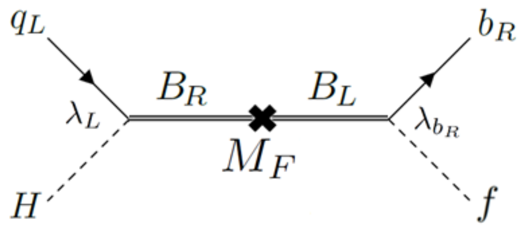
Composite Flavon [2104.11719]

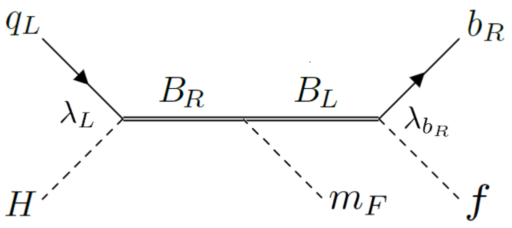
- $U(1)_F \subset \mathcal{H}$
- $SU(6)/Sp(6)$ CHM
- Flavor breaking scale $v_s \sim 100\ \mathrm{GeV}$
- flavor conserving $f \sim 1\ \mathrm{TeV}$
- Suppression $\boldsymbol{\varepsilon} = \frac{\boldsymbol{v_s}}{\boldsymbol{f}}$



Flavorful CHM [2106.XXXXX]

- $U(1)_F \subset \mathcal{G}$ but not $\mathcal{H}$
- $SU(4)/Sp(4)$ CHM
- Flavor breaking scale $f \sim 1\ \mathrm{TeV}$
- flavor conserving ~ technifermion mass
- Suppression $\boldsymbol{\varepsilon} = \frac{\boldsymbol{f}}{\boldsymbol{M_F}}$ or $\frac{\boldsymbol{m_F}}{\boldsymbol{f}}$





Conclusions

- **Dynamical origin of flavor scale** under the framework of CHMs
- Strong dynamics can automatically generate required **vector-like fermions**
- Multiple scenarios to introduce the required **vacuums and suppression**
- Combining with CHMs provides testable **TeV-scale flavor models**

To go further!?

- Non abelian flavor symmetry (ex: SU(3), SO(3)….)
- Flavor violating Higgs and Minimal Flavor Violation

Thank you

Backup

Inverse Froggatt-Nielsen mechanism

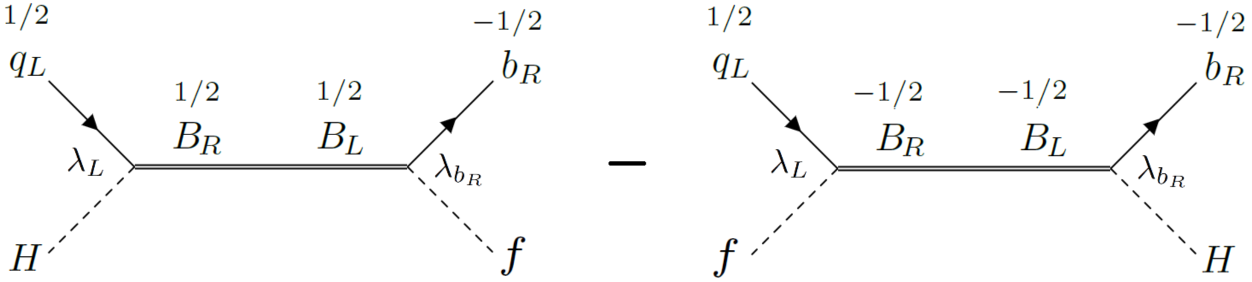
In the original FN mechanism, the small parameter comes from

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{v_s}}{\boldsymbol{M}} = \frac{\boldsymbol{flavor\ violating}}{\boldsymbol{flavor\ conserving}} \xrightarrow{\boldsymbol{inverse}} \frac{\boldsymbol{flavor\ conserving}}{\boldsymbol{flavor\ violating}}$$

Example: in SU(4)/Sp(4) CHM, embed both LH and RH quarks in the fourplet

$$4_{1/6,\,0} = 2_{1/6,\,1/2}\ (\to q_L) \oplus 1_{2/3,\,-1/2}\ (\to t_R) \oplus 1_{-1/3,\,-1/2}\ (\to b_R)$$

But these mixing terms didn’t break SU(4)



$\Rightarrow \quad \mathbf{0}$

If there is small difference between $M_{1/2}$ and $M_{-1/2}$

$$M_{1/2} - M_{-1/2} = m_F\ \text{(technifermion mass)} \qquad \Rightarrow \qquad \sim \frac{\boldsymbol{m_F}}{\boldsymbol{f}}$$

yichung@ucdavis.edu

Mass hierarchy by partial compositeness

In partial compositeness scenario, one general way to get fermion mass hierarchy is

Consider $\mathcal{L} = \frac{\lambda}{\Lambda_{UV}^{d-5/2}} \bar{q}_{L,R} O_{L,R}$ with composite operators $O_{L,R} \sim \Lambda_{IR}^{d-3/2} Q_{L,R}$

It will result in the suppression $\Longrightarrow \frac{\Lambda_{IR}^{d-3/2}}{\Lambda_{UV}^{d-5/2}} \sim \left(\frac{\Lambda_{IR}}{\Lambda_{UV}} \right)^{d-5/2} \Lambda_{IR}$ if $\Lambda_{UV} > \Lambda_{IR}$ and $d > 5/2$

In our case, the dimension of the operators could all be the same and only one scale Λ_F but only composite resonances with correct flavor charges can give us Yukawa coupling.

Therefore, the correct estimation of scale looks like $O_{L,R} \sim v_s^a \Lambda_F^{d-3/2-a} Q_{L,R}$

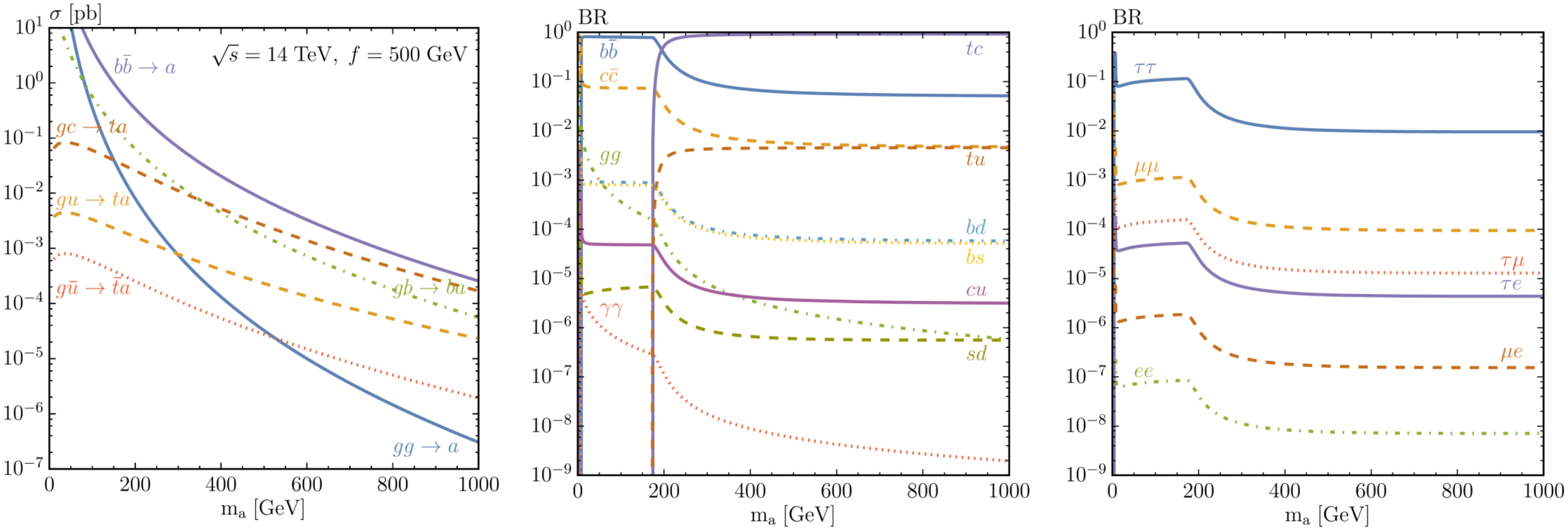
,which include the consideration of flavor charge and flavor violating scale v_s.

The suppression becomes $\Longrightarrow \frac{v_s^a \Lambda_F^{d-3/2-a}}{\Lambda_F^{d-5/2}} \sim \left(\frac{v_s}{\Lambda_F} \right)^a \Lambda_F$ with a determined by charges.

Flavon Phenomenology

The primary target is the **Flavon** (scalar / pseudo-scalar)

Bauer et al., arXiv:1603.06950



Similar to Higgs boson but depends on flavon VEV and Yukawa matrices.

Other targets: the second Higgs doublet, vector-like fermions…..

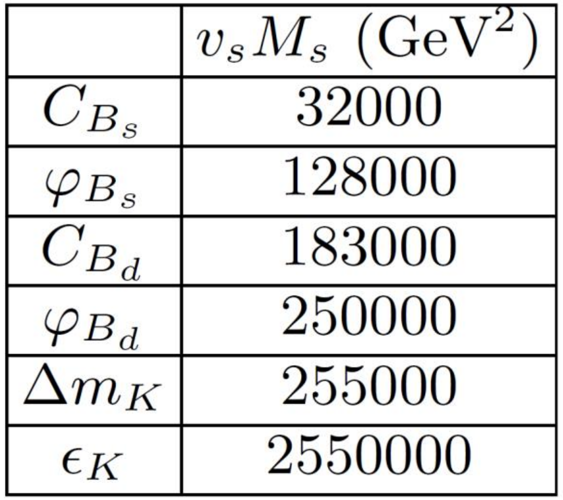
Neutral Meson Mixing

The neutral meson mixing depends on the scenario we use. Take one of them as example

$$C_4^{ij}(\bar{q}_R^i q_L^j)(\bar{q}_L^i q_R^j) \quad \text{with} \quad C_4^{ij} = -g_{ij} g_{ji}^* \left(\frac{1}{M_s^2}\right)$$

The coupling g_{ij} is determined by the observed fermion masses over the flavon VEV v_s.

The current constraints on the product of flavon vacuum and flavon mass–



	$v_s M_s$ (GeV^2)
C_{B_s}	32000
φ_{B_s}	128000
C_{B_d}	183000
φ_{B_d}	250000
Δm_K	255000
ϵ_K	2550000

(1) Constraints from flavor physics are much stronger

(2) Yukawa matrices and CP properties are important

(3) Scenarios with small v_s are probably ruled out

(4) TeV VEV × TeV Mass is around the corner!!