Z_2 breaking effects in 2-loop RG evolution of 2HDM

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[Based on work soon to be on the arXiv...]

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Renormalization group equation(RGE) analysis of 2HDM

→ Useful when investigating parameter space of model.
Can look for finetuning; instabilities; violation of perturbativity and unitarity; etc.

→ There exist plenty of work employing 1-loop RGE equations for scalar or Yukawa sector.

Ex. of recent ones [1001.2561, 1111.5760, 1408.3405, 1505.04001, 1703.05873, 1710.10410, 1803.08521, etc.]

→ More recently, even (Z_2 symmetric) 2-loop RGEs derived with PyR@TE and SARAH.

Chowdhury, Eberhardt [1503.08216]
M.Krauss et.al. [1711.08460, 1807.07581]

→ We have derived the general set of 2-loop RGEs for any, potentially complex, 2HDM and implemented them in, to be publicly available, C++ code.

RGEs were derived using framework in [Machacek & Vaughn 83-84, Luo, Wang, Xiao 02]

→ This talk: comparing parameter space of 2HDM with different choices of Z_2 symmetries imposed on scalar/Yukawa sector.

Notation for 2HDM

→ Generic basis:

$$
\begin{aligned}
-\mathcal{L}_V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 \\
&+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
&+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_1^\dagger \Phi_2\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\}
\end{aligned}
$$

$$
-\mathcal{L}_Y = \bar{Q}_L^0 \cdot \tilde{\Phi}_a \eta_a^{U,0} U_R^0 + \bar{Q}_L^0 \cdot \Phi_a \eta_a^{D,0} D_R^0 + \bar{L}_L^0 \cdot \Phi_a \eta_a^{L,0} E_R^0 + \text{h.c.}\ .
$$

→ For simplicitly, assume CP conservation, i.e. *real basis*.

→ Softly Z_2 breaking parameter: m_{12}^2

→ Hard Z_2 breaking parameters: $\lambda_6,\ \lambda_7$

Notation for 2HDM

→ Scalar potential in Higgs basis:

$$-\mathcal{L}_V = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left(Y_3 H_1^\dagger H_2 + h.c.\right) + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2$$
$$+ \frac{1}{2} Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{1}{2} Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\}.$$

→ Yukawa sector in fermion mass basis:

$$-\mathcal{L}_Y = \bar{Q}_L \tilde{H}_1 \kappa^U U_R + \bar{Q}_L H_1 \kappa^D D_R + \bar{L}_L H_1 \kappa^L E_R$$
$$+ \bar{Q}_L \tilde{H}_2 \rho^U U_R + \bar{Q}_L H_2 \rho^D D_R + \bar{L}_L H_2 \rho^L E_R + \text{h.c.},$$

→ κ^F diagonal mass matrices.
ρ^F arbitrary complex matrices.

→ If Z_2 symmetric: $\rho^F \propto \kappa^F$

Z_2 symmetry scenarios

→ Four CP conserving scenarios:

→ I) Exact Z_2 symmetry.
→ II) Softly broken Z_2 symmetry:

$$0 \neq m_{12}^2 \in \mathbb{R}$$

→ III) Hard broken Z_2 in scalar sector:

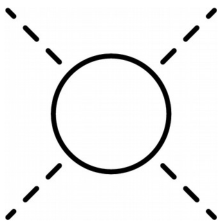
$$0 \neq \lambda_6, \lambda_7 \in \mathbb{R}$$

→ IV) Hard broken Z_2 in Yukawa sector by a disalignment ansatz:

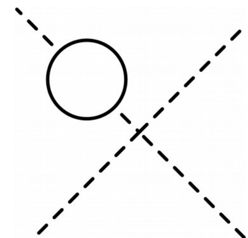
$$\rho^F = a^F \kappa^F, \; a^F \in \mathbb{R}$$

2-loop RGEs of 2HDM

→ At 1-loop, Yukawa evolves independently from scalar sector.
But, Yukawa couplings enter in quartics beta functions through:

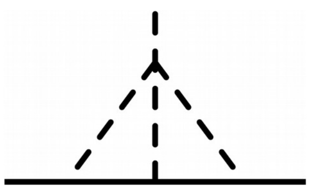


$$\Rightarrow \beta_\lambda \supset \mathrm{tr}(\eta^4)$$

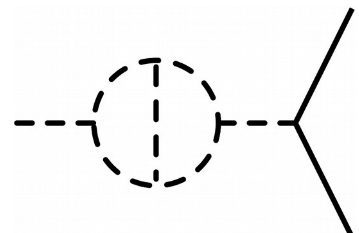


$$\Rightarrow \beta_\lambda \supset \lambda \mathrm{tr}(\eta^2)$$

→ At 2-loop, Yukawa sector get contributions from quartics:



$$\Rightarrow \beta_\eta \supset \lambda \eta^3$$



$$\Rightarrow \beta_\eta \supset \lambda^2 \eta$$

→ A small breaking of Z_2 at one scale will spread in the RG evolution and induce additional Z_2 breaking parameters.

RG evolution algorithm

→ Start at top mass scale. Generate a tree-lvl stable, unitary and perturbative parameter point with 125 GeV Higgs boson.

1-loop corrected mass using [Spheno]

→ Solve the coupled ODE system for the 129 real parameters in the generic basis.

Using libraries [GSL, Eigen]

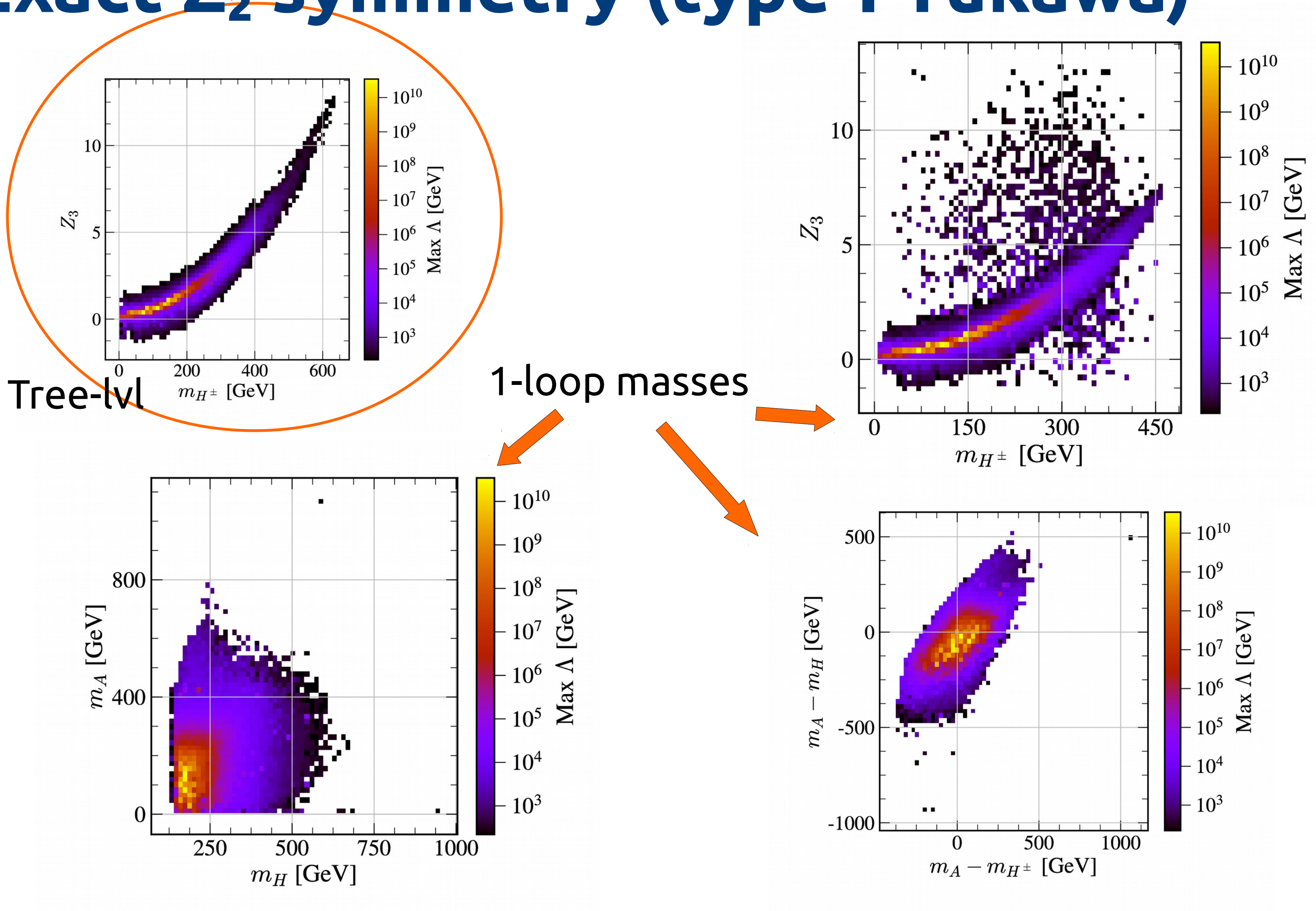
→ The VEVs evolve according to the anomalous dimensions. This means that β runs.

→ The transformation to the Higgs basis and diagonalization of the Yukawa sector is performed at each step in the evolution.

→ The breakdown energy Λ refers to lowest energy where either perturbativity, unitarity or stability is violated.

Scenario I: Exact Z_2 symmetry

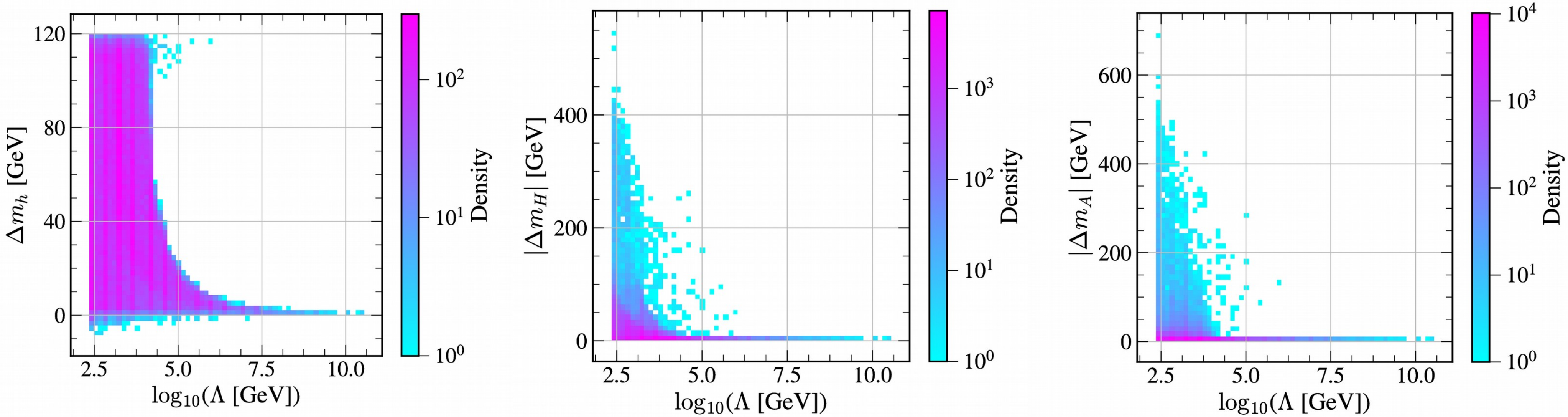
Exact Z_2 symmetry (type-I Yukawa)



Exact Z_2 symmetry (type-I Yukawa)

→ Large loop corrections for scalar masses.

See also [1711.08460, 1807.07581]



→ Large quartic couplings responsible,
i.e. points break down fast in RG evolution.

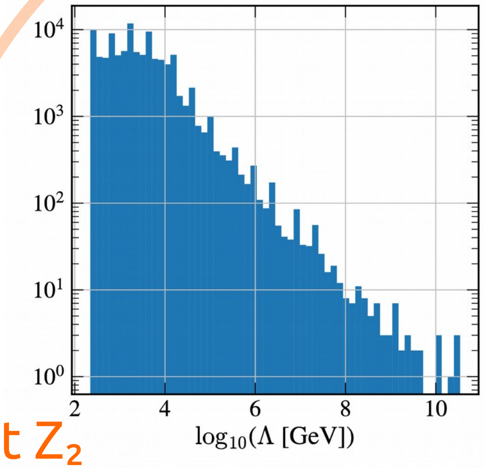
→ Higher order quantum corrections vital in these regions.

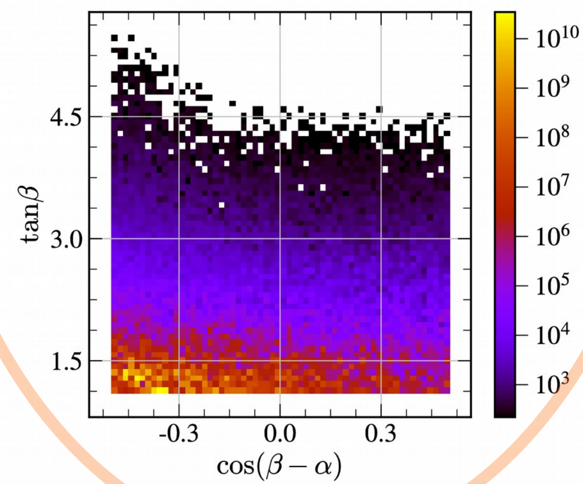
Scenario II: Softly broken Z_2 symmetry

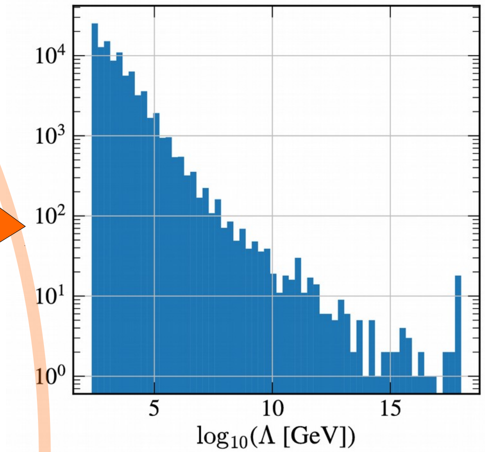
Softly broken Z_2 symmetry

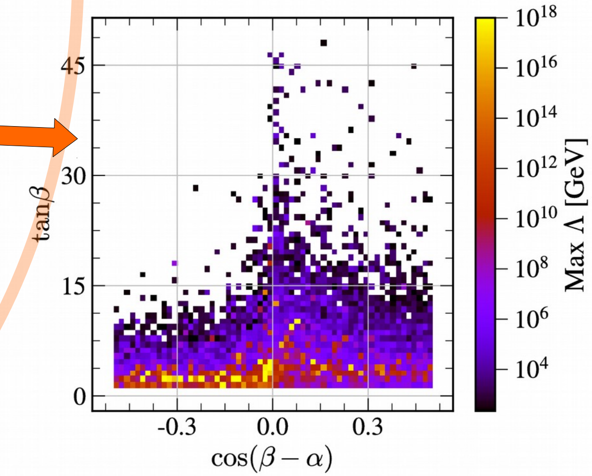
→ Soft Z_2 breaking opens up parameter space that is stable all the way to the Planck scale.

Exact Z_2



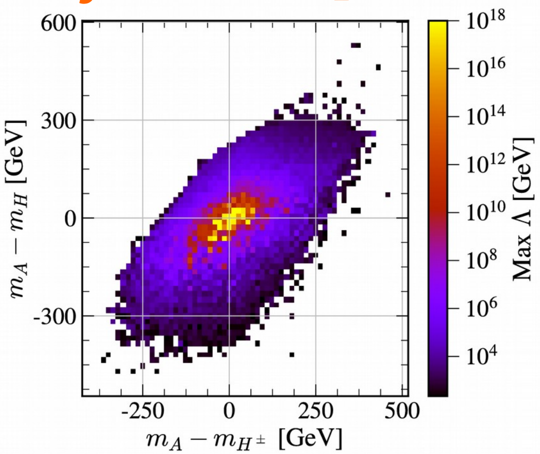


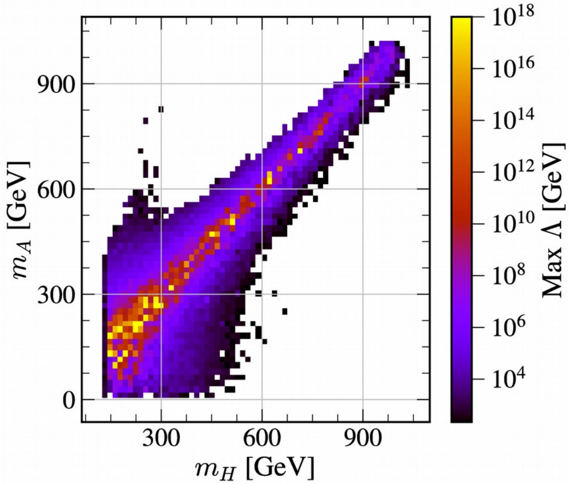




Softly broken Z_2

Softly broken Z_2



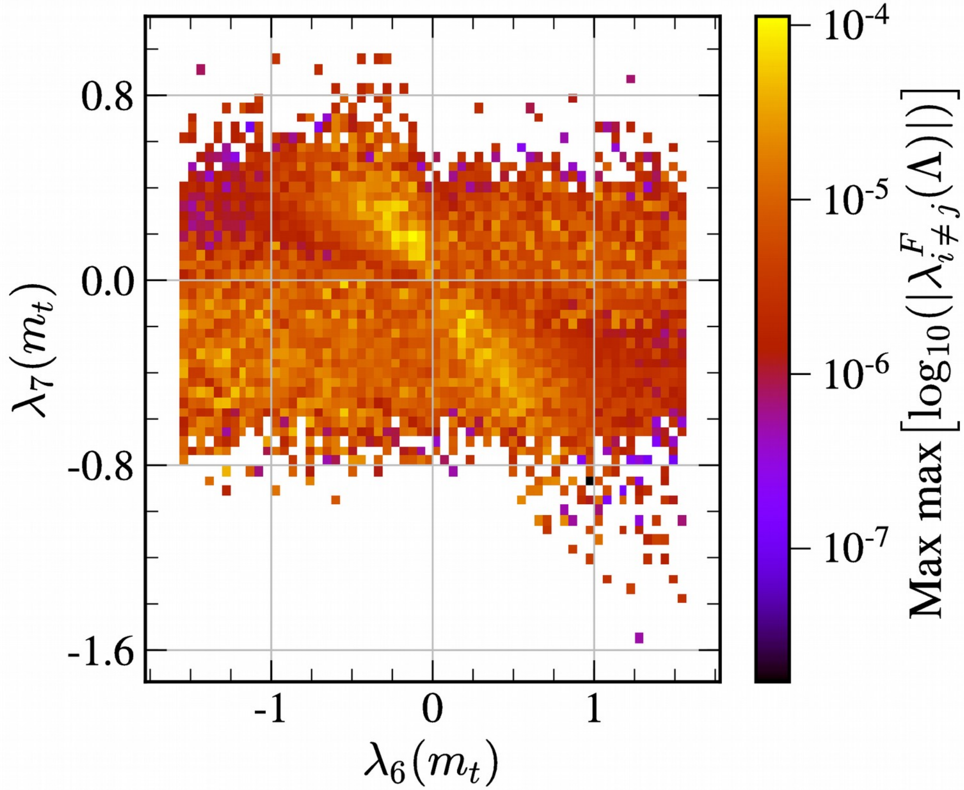


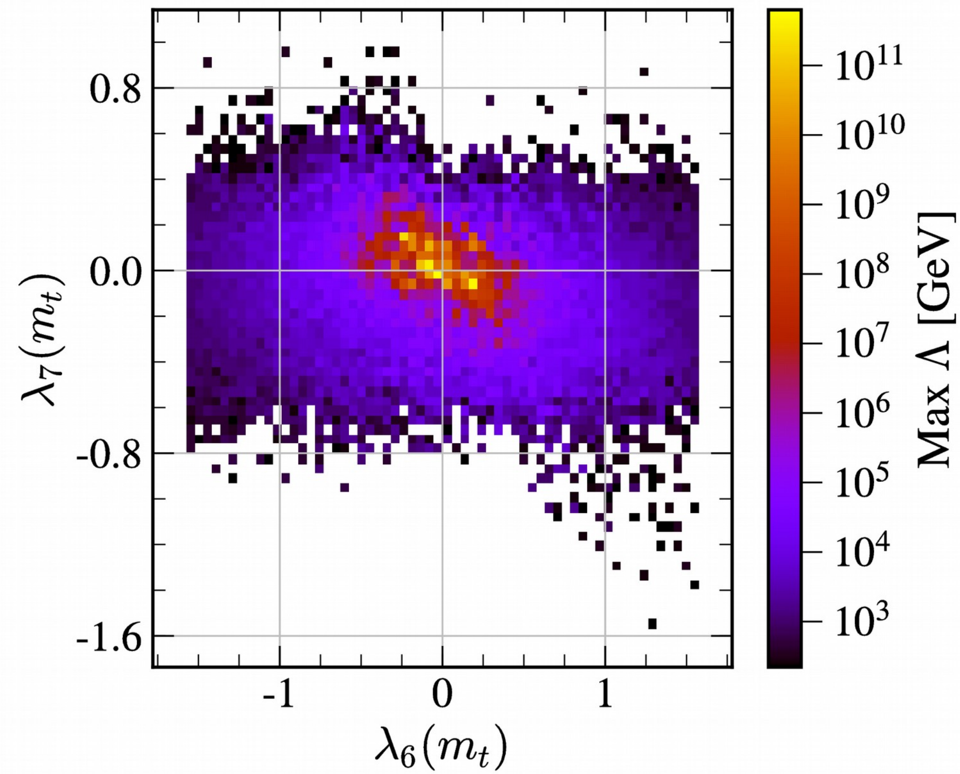
Scenario III: Hard broken Z_2 symmetry in scalar sector

Hard broken Z_2 symmetry

→ Breaking the Z_2 symmetry hard by having non-zero λ_6, λ_7 makes it much harder to get "good" parameter points.

→ The symmetry of the Yukawa sector is lost in the RG evolution and non-diagonal FCNC are induced.





→ Parametrized by Cheng-Sher ansatz:

$$\rho_{ij}^F = \lambda_{ij}^F \sqrt{\frac{2 m_i^F m_j^F}{v^2}}$$

Approximate limit: $\lambda_{i \neq j} \leq 0.1$

[1111.5760]

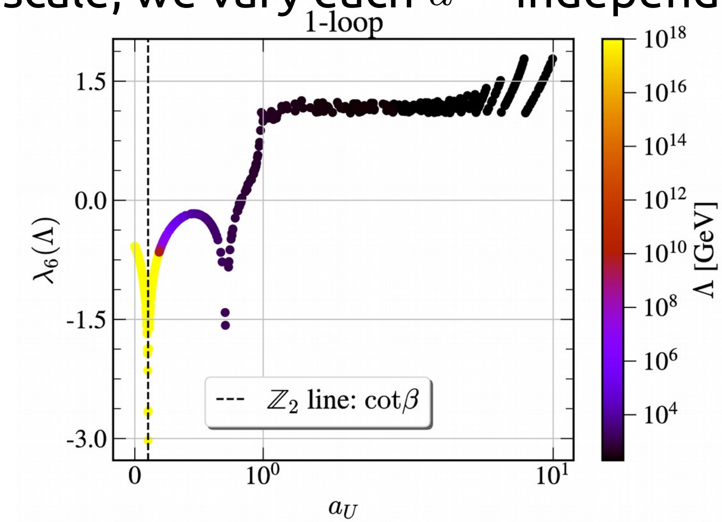
Scenario IV: Disalignment of Z_2 symmetry in Yukawa sector

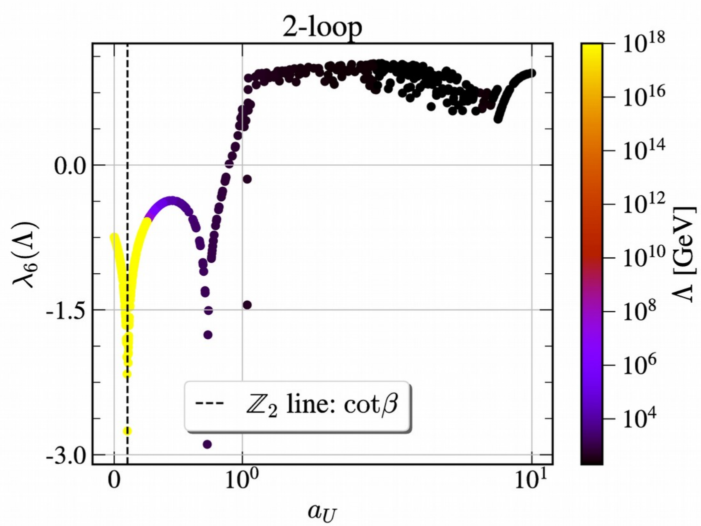
Yukawa breaking of Z_2 symmetry

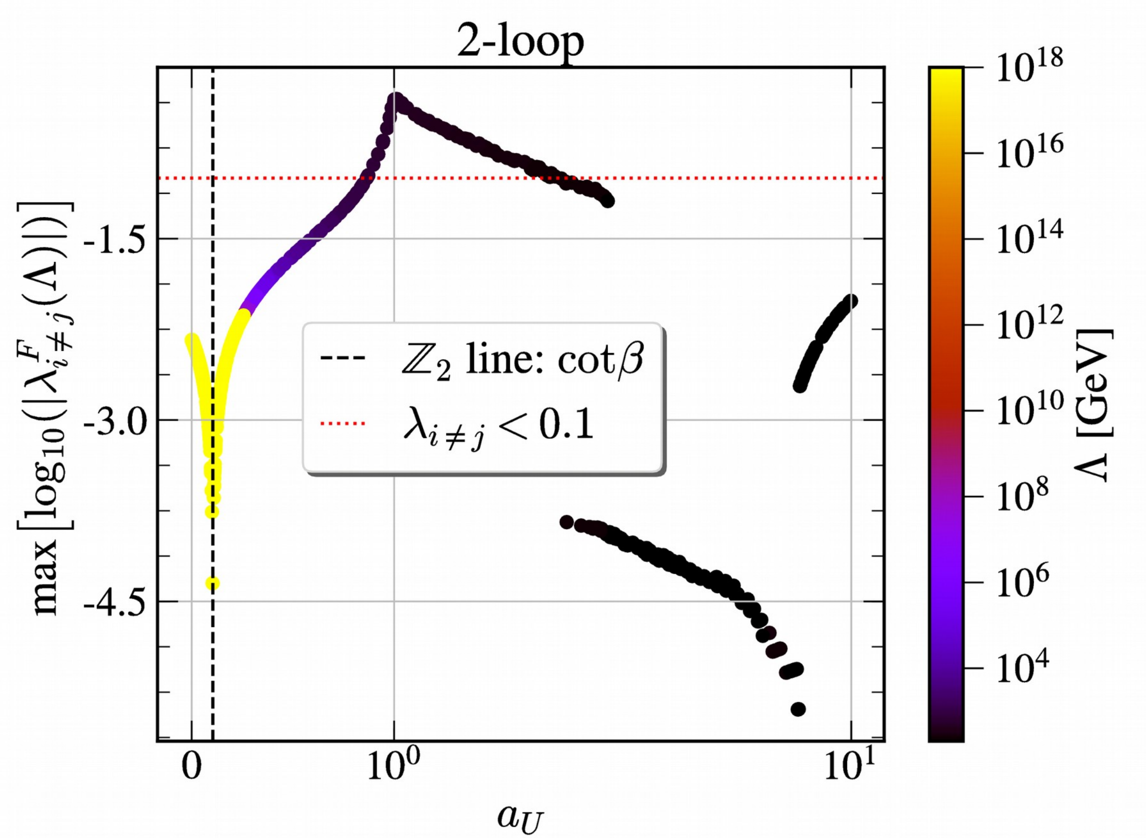
→ To measure Z_2 breaking in Yukawa sector. We set at top mass scale an (dis)alignment ansatz with real coefficients:

$$\rho^F = a^F \kappa^F$$

→ Starting from a softly broken Z_2 parameter point that is valid all the way to the Planck scale, we vary each a^F independently.

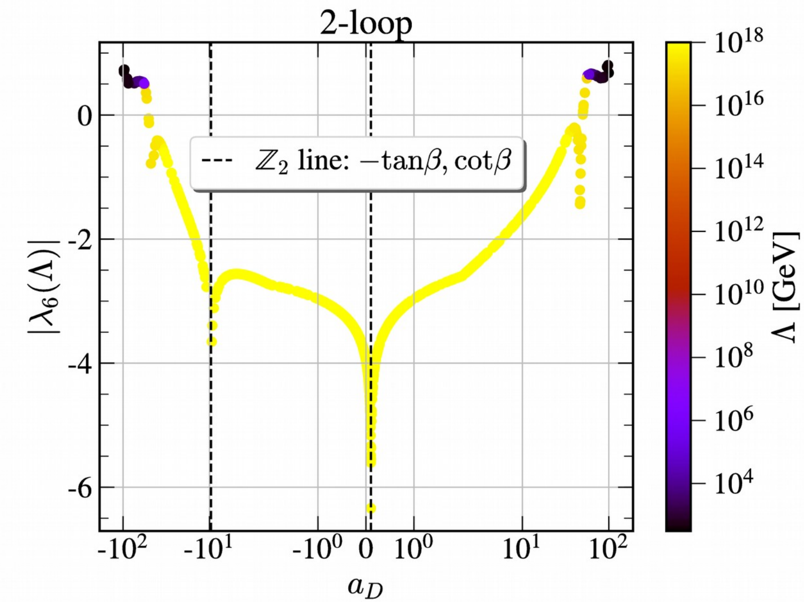


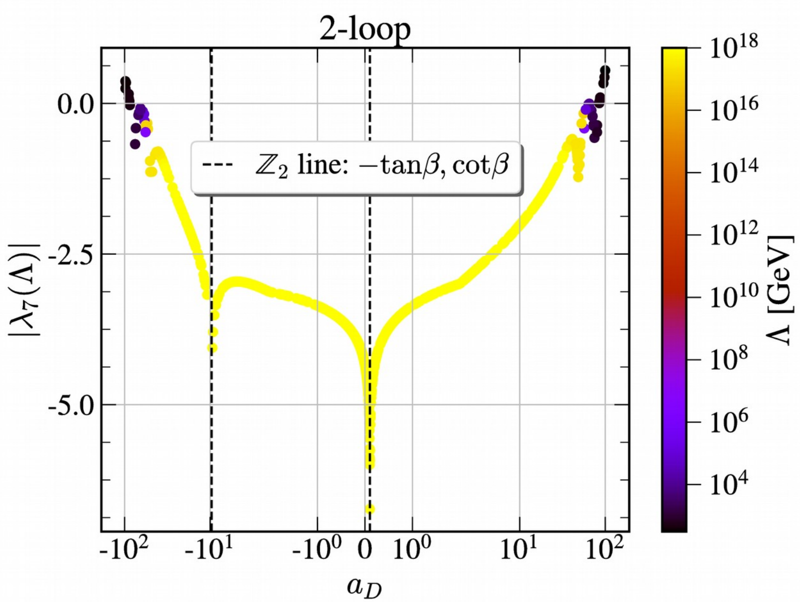


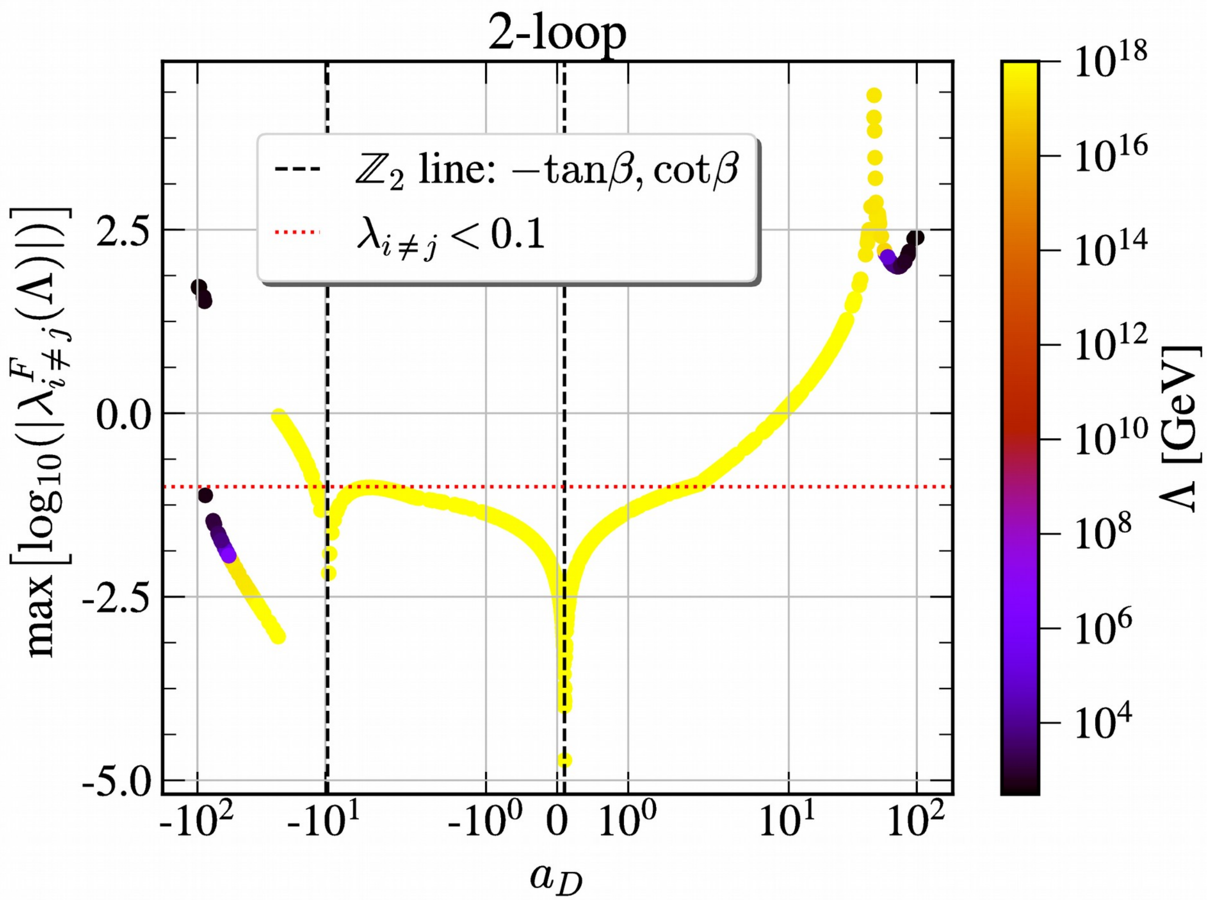


Yukawa breaking of Z_2 symmetry

→ Down sector:

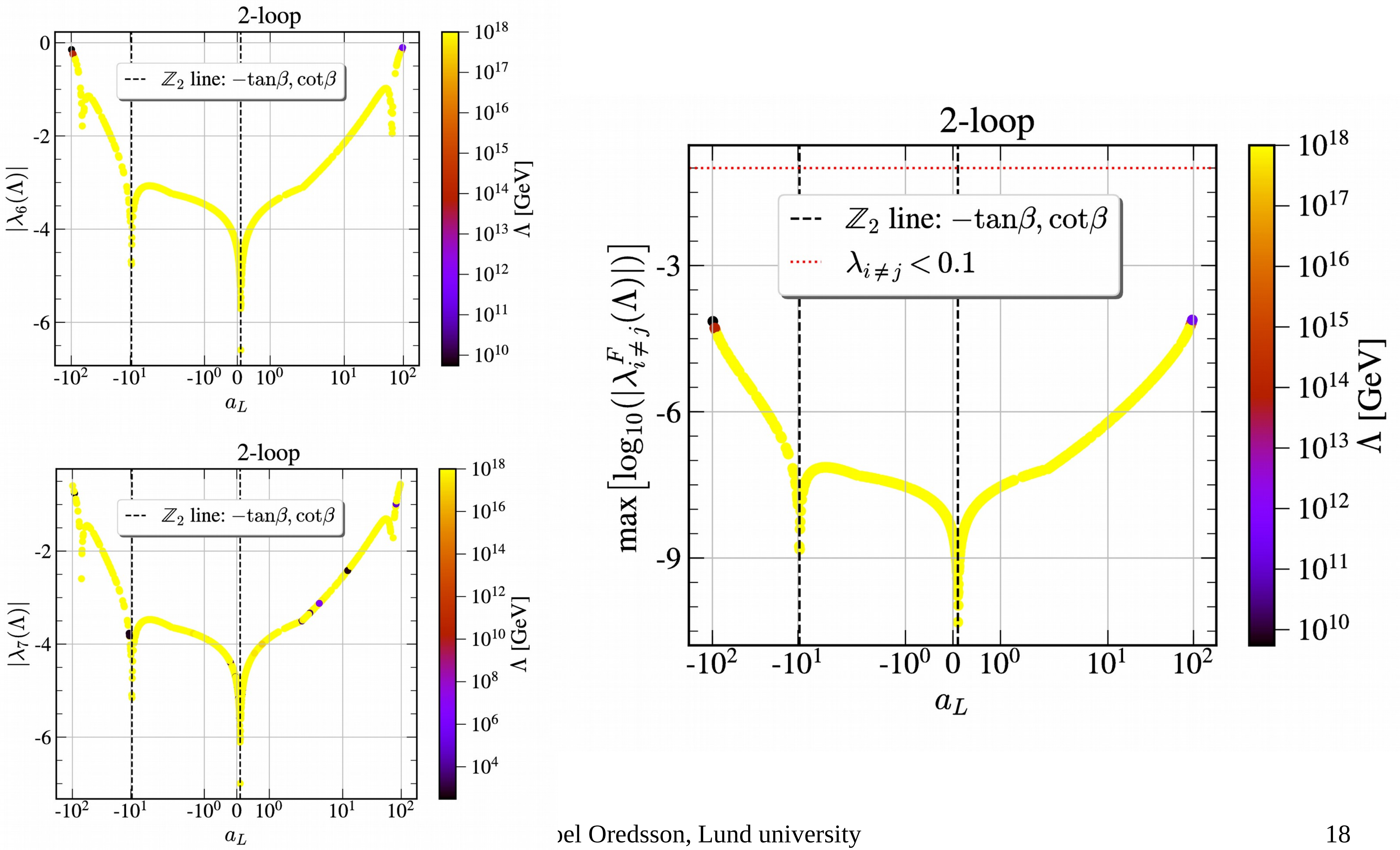






Yukawa breaking of Z_2 symmetry

→ Lepton sector:



Conclusions

→ Derived and implemented 2-loop RGEs for the general, potentially complex, 2HDM.

→ Investigated the parameter space of a CP conserving 2HDM with different levels of Z_2 breaking in the scalar sector.

→ The scenario of an exact Z_2 is very constrained.

→ Breaking the Z_2 symmetry softly opens up parameter space that is valid to higher energies, even all the way to the Planck scale.

→ Hard breaking in the scalar sector spreads fast unless some sort of fine-tuning is present.

→ Even though the non-zero λ_6, λ_7 induces non-diagonal FCNCs in RG running, the problems in the scalar sector are more urgent.

→ A Z_2 breaking Yukawa sector generates non-zero λ_6, λ_7 already at 1-loop order.

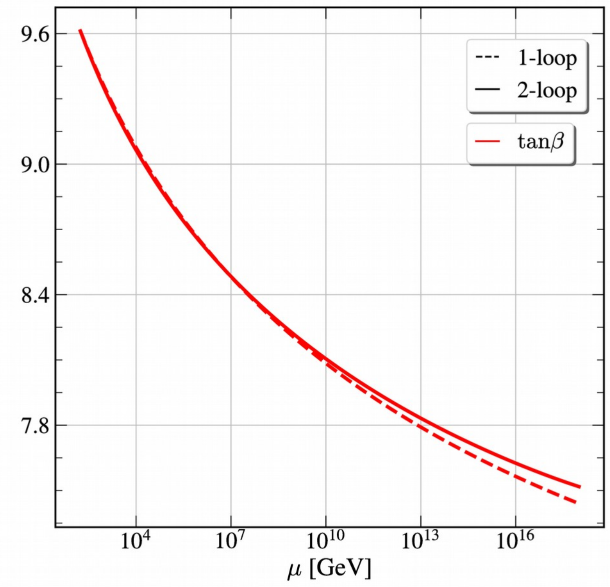
→ The up sector is sensitive and generates non-trivial λ_6, λ_7 that decreases the energy range of parameter points substantially.

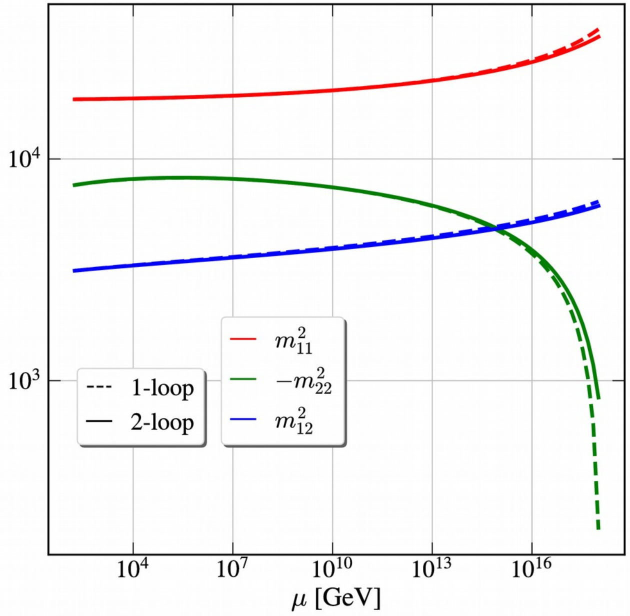
→ One could allow for some misalignment in the down/lepton sector, in that one could still have a “good” scalar potential at all energies, but one generates non-trivial FCNCs.

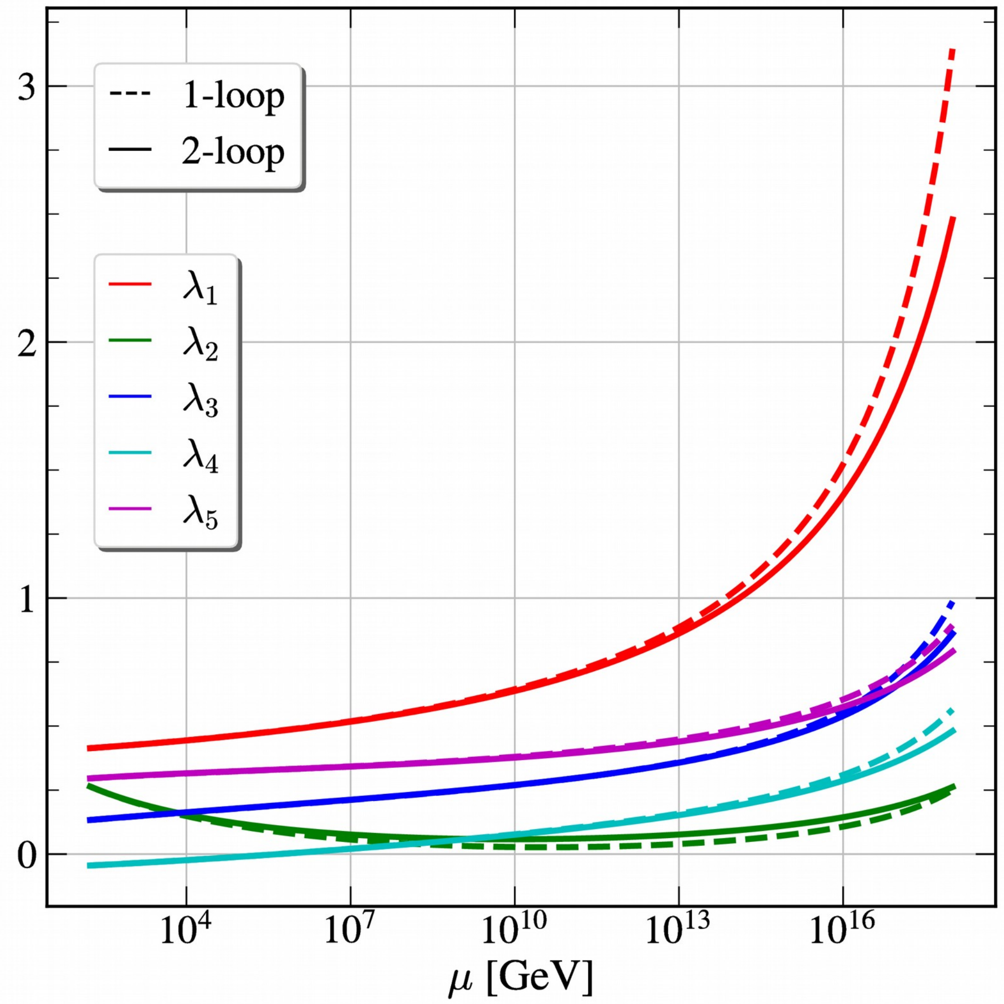
Thank you for your attention!

Backup: Example parameter point

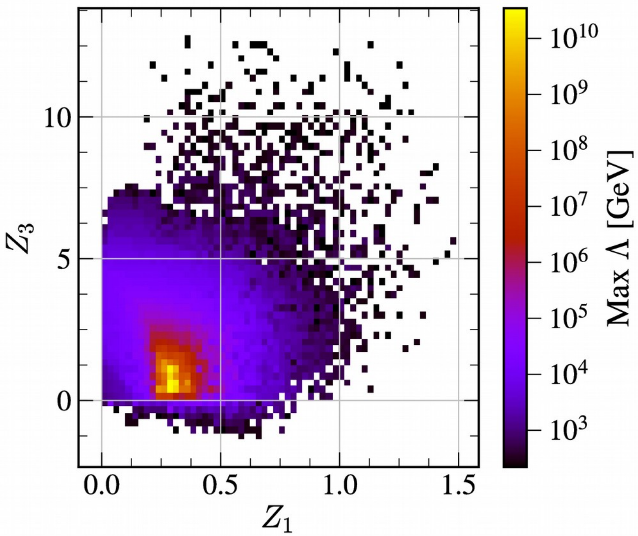
→ RG evolution of example parameter point used in Yukawa (dis)alignment scan.

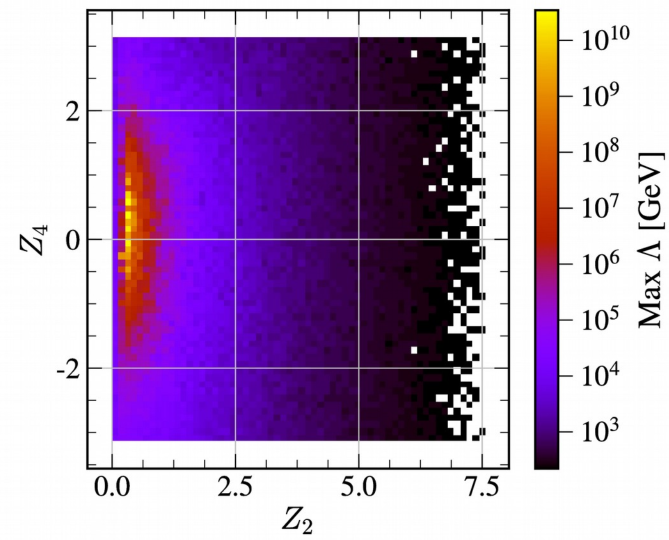


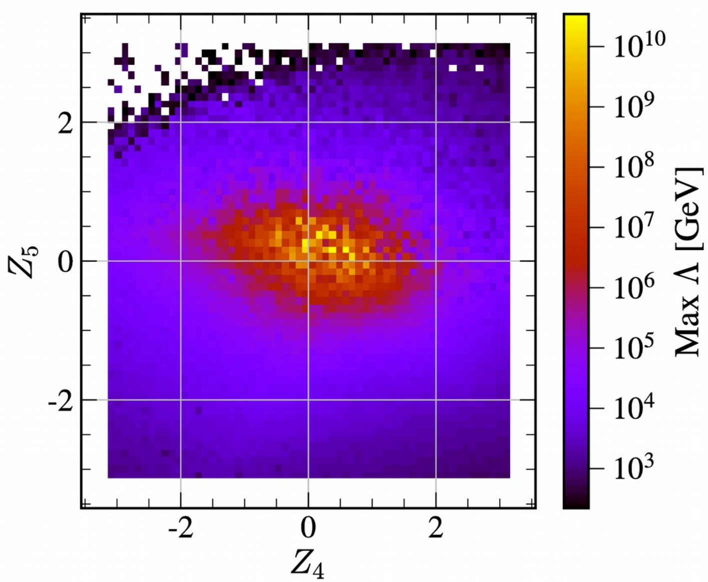


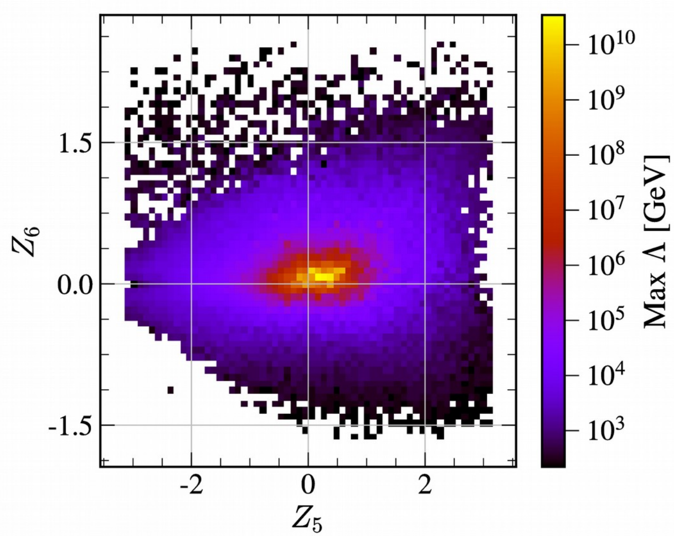


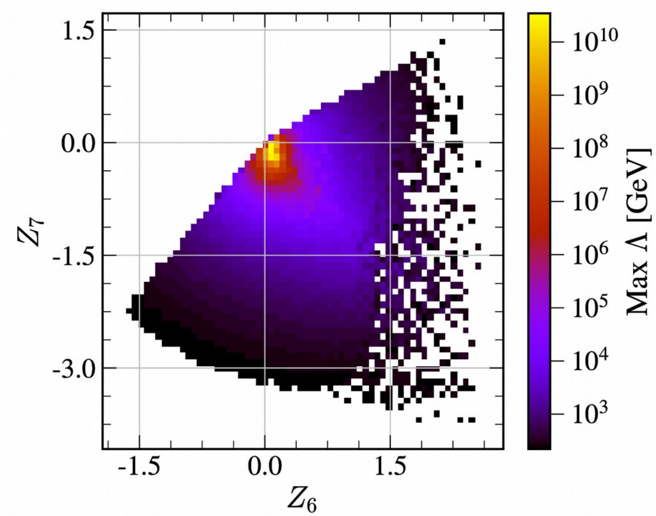
Backup: Higgs basis, exact Z_2 symmetry



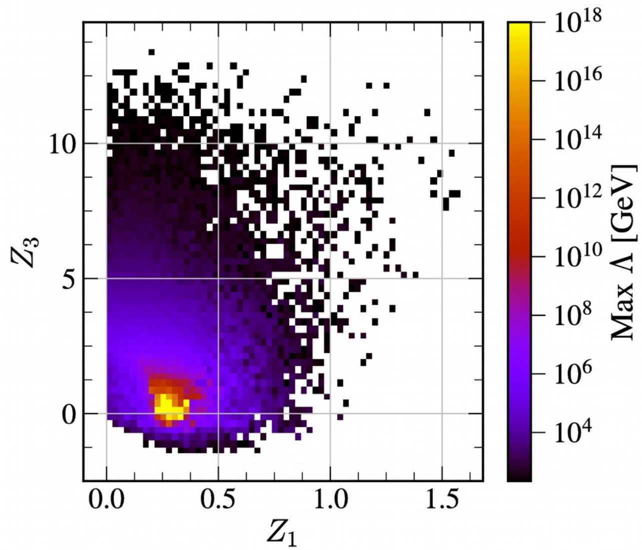


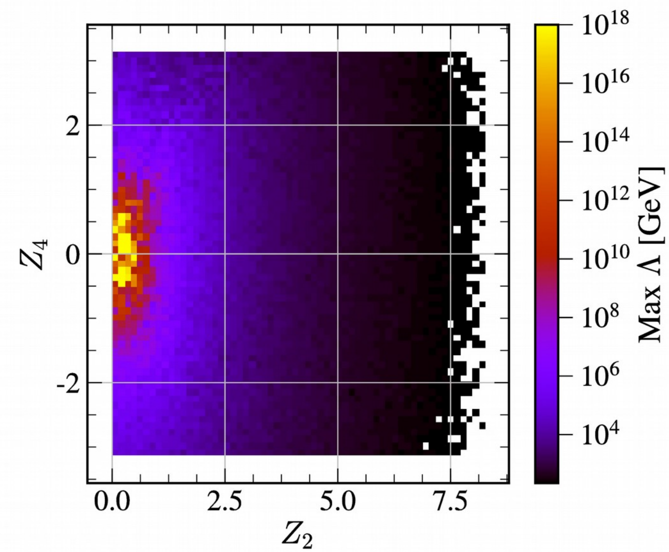


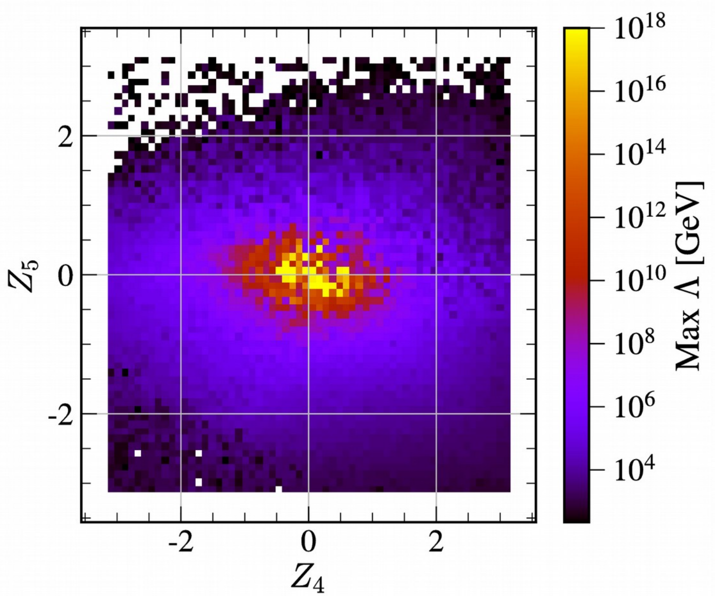


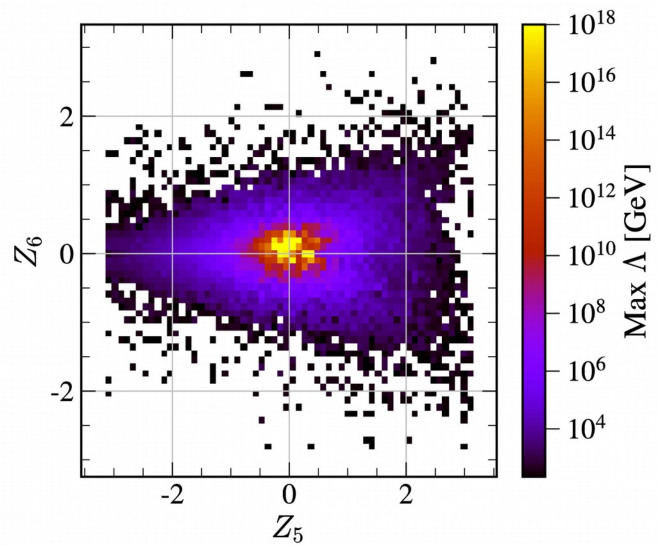


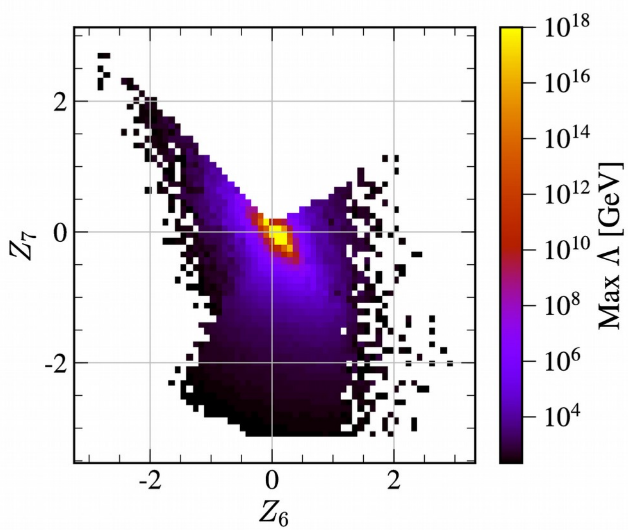
Backup: Higgs basis, softly broken Z_2











Backup: Higgs basis, hard broken Z_2