Implications of Yukawa Interactions in Scalar Sector

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2025-12-02

Abstract

In this work, a field theory model containing a real scalar singlet and an SU(2) symmetry preserving complex doublet is studied using the method of lattice simulations. The model considers all quartic vertices along with the Yukawa vertex between a real scalar singlet and an SU(2) symmetry preserving complex doublet field. Machine learning is used to extract representative functions of the field propagators, lattice regulator, and the Yukawa vertex. In the considered renormalization scheme the field propagators are found enhanced compared to their respective tree level structure.

Abstract

It is found that mixing of operators containing scalar singlet with SU(2) invariant field operators results in 0+ states with a peculiar scarcity in hundreds of GeV s. The Yukawa vertex shows weak dependence on the field momenta while the theory remain interactive as found by the renormalized field propagators. The impact of the real scalar quartic self interaction is found mitigated due to other interaction vertices. The field expectation values exhibit a certain classification despite no conclusive signal of phase transition.

Motivation

- Higgs found! But more scalar bososn needed to explain Inflation, Dark Matter, SUSY
- Phase structure of Higgs when interacting with other bosons
- ϕ^4 is trivial. Is Higgs + Scalar also trivial?
- Quantitative expressions for further study (which can be used in DSE)

Real Scalar Singlet with Complex Higgs Doublet Model

Lagrangian in Minkowski

$$L_M = \sum_{\mu=0}^{3} \frac{1}{2}(\partial_\mu \phi)^2 + \sum_{\mu=0}^{3}\sum_{i=0}^{1} \partial_\mu (h^i)^\dagger \partial_\mu (h^i) - \frac{1}{2} m_\phi^2 \phi^2 - \sum_{i=0}^{1} m_h^2 (h^i)^\dagger h^i$$
$$- \xi_1 \sum_{i=0}^{1} \phi (h^i)^\dagger h^i - \xi_2 \sum_{i=0}^{1} \phi^2 (h^i)^\dagger h^i - \xi_3 \phi^4 - \xi_4 \sum_{i=0}^{1} ((h^i)^\dagger h^i)^2$$

Here

$$\phi \equiv \phi_{x,y,z,t}$$

and

$$h \equiv h_{x,y,z,t}$$

Lattice Simulation Method

- The scalar sector is not new but still no. of problems and aspects are to be addressed non-perturbatively. Because we don't know whether the new physics (beyond standard model) is perturbative or not. One of the famous non-perturbative technique is lattice simulation method.
- It is a formulation of field theory. It discretize the space-time continuum, which makes the path integral well defined.
- However our space-time is not discrete so the results have to be extrapolated to the continuum limit, where the lattice spacing a approach to zero.

Setup of calculation

- Lattice simulation method is used.
- Metroplis method is used for updates.
- Among would be gauge invariant quantities, 0^+ channel is being studied.
- Among gauge dependent quantities, two point (propagators) and three point (vertices) vertices correlation functions are being studied.

- Higgs operator in 0^+ channel is used to set the scale.
- 192 different paratmers has been studied in this model.
- Two different lattice sizes has been studied 12^4 and 18^4.
- Different choices of parameters gave bound states masses in diffrent energy scale.
- Supervised Machine Learning (SML) techniques are used to get the quantitative expressions of each energy states, Propagators and Yukawa vertex.

Correlation functions

In quantum field theory, the n-point correlation function is defined as the functional average (expectation value) of a product of n field operators at different positions.

$$\langle \phi(x)\phi(y)...\rangle = \frac{\int D\phi(\phi(x)\phi(y)...)\exp^{-S_E[\phi]}}{\int D\phi \exp^{-S_E[\phi]}}$$

Propagators

The **connected propagator** can be written as:

$$\langle \phi(x)\phi(y)\rangle = \frac{\int D\phi(\phi(x)\phi(y))\exp^{-S_E[\phi]}}{\int D\phi \exp^{-S_E[\phi]}} - \langle \phi(x)\rangle\langle \phi(y)\rangle$$

Scalar Propagator

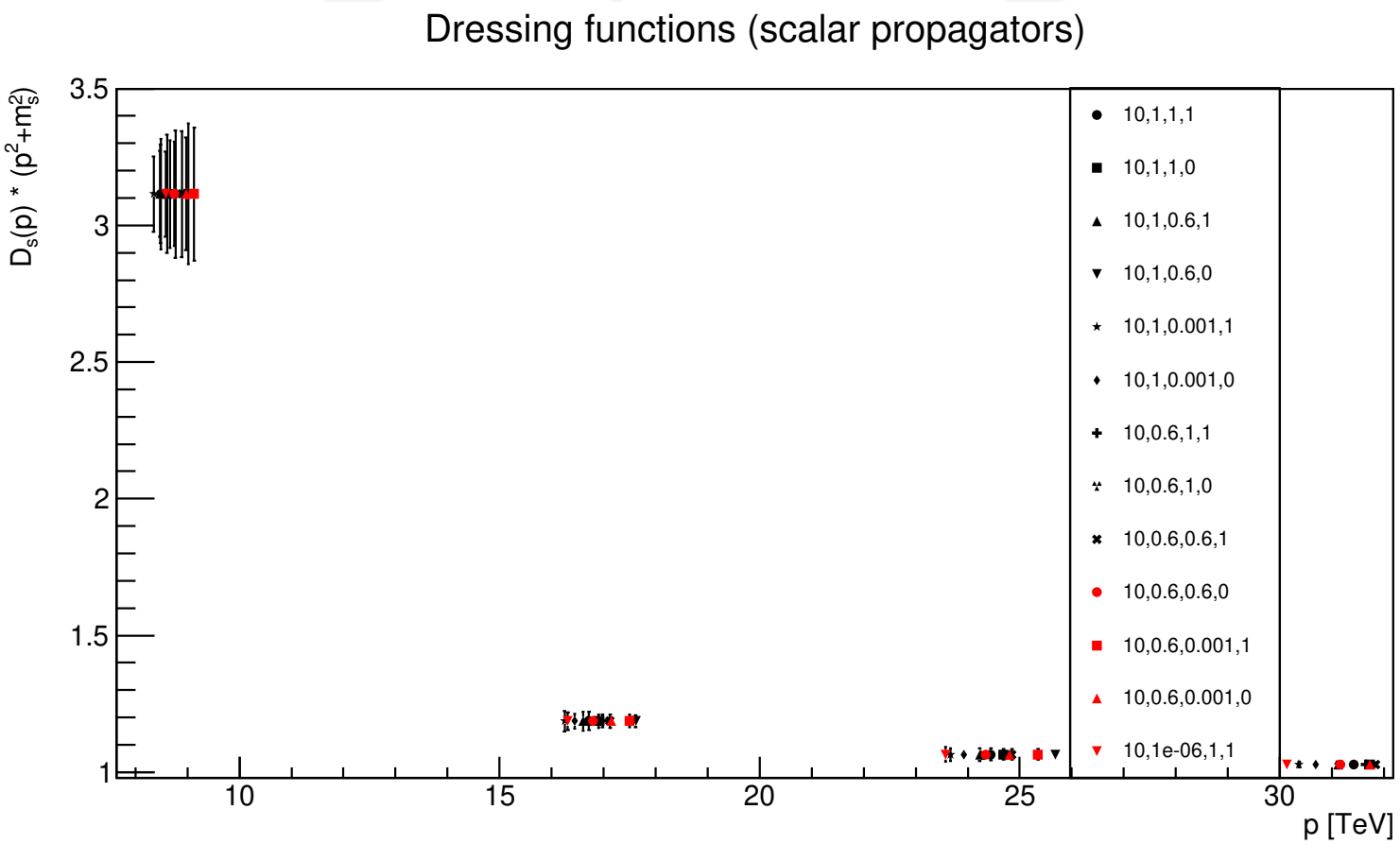

Figure: Dressing function for the Scalar Propagators for the scalar lattice mass 10.0 against parameters (m_s,ξ_3,ξ_1,ξ_2).

Higgs Propagator

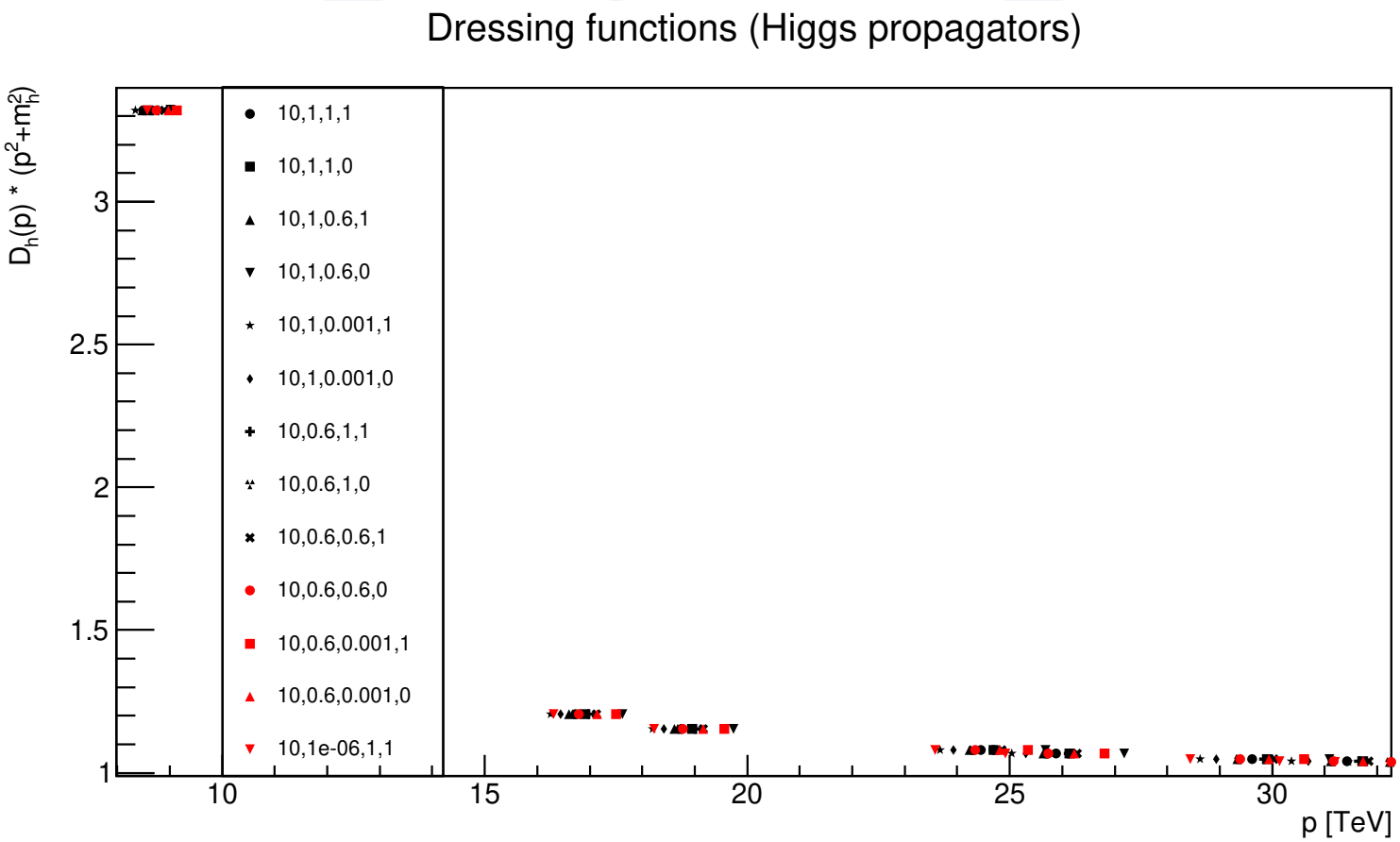

Figure: Dressing function for the Higgs Propagators for the scalar lattice mass 10.0 against parameters (ms,ξ_3,ξ_1,ξ_2).

0^+ Channel Spectroscopy

The Spectroscopy have been done for the following gauge indepenent operators

$$O_1 = (h^i)^\dagger h^i$$

$$O_2 = \phi^2$$

$$O_3 = \phi^2 (h^i)^\dagger h^i$$

Higgs Operator

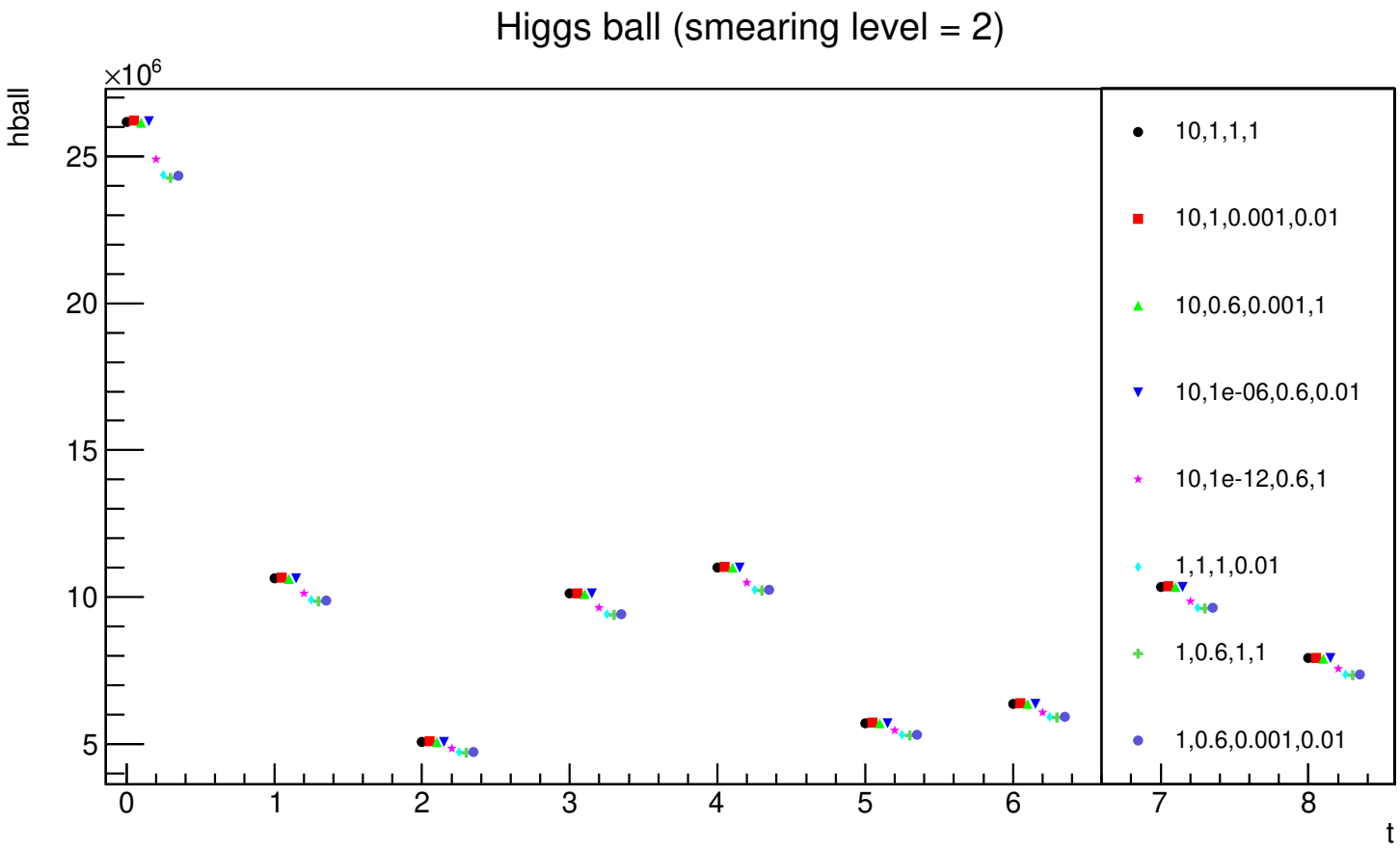

Figure: The Higgs ball operator for 2nd smearing level are plotted against the parameters (ms,ξ_3,ξ_1,ξ_2).

Scalar-Higgs Ball Mass Difference

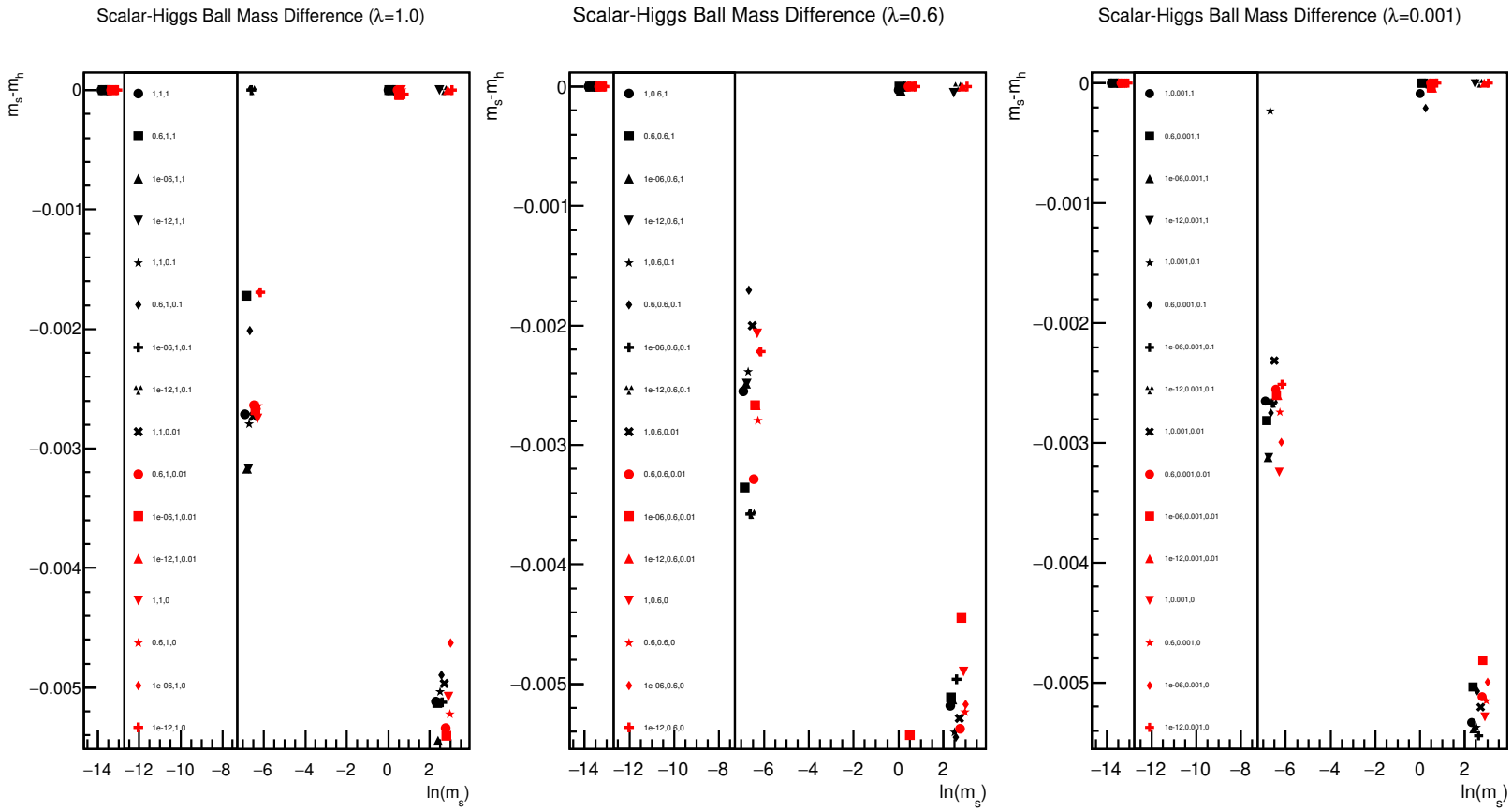

Figure: Difference between scalar ball mass and the Higgs ball mass are plotted for parameters (ξ_3, ξ_1, ξ_2).

Lattice Spacing

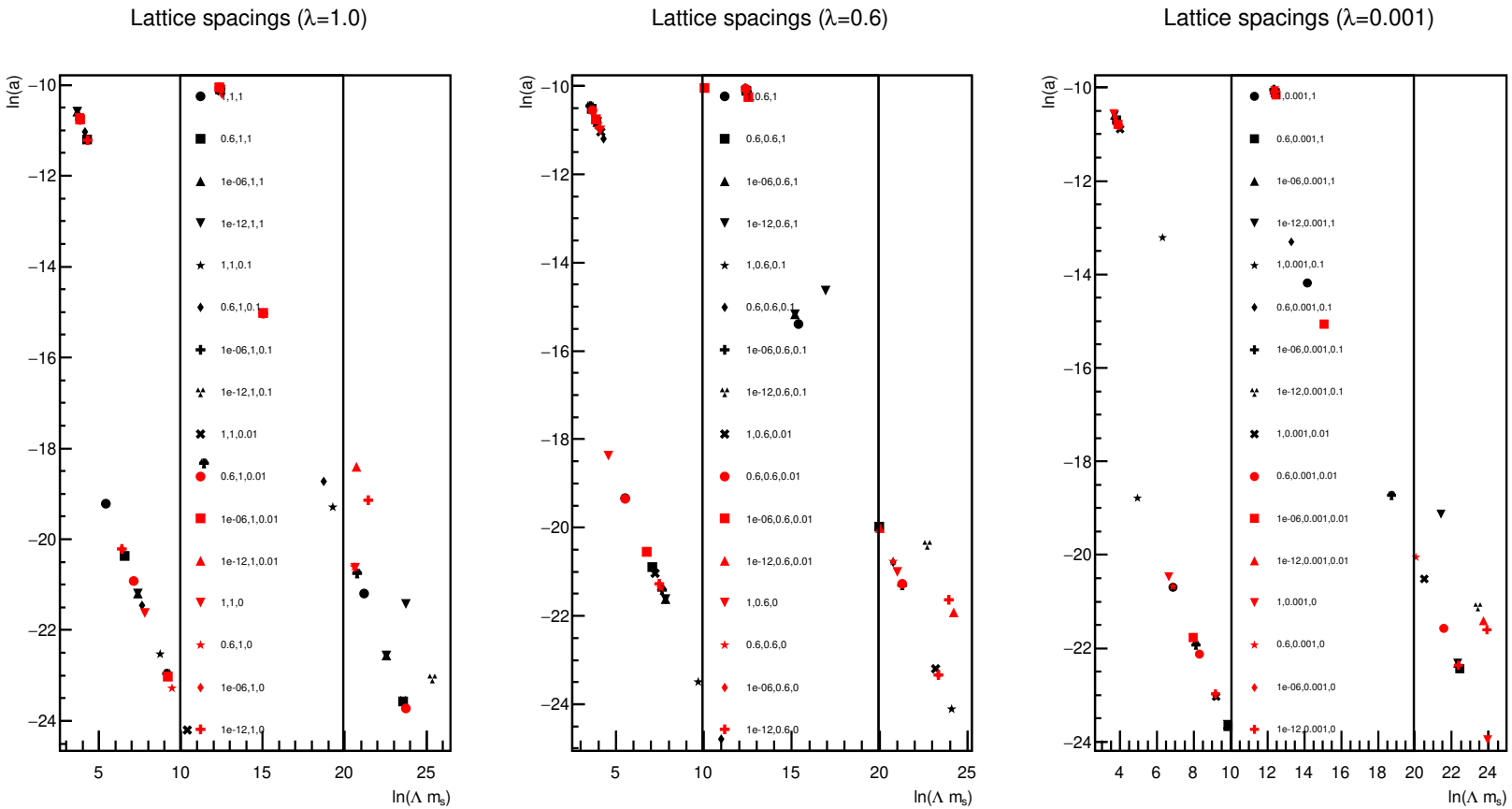

Figure: Lattice spacings against scalar mass Λms are plotted for couplings (ξ_3,ξ_1,ξ_2).

0^+ Channel Higgs Operator Masses

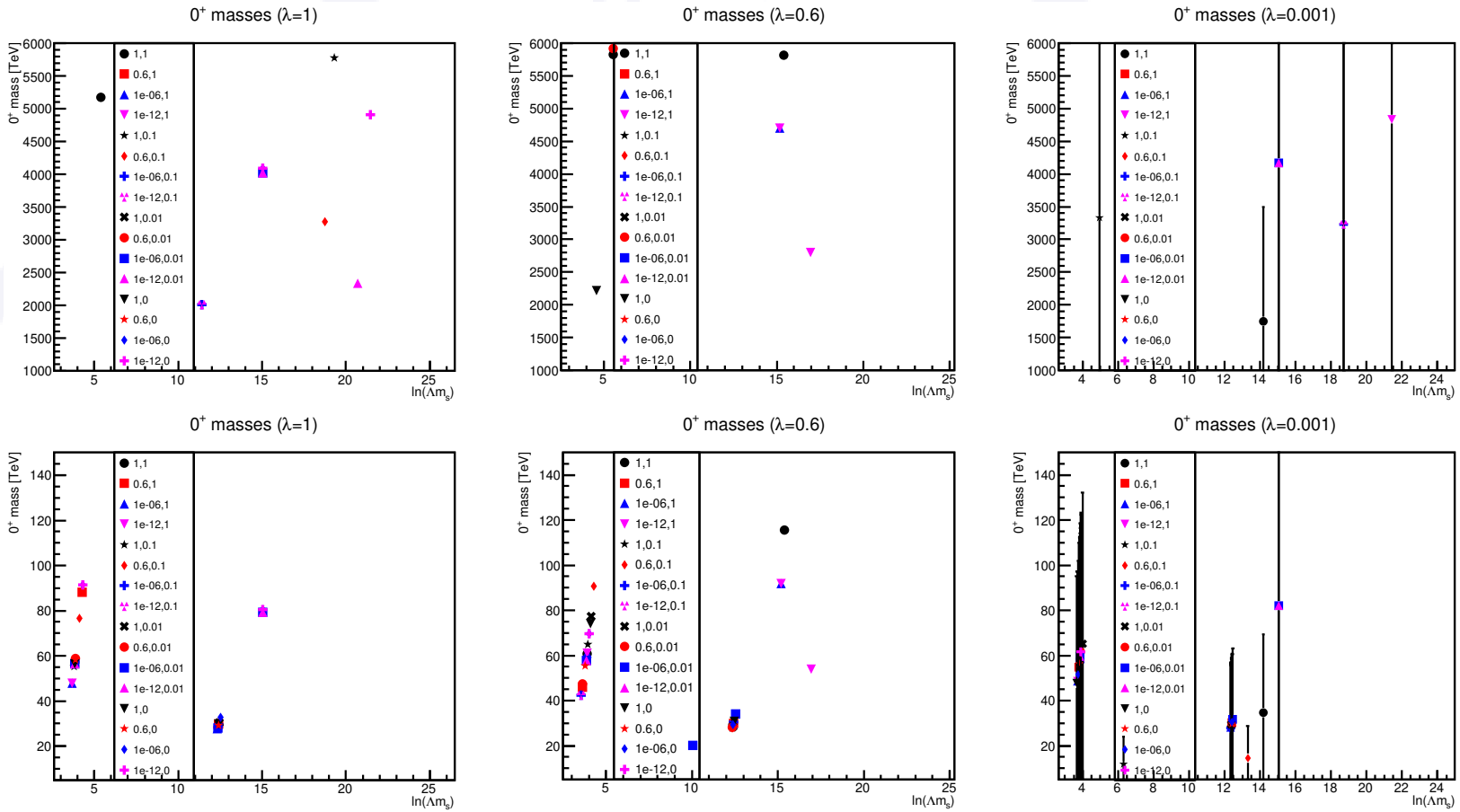

Figure: 0+ masses against the parameters (ξ_3,ξ_2) with only Higgs operators

0^+ Higgs-Scalar Operator Masses

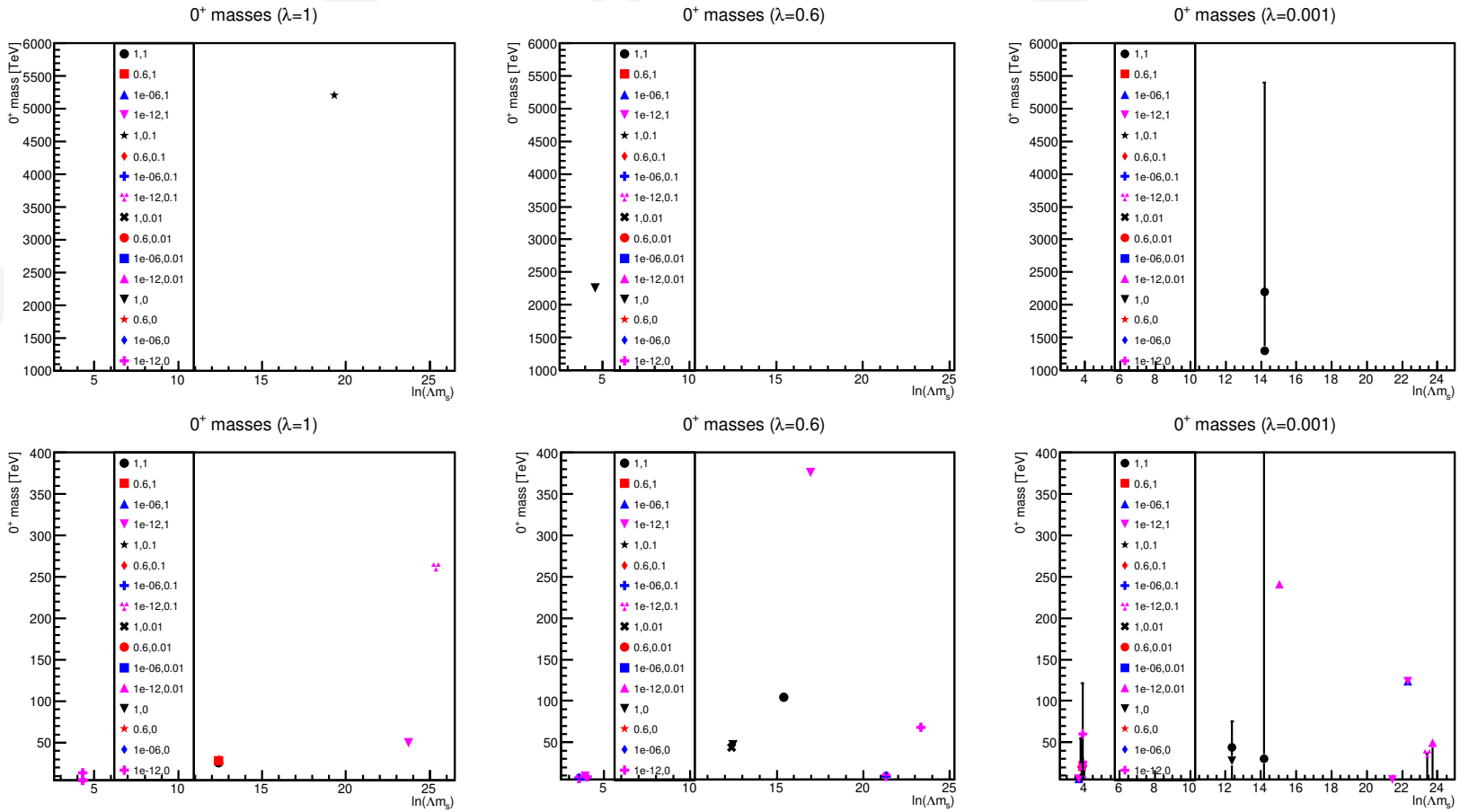

Figure: 0+ masses against the parameters (ξ_3,ξ_2)

0^+ Channel Higgs Operator Masses

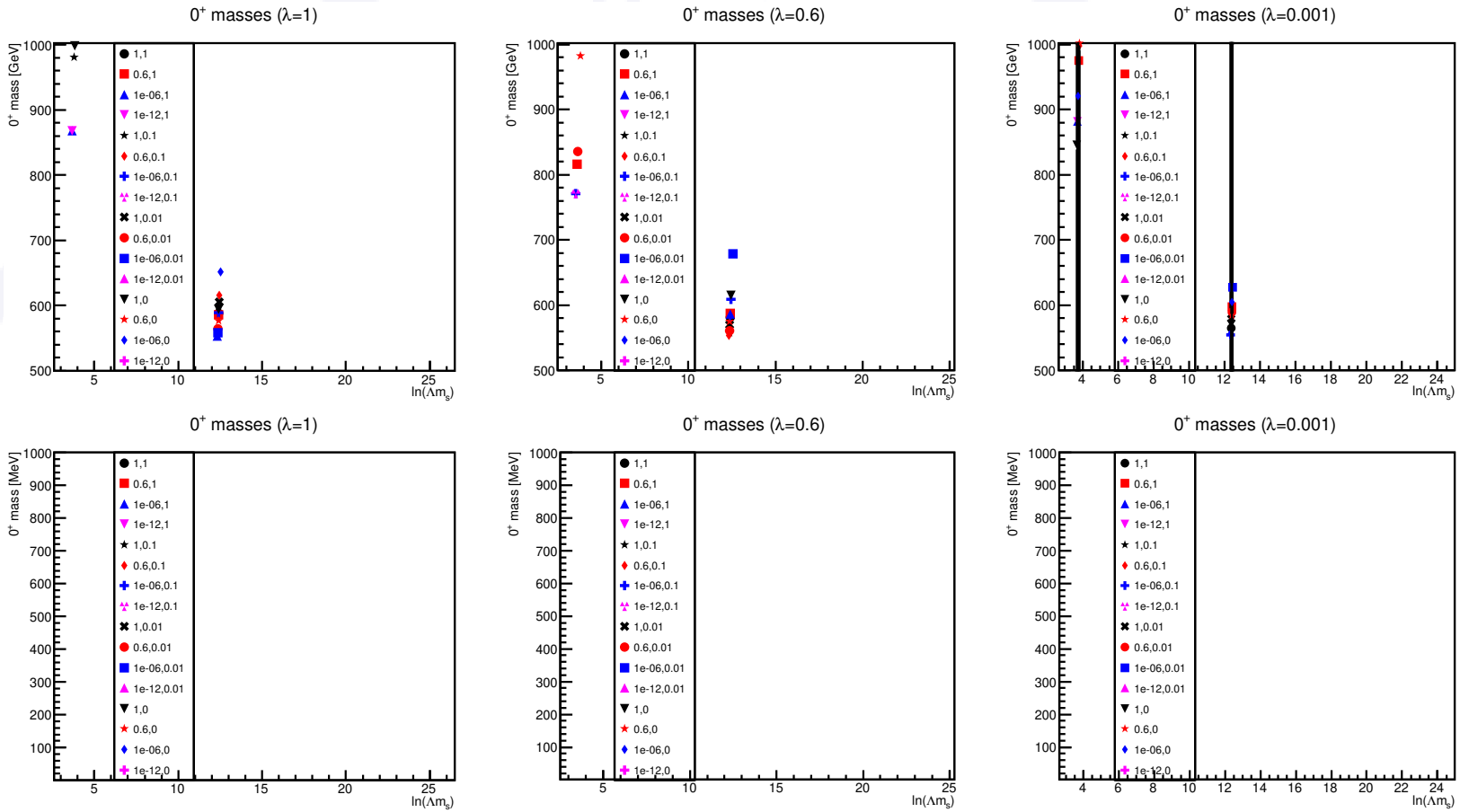

Figure: 0+ masses against the parameters (ξ_3,ξ_2) with only Higgs operators

0^+ Higgs-Scalar Operator Masses

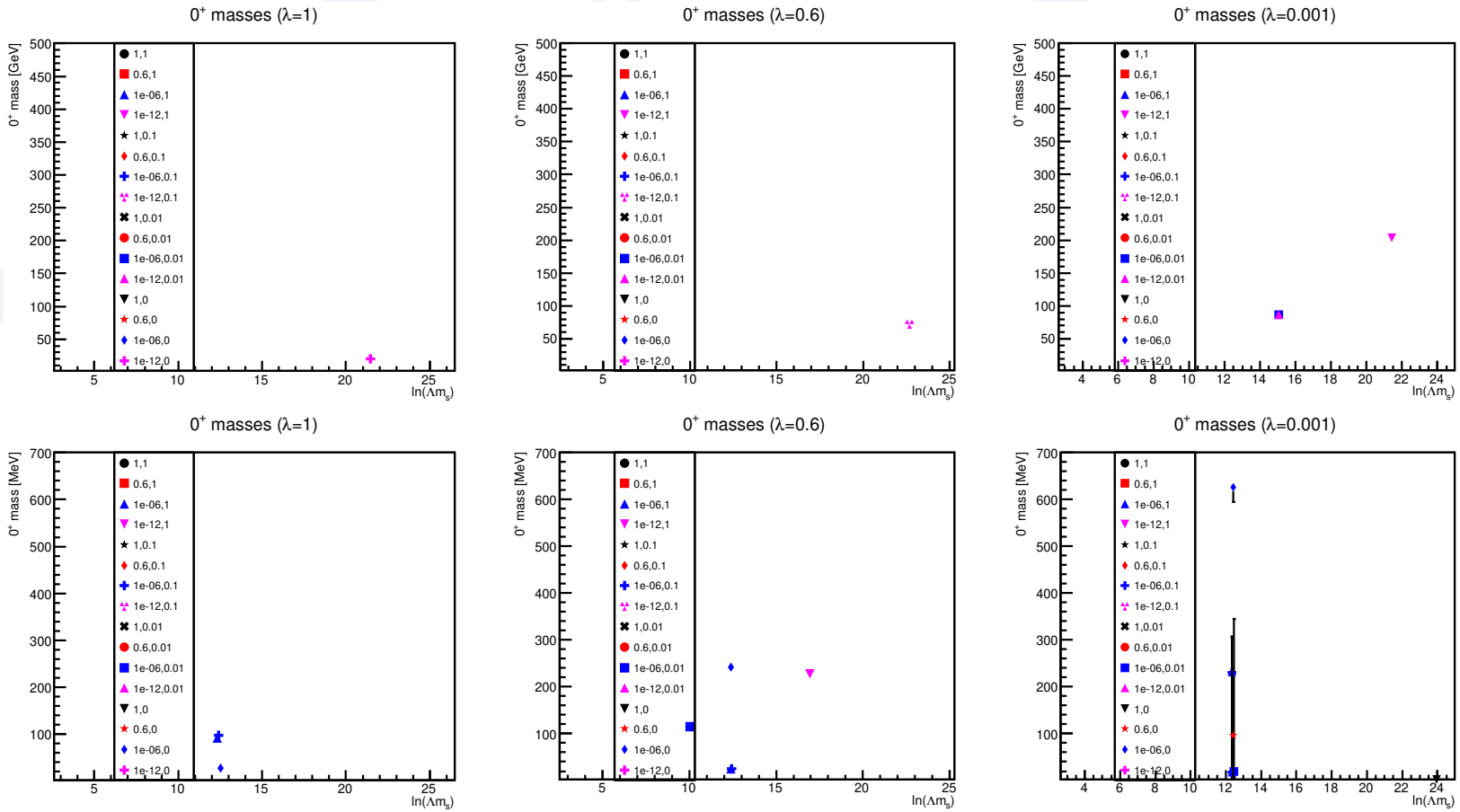

Figure: 0+ masses against the parameters (ξ_3,ξ_2)

0^+ Channel Higgs Operator Masses

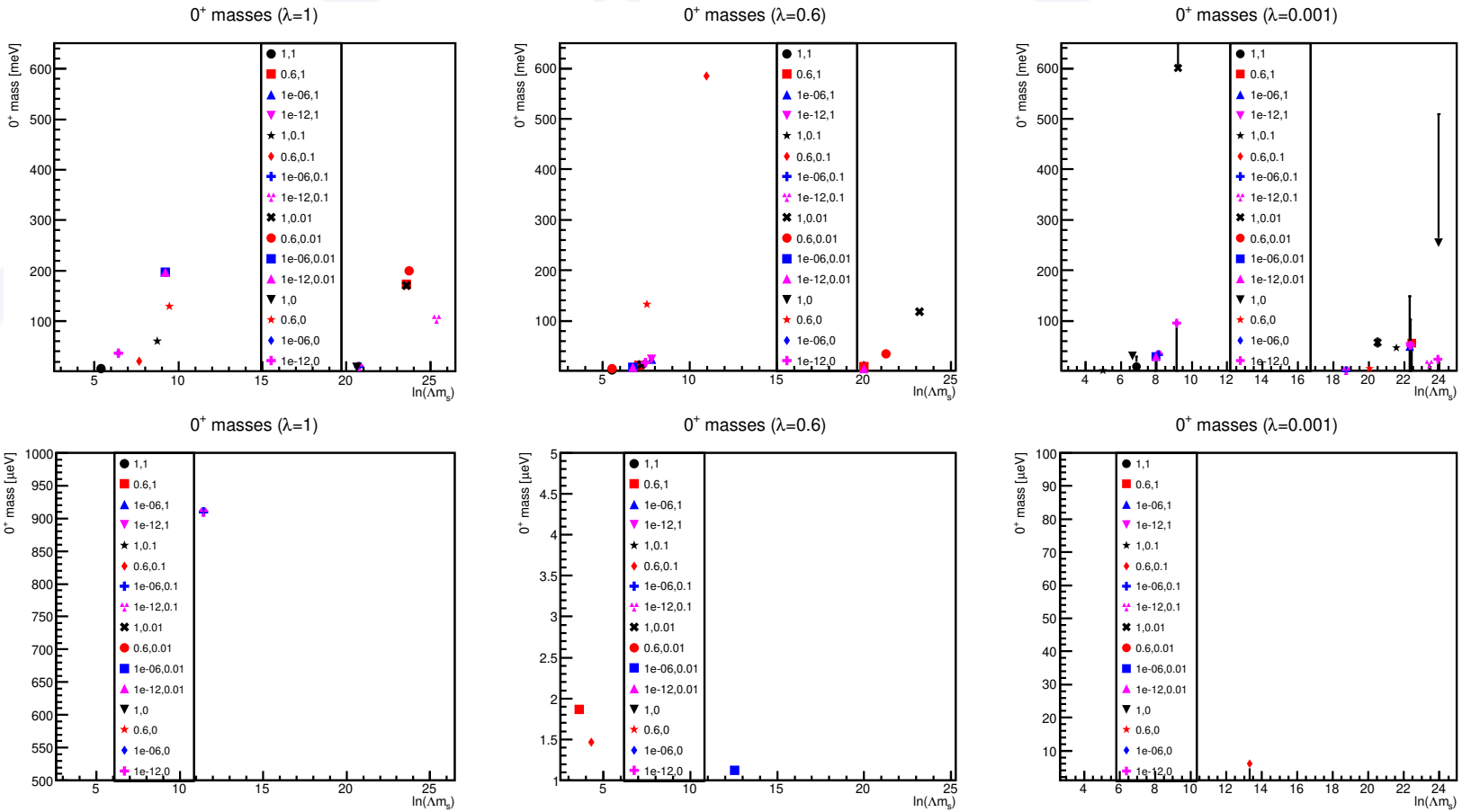

Figure: 0+ masses against the parameters (ξ_3,ξ_2) with only Higgs operators

0^+ Higgs-Scalar Operator Masses

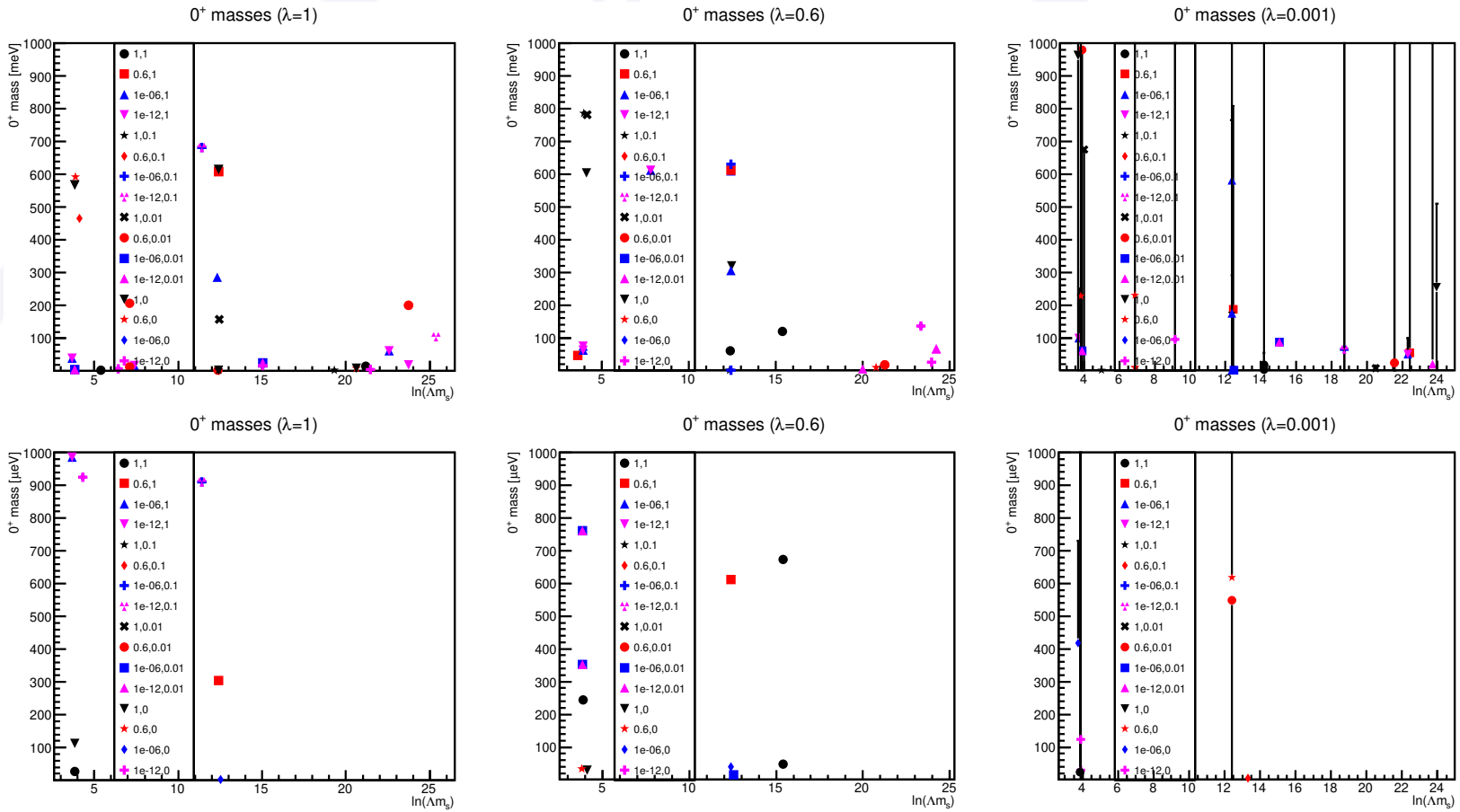

Figure: 0+ masses against the parameters (ξ_3,ξ_2)

Higgs Expectation

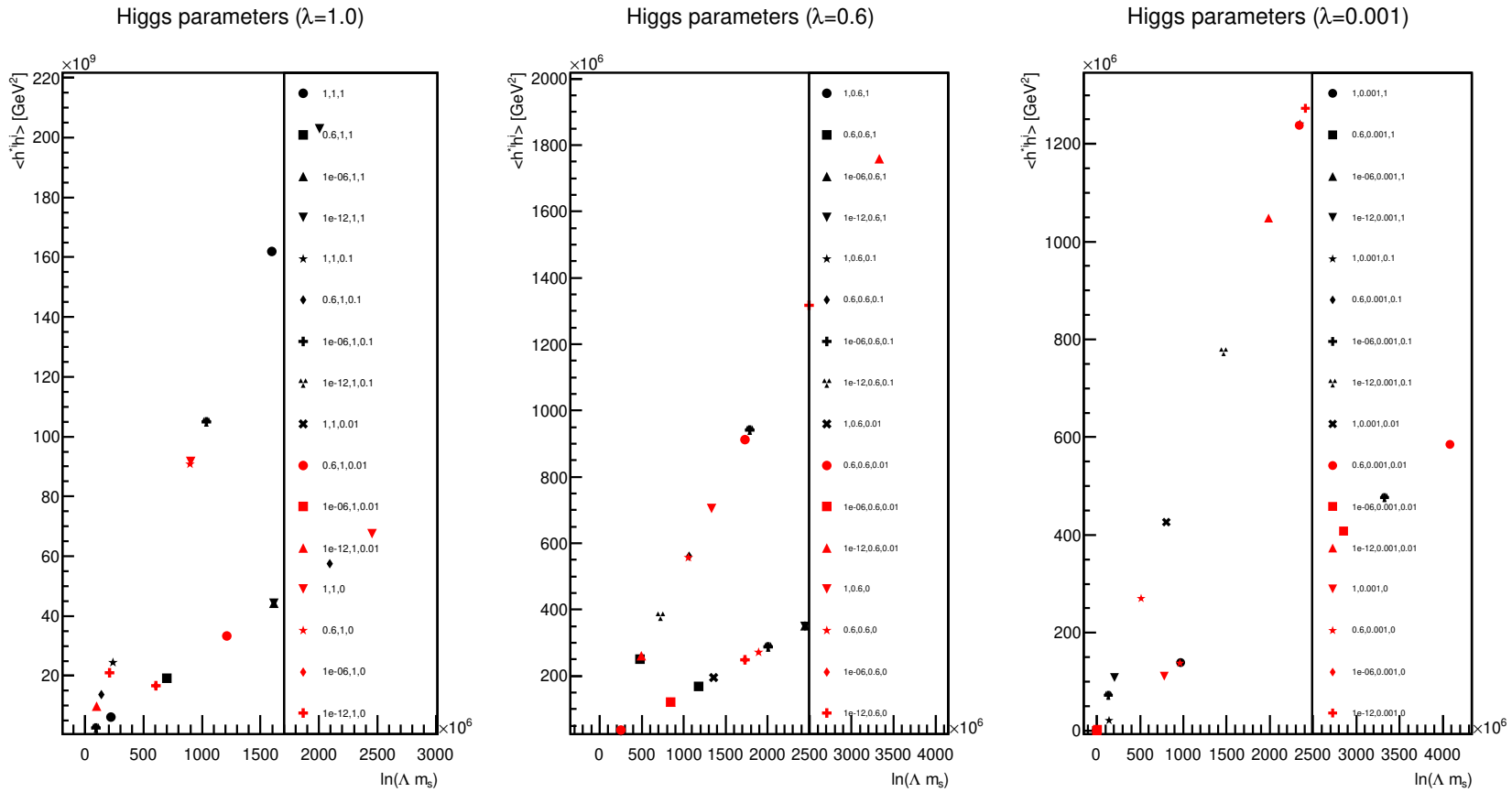

Figure: Gauge invariant Higgs parameter is plotted at different strengths of Yukawa coupling against the parameters (ξ_3,ξ_1,ξ_2).

Scalar Expectation

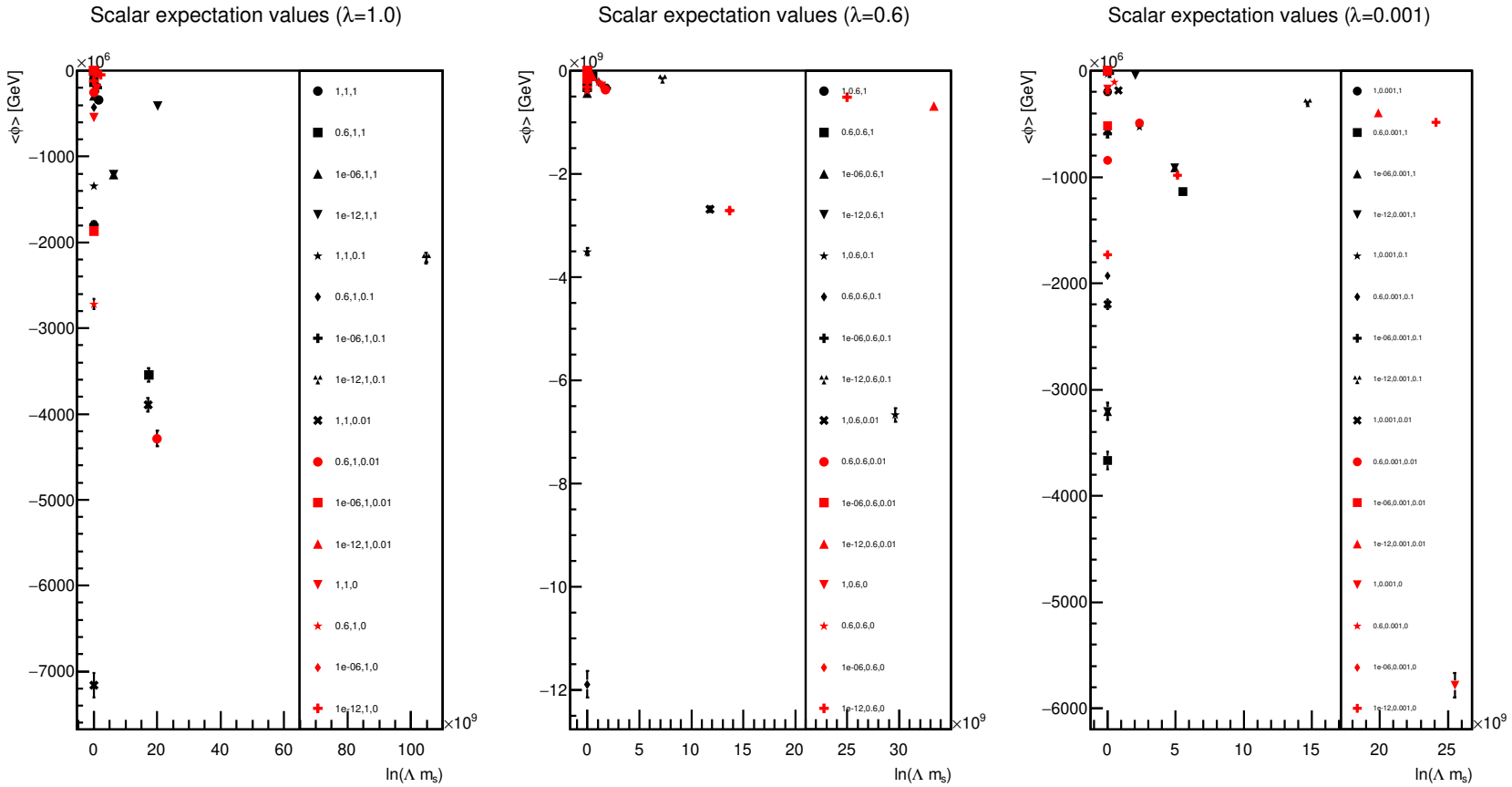

Figure: Scalar expectation against Λms in GeVs is plotted at different strengths of Yukawa coupling against the parameters (ξ_3,ξ_1,ξ_2).

Higgs-Phi Yukawa Vertex

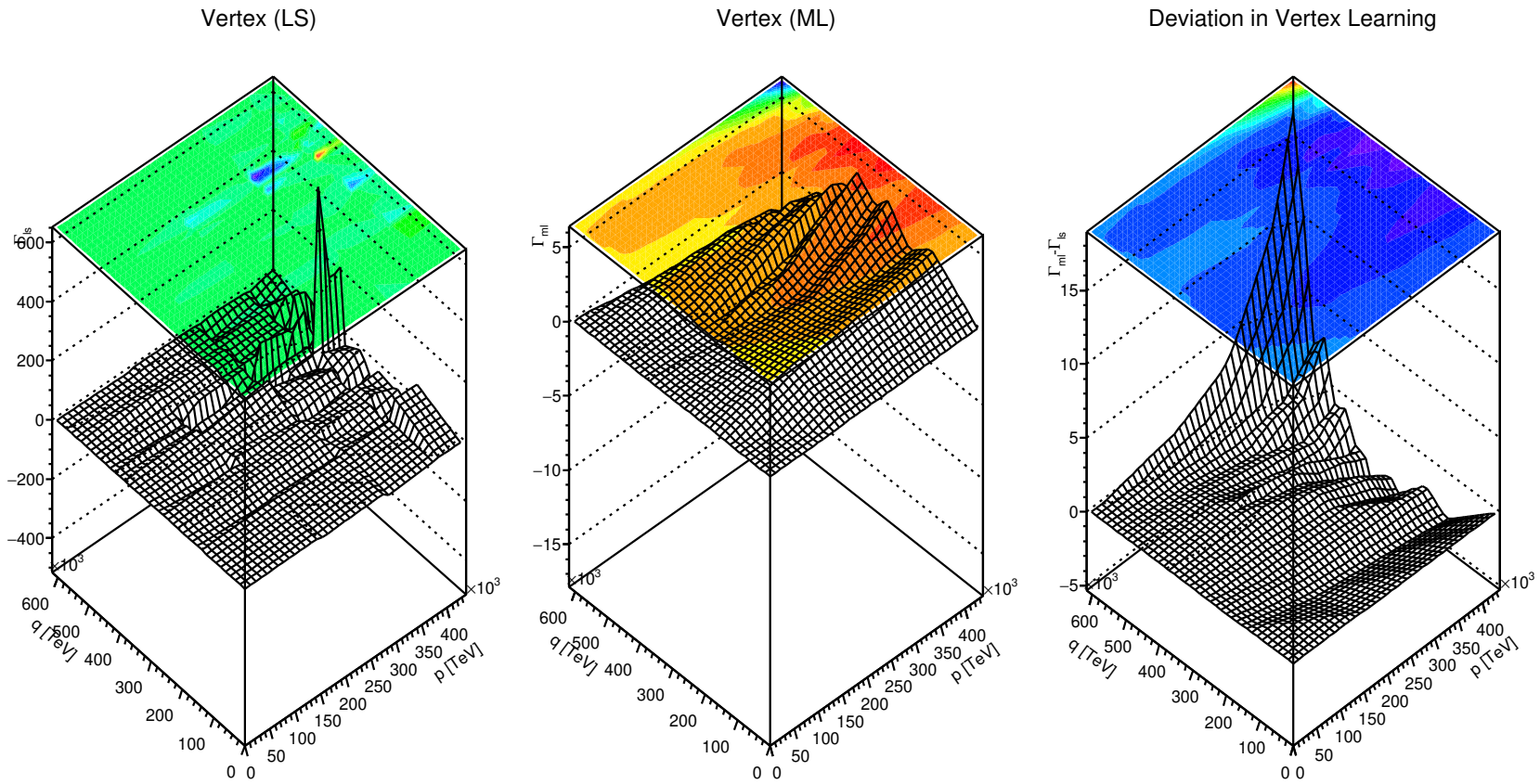

Figure: Higgs-Phi Yukawa vertex.

Machine Learning

We have used machine learning techniques on the masses and find out the quantitative expressions.

$$C_0+C_1m+C_2a+C_3b+C_4c+C_5m^2+C_6a*m+C_7b*m+C_8c*m+$$
$$C_9a^2+C_{10}b^2+C_{11}a^c+C_{12}a*b+C_{13}a*c+C_{14}b*c$$

Coeff.	Values	Coeff.	Values	Coeff.	Values
C_0	0.0000596	C_5	0.0000000	C_{10}	0.0195436
C_1	0.0000000	C_6	0.0000000	C_{11}	-0.001750
C_2	0.0018304	C_7	0.0000000	C_{12}	0.0000697
C_3	-0.000144	C_8	0.0000000	C_{13}	0.0000245
C_4	-0.000668	C_9	-0.000110	C_{14}	0.0006395

Table: Unknown coefficients of a 3*3 matrix mass

Conclusion

- Non Zero ground states is observed in 0^+ *Channel*.
- Strong suppression is observed at IR region in Vertex.
- Strong deviation is observed in propagators which indicate the dynamical mass generation.

References

(1) Muhammad Saad and Tajdar Mufti. Implications of Yukawa interactions in scalar sector. submitted to JHEP, 2025.

Thank You

for listening me till now ☺

QUESTIONS?