Fermion Masses as Localized Energy Functionals: A Geometric Interpretation of Higgs–Lepton Couplings

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Abstract

Recent evidence for the Higgs boson decay into a muon pair provides a direct probe of the Higgs coupling to second–generation charged leptons. In the Standard Model, such couplings are parametrized by Yukawa constants whose origin and hierarchical structure remain unexplained. In this work, we propose an alternative but fully compatible interpretation in which fermion masses arise from localized energy functionals associated with stable fermionic configurations, and Higgs couplings are identified with scalar susceptibilities of these configurations. Within this framework, Yukawa couplings scale automatically with fermion mass, independently of microscopic details. We show that this interpretation naturally accommodates the observed Higgs–muon coupling strength, reproduces charged–lepton mass hierarchies, and yields testable constraints for future precision Higgs measurements. The construction is purely effective, introduces no new particles or interactions, and remains fully consistent with the Standard Model at presently accessible energies.

1 Introduction

The discovery of the Higgs boson completed the particle content of the Standard Model (SM) and provided a mechanism for fermion mass generation via Yukawa interactions. Despite its empirical success, the Yukawa sector remains largely phenomenological: fermion masses and couplings span several orders of magnitude without an underlying structural explanation.

Recent experimental progress has opened a new window into this sector. In particular, the observation of the decay $H \to \mu^+\mu^-$ provides the first direct probe of the Higgs coupling to a second–generation charged lepton. The measured rate is compatible with Standard Model expectations within current uncertainties, reinforcing the approximate proportionality between fermion mass and Higgs coupling strength.

This development motivates a reconsideration of the physical meaning of Yukawa couplings. Rather than treating them as fundamental parameters, one may ask whether they admit an effective interpretation in terms of more primitive, universal quantities.

In this paper, we explore a conservative possibility: fermion masses are modeled as localized energy functionals associated with stable fermionic configurations, and Higgs couplings are identified with the response of these energies to a scalar background field. This viewpoint does not modify the Standard Model Lagrangian, but reinterprets its parameters in a geometric and energetic language.

2 Localized Energy Picture of Fermion Mass

We begin by adopting a general and model–independent definition of fermion mass. For a fermionic excitation labeled by f, we write its rest energy as

$$M_f c^2 \equiv \int_{V_f} \mathcal{E}_f(\mathbf{x})\, d^3x, \tag{1}$$

where $\mathcal{E}_f(\mathbf{x})$ is an effective localized energy density and V_f denotes the spatial region over which the excitation is supported.

Equation (1) is intentionally agnostic about microscopic structure. It merely encodes the assumption that fermion mass corresponds to energy stored in a localized, stable configuration. Such a viewpoint is familiar from solitonic models, bag models, and effective descriptions of bound states.

For later convenience, we factorize the mass as

$$M_f = \mathcal{K}\,\mathcal{G}_f, \tag{2}$$

where $\mathcal{K}$ is a universal energy–density scale, common to all fermions, and $\mathcal{G}_f$ is a dimensionless configuration factor encoding geometry, internal structure, and coherence properties of the fermionic state.

All fermion mass hierarchies are therefore attributed to differences in $\mathcal{G}_f$.

3 Scalar Susceptibility Interpretation of Yukawa Couplings

In the Standard Model, fermion masses arise through Yukawa interactions with the Higgs field H,

$$\mathcal{L}_Y = -y_f\,\bar{\psi}_f \psi_f H. \tag{3}$$

We propose to reinterpret the Yukawa coupling y_f as a scalar susceptibility:

$$y_f \;\equiv\; \frac{\partial M_f}{\partial \Phi}, \tag{4}$$

where Φ is a scalar background field identified, at low energies, with the Higgs vacuum expectation value.

If the scalar field rescales the underlying energy density entering Eq. (1), then

$$\mathcal{E}_f(\mathbf{x}) \to \mathcal{E}_f(\mathbf{x})\,[1 + \epsilon\,\Phi], \tag{5}$$

and one finds

$$y_f \propto M_f. \tag{6}$$

Thus, the observed proportionality between fermion mass and Higgs coupling emerges as a generic consequence of energy localization, without requiring fermion–specific fundamental couplings.

4 Charged–Lepton Mass Hierarchy

Applying Eq. (2) to the charged leptons $f \in \{e, \mu, \tau\}$, we write

$$M_\ell = \mathcal{K}\,\mathcal{G}_\ell. \tag{7}$$

Using experimental masses, one infers the dimensionless hierarchy

$$\mathcal{G}_e \ll \mathcal{G}_\mu \ll \mathcal{G}_\tau. \tag{8}$$

Importantly, no assumption is made regarding the microscopic origin of $\mathcal{G}_\ell$. It may reflect differences in effective support volume, internal coherence, or other geometric characteristics of the fermionic configuration.

Under the susceptibility interpretation (4), the same factors $\mathcal{G}_\ell$ govern the Higgs couplings, leading directly to

$$\frac{y_\mu}{y_e} \approx \frac{M_\mu}{M_e}, \qquad \frac{y_\tau}{y_\mu} \approx \frac{M_\tau}{M_\mu}. \tag{9}$$

This behavior is precisely what is being tested by Higgs decay measurements.

5 Implications of Higgs–Muon Measurements

The recent observation of the decay $H \to \mu^+\mu^-$ indicates that the Higgs coupling to the muon is consistent with Standard Model expectations within current uncertainties. In the present framework, this result implies that the scalar susceptibility of the muonic configuration is proportional to its localized energy, with no anomalous generation–dependent suppression or enhancement.

This provides a nontrivial consistency check. Any effective theory in which fermion masses arise from localized energy structures must reproduce the near–linear scaling of scalar couplings with mass. Conversely, future deviations from this scaling would signal either a breakdown of the localization picture or the presence of additional dynamical structure.

6 Predictions and Falsifiability

The proposed interpretation yields several testable consequences:

- Precision measurements of $H \to \tau^+\tau^-$ should continue to follow mass–proportional scaling, up to radiative corrections.
- Any significant deviation from linear scaling in Higgs–fermion couplings would indicate generation–dependent scalar responses.
- The framework predicts no new particles or interactions; deviations must appear only as modifications of effective couplings.

These predictions are directly accessible to ongoing and future collider experiments.

7 Conclusion

We have presented an effective and fully orthodox reinterpretation of fermion masses and Higgs couplings in terms of localized energy functionals and scalar susceptibilities. Within this framework, Yukawa couplings emerge as responses of fermionic energy configurations to a scalar background, naturally explaining their proportionality to fermion masses.

The recent observation of Higgs decay into muon pairs provides the first experimental anchor for this picture beyond the third generation. Future precision measurements will further test whether fermion masses and scalar couplings share a common geometric origin.

This work does not modify the Standard Model, but offers a complementary perspective on its parameter structure, potentially guiding the search for a deeper underlying theory.

References

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