**Higgs boson physics and LHC phenomenology in an inverted-hierarchy flavor symmetry model**

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Based on:  
“Higgs-flavon mixing and LHC phenomenology in a simplified model of broken flavor symmetry”

arXiv:1406.6054, in collaboration with  
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Outline

• LHC implications of a model of broken flavor symmetry with inverted-hierarchy.

• Minimal new particle content:
  – Scalar flavon $\phi$
  – Heavy fermion top-partner $T$
  – Neutral top-philic gauge boson $Z_T$

• Focus in this talk on:
  – Modification of SM Brout-Englert-Higgs (BEH) production and decay
  – Flavon phenomenology at the LHC: $\phi \to hh$ and $\phi \to ZZ$

• Summary
The origin of the flavor structure in the SM is one of its most interesting puzzles. Explore the relationship of broken flavor symmetry to broken electroweak symmetry physics.

Begin from a flavor symmetry model with inverted-hierarchy proposed to suppress additional contributions to flavor changing processes after flavor symmetry breaking. (Grinstein, Rebi, and Villadoro, JHEP 1011 067 (2010)).

After flavor symmetry breaking (and spontaneous electroweak symmetry breaking), a flavon associated with flavor symmetry, and the BEH field get vev's. The new neutral scalar boson, the flavon, will generally mix with the SM BEH boson. The mixing term, even if forbidden artificially at tree-level, will be generated through loop corrections.

\[
H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \tilde{h} \end{pmatrix}, \quad \Phi = \frac{v \varphi + \tilde{\varphi}}{\sqrt{2}}, \quad \begin{pmatrix} \tilde{h} \\ \tilde{\varphi} \end{pmatrix} = \begin{pmatrix} \cos \theta_H & \sin \theta_H \\ -\sin \theta_H & \cos \theta_H \end{pmatrix} \begin{pmatrix} h \\ \varphi \end{pmatrix}
\]
Modification of BEH couplings

- Mixing between the SM-like BEH boson and the flavon modifies the coupling strength between the SM-like BEH boson and the SM fermions and SM gauge bosons.

1. Gauge interactions: \( hW^+W^- \), \( hZ^0Z^0 \), a factor of \( \cos \theta_H \).

2. Yukawa interactions (non-top): \( h\bar{f}f \), a factor of \( \cos \theta_H \).

3. Top-quark Yukawa interaction:
   \[
   \frac{v_{SR}}{\sqrt{2}m_t} (\lambda c_H c_L - \lambda' s_H s_L).
   \]

4. Loop induced interactions: \( hgg \), \( h\gamma\gamma \), \( hZ^0\gamma \).

5. BEH self-interaction: \( \lambda_{hhh} \)

- A full calculation shows that the loop induced interactions are also corrected by approximately \( \cos \theta_H \).

- The BEH self-interaction coupling is (\( \lambda_\Phi \) is the self-interaction strength of the flavon field \( \Phi \))

\[
\lambda_{hhh} = \frac{m_h^2}{2v} \left( c_H^3 - s_H^3 \sqrt{\frac{\lambda_\Phi v^2}{m_\varphi^2 c_H^2 + m_h^2 s_H^2}} \right)
\]
The SM-like BEH boson decay branching ratios are nearly the same as those in the SM since the overall rescaling factor drops out.

The production rate of the SM-like BEH boson is suppressed by a factor of $\cos^2\theta_H$.

According to the 7 and 8 TeV data (ATLAS-CONF-2014-009, CMS PAS HIG-13-005), the limits on the mixing angle are

$$\sin^2 \theta_H < 0.62 \quad \text{(CMS)}$$

$$\sin^2 \theta_H < 0.19 \quad \text{(ATLAS)}$$

at $3\sigma$ C.L. Some room for the new physics we discuss.

The SM $h h$ pair production cross section (continuous spectrum, flavon resonance decay omitted) is generally suppressed by the mixing effect.
Flavon phenomenology

- The flavon can be produced at the LHC though the gluon fusion process: $gg \rightarrow \varphi$.
- The cross section is not rescaled by just $\sin^2\theta_H$. (Because the flavon is heavy, the heavy top limit is no longer a good approximation).
- We calculate the flavon production cross section with the full expressions for the top and heavy fermion loops.
- The flavon is a heavy scalar boson which may decay into a top-pair and other SM particles through mixing. The dominant SM decay channels of the flavon are $WW$, $ZZ$, and $tt\bar{t}$.
- A flavon-BEH trilinear interaction will induce the SM-like BEH pair final state in flavon decay.

$$
\lambda_{\varphi hh} = \left( \frac{m_\varphi^2 + 2m_h^2}{2v} \right) s_H c_H \left( c_H + s_H \sqrt{\frac{\lambda_\Phi v^2}{m_\varphi^2 c_H^2 + m_h^2 s_H^2}} \right)
$$
Flavon branching fractions

- The SM-like $h \ h$ pair channel might be the most important decay mode of the flavon.

\[
\frac{\lambda_\phi}{4\pi} = 0.5 \\
\sin^2 \theta_H = 0.20
\]
Flavon phenomenology at 14 TeV

- Flavon production and decay
  
  \[ \varphi \rightarrow ZZ \rightarrow 2l2l' \]


- \[ \varphi \rightarrow hh \]

  Focus in this talk on the two b-jet plus diphoton signal:
  \[ \varphi \rightarrow bbyy. \]

Flavon signal and background generation

- We generate signal events for flavon plus one jet at parton level using MadGraph5/MadEvent, shower them using PYTHIA6.4 with the MLM matching scheme, and simulate the detector effects using PGS4.

- The total cross section of the signal is normalized to the NNLO SM-like BEH boson value (S. Dittmaier et al. (LHC Higgs Cross Section Working Group) (2011), 1101.0593) times the rescaling factor from the $gg\phi$ effective vertex.

- The important SM backgrounds are

  \[ pp \rightarrow bb\gamma\gamma, \]
  \[ pp \rightarrow Z^0 h \rightarrow b\bar{b}\gamma\gamma, \]
  \[ pp \rightarrow Z^0 \gamma\gamma \rightarrow b\bar{b}\gamma\gamma, \]
  \[ pp \rightarrow \bar{b}b j j (j \rightarrow \gamma), \]
  \[ pp \rightarrow jj\gamma\gamma (j \rightarrow b), \]
  \[ pp \rightarrow t\bar{t} \rightarrow b j j \bar{b} j j (j \rightarrow \gamma), \]
  \[ pp \rightarrow t\bar{t}h \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu}\gamma\gamma (\ell^\pm \text{ missed}). \]
Flavon: signal and background results

- The energy resolution of b-jets and photons as a function of their transverse energy is obtained from the simulation of Z+b and Z+γ processes, where the Z boson decays into a di-muon.

- Events which pass the basic cuts are required to satisfy

\[
|m_{\gamma\gamma} - 125.4\text{GeV}| < \Delta m_{h,\text{cut}}, \quad |m_{bb} - 125.4\text{GeV}| < \Delta m_{h,\text{cut}},
\]

\[
p_T^{\gamma_1} > p_T^{\text{cut}}, \quad p_T^{\gamma_2} > p_T^{\text{cut}}, \quad \Delta\phi_{\gamma b}^\text{min} < \Delta\phi_{\gamma b,\text{cut}}
\]

- These cuts (diphoton and two-b-jets invariant mass, leading and sub-leading photon transverse momentum, and the minimum azimuthal angle between b-jet and photon) are chosen to be different for different flavon masses to get a larger cut efficiency.
From our simulation, we derive the discovery and exclusion bounds for the flavon at 14 TeV. For the final results, we combine the ZZ and the $hh$ channels. In the upper part of the figures, in the irregularly shaped region above the broad-dashed line, the BEH-pair signal yields a stronger constraint.
Summary

- Model of new physics based on broken gauged flavor symmetry.
- Flavon -- new gauge singlet scalar -- is introduced, with mass in the hundreds of GeV range.
- Flavon mixes with the Brout-Englert-Higgs boson, mixing angle $\theta_H$.
- BEH couplings scaled by $\cos\theta_H$, but SM branching fractions preserved.
- Flavon production and decay phenomenology discussed in detail [arXiv: 1406.6054].
- Possibility opened for enhanced $hh$ production via resonant $\varphi \to hh$.  

![Graph showing event distribution](image)
Backup Slides
Flavor symmetry model

- The origin of the flavor structure in the SM is one of its most interesting questions. Relationship to Brout-Englert-Higgs physics?

- A flavor symmetry model with inverted-hierarchy was proposed recently to suppress additional contributions to flavor changing processes after flavor symmetry breaking. (B. Grinstein, M. Rebi, and G. Villadoro, JHEP 1011 067 (2010))

- The seesaw-like structure makes the lightest new particles couple mainly to the top sector of the SM.

- The TeV scale effective Lagrangian can be written

\[ \mathcal{L}_{\text{top flavor}} = \lambda \bar{Q}_L \tilde{H} \Psi_{tR} - \lambda' \bar{\Psi}_t \Phi \Psi_{tR} - M \bar{\Psi}_t t_R + \text{h.c.} \]

with the scalar potential

\[ V(H, \Phi) = \frac{\lambda_H}{2} (H^\dagger H)^2 + \frac{\lambda_\Phi}{2} (\Phi^* \Phi)^2 - \frac{m_H^2}{2} (H^\dagger H) - \frac{m_\Phi^2}{2} (\Phi^* \Phi) + \xi (\Phi^* \Phi) (H^\dagger H) \]

and a residual U(1) gauged flavor symmetry which rotates \( t_R, \Psi_t \)

and the flavon \( \Phi \).
Flavor symmetry model

- After flavor symmetry breaking and spontaneous electroweak symmetry breaking, the flavon and BEH fields get vev's. The new neutral scalar boson, the flavon, will generally mix with the SM BEH boson. The mixing term, even if forbidden artificially at tree-level, will be generated through loop corrections.

\[
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\]

- The SM top-quark mixes with a heavy Dirac fermion $T$ as a seesaw partner of the SM top-quark. The neutral flavor gauge boson is a top-philic massive gauge boson.

- Constraints from the electroweak oblique parameters were verified (B. Grinstein, M. Rebi, and G. Villadoro, JHEP 1011 067 (2010)) and rechecked in our work. The flavor physics constraints were investigated carefully ((B. Grinstein, M. Rebi, and G. Villadoro, JHEP 1011 067 (2010); A J. Buras, M V. Carlucci, L. Merlo, and E. Stamou, JHEP 1203 088 (2012))).
Flavon phenomenology at 7 and 8 TeV

- Constraint from the heavy SM-like BEH boson searches at 7 and 8 TeV. (ATLAS-CONF-2013-013, CMS collaboration, arXiv: 1312.5353[hep-ex])

- The strongest constraint is from the channel with four charged-leptons.

- We present the 95% C.L. exclusion bound to the parameter space.

- Owing to the small production rate, the BEH-pair signal cannot give a stronger constraint on the mixing angle than the global-fit to the SM-like BEH production rate.
**Flavon phenomenology**

- For the background processes, we simply rescale the event weight with a K-factor if it is available as an approximation.

- The b-tagging efficiency is normalized to 70%. The mistagging rate from light quarks and gluon is normalized to 3.9%. The mistagging rate from the charm quark is normalized to 25.7% (ATL-PHYS-PUB-2013-009).

- The rate of jets faking a photon is (ATLAS-PHYS-PUB-2013-009)

\[ \epsilon(p_T)_{j\rightarrow\gamma} = 9.3 \times 10^{-3} \times \exp\left(-\frac{p_T}{27.5 \text{ GeV}}\right). \]

- We require the events to have at least two hard isolated photons and two b-tagged jets.

\[ p_T^\gamma > 20 \text{ GeV}, |\eta^\gamma| < 2.0, \quad p_T^b > 40 \text{ GeV}, |\eta^b| < 2.0. \]

- To suppress the \( htt \) bkgd, we reject events with hard lepton or large missing transverse energy.

\[ p_T^\ell > 20 \text{ GeV}, |\eta^\ell| < 2.5, (I_{iso} < 0.1 \text{ for } \mu^\pm) \text{ or } \not{E}_T > 30 \text{ GeV}. \]
Flavon phenomenology

- After an invariant mass cut on the diphoton + 2b-jet system, we derive the exclusion and discovery prospects for the $hh$ decay channel. The results are compared with those for the $ZZ$ channel. (The standard strength is assumed to be the SM-like heavy BEH cross section with 100% decay branching ratio to the final state.)

- If the $hh$ decay channel has a larger branching ratio, it could give stronger constraint (or earlier discovery) than the $ZZ$ channel.

![Graph](image1)

![Graph](image2)
Using the expected bounds at the 14 TeV from the ATLAS and CMS collaborations, we show the 95% C.L. exclusion bound on the parameter space for the ZZ final state.

The $hh$ signal should be examined at 14 TeV.

We focus on the two b-jet plus diphoton signal: $\varphi \rightarrow bb\gamma\gamma$.