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Pyr@te

Python RGEs at Two-Loop

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Goal

Generate the RGEs for non-supersymmetic theories @ 2-loop

- No evidence of SUSY so far
- Could have shown up in many places
  - $(g-2)_\mu,\ B_s \to \mu^+\mu^-,\ b \to s\gamma, \ldots$
  - collider experiments
  - direct DM detection experiments
- Alternatives to SUSY are becoming more interesting
- One possible application: constraining non-SUSY BSM models via the stability bound (see end of talk)

- RGEs for general gauge theories known for a long time:
  - *M. Machacek and M. T. Vaughn, 1983 Nuc.Phys.B222*
  - *M. Luo et al. Phys.Rev. D67 (2003) 065019*
- Calculation of beta functions "by hand" is time consuming and prone to error ⇒ Difficult to use in practice.
- Full set of 2-loop RGEs known only for few specific cases:
  - SM + Neutrinos from *A. Wingerter Phys.Rev. D84 (2011) 095012*
  - SM + chiral fourth generation

  from *C. Cheung et al. JHEP 1207 (2012) 105*
  - SM + real singlet scalar
  - SM + real triplet scalar
  - SM + complex doublet scalar
  - ...

SUSY

- SARAH *Comp. Phys. Com. 182 (2011) pp. 808-833* (spectrum generator generator)
- SUSYNO *Comput.Phys.Commun. 183 (2012) 2298-2306*

NON-SUSY

- **PyR@TE** cross checked with the beta version of SARAH 4.0.

Definition

$G_1 \times G_2 \times \cdots \times G_n$ direct product of simple groups

$$\begin{aligned}
\mathcal{L} \supset \quad & - \quad N_a Y^a_{jk} \psi_j \xi \psi_k \phi_a + h.c. \Rightarrow \beta^a_{jk} \\
& - \quad N_\lambda \lambda_{abcd} \phi_a \phi_b \phi_c \phi_d \Rightarrow \beta_{abcd} \\
& - \quad N_{mf} (mf)_{jk} \psi_j \xi \psi_k + h.c. \Rightarrow (\beta_{mf})_{jk} \\
& - \quad N_{mab} m^2_{ab} \phi_a \phi_b \Rightarrow \beta_{ab} \\
& - \quad N_h \phi_a \phi_b \phi_c \Rightarrow \beta_{abc},
\end{aligned}$$

$\Rightarrow$ 6 types of beta functions to calculate:

- $\beta(g) \Rightarrow$ gauge couplings
- $\beta^a_{jk} \Rightarrow$ yukawas
- $\beta_{abcd} \Rightarrow$ quartic couplings
- $\beta_{ab} \Rightarrow$ scalar mass
- $(\beta_{mf})_{jk} \Rightarrow$ fermion mass
- $\beta_{abc} \Rightarrow$ trilinear couplings

The Quartic terms

- New beta functions with respect to the SUSY case.
- One needs the explicit matrices of the representation for the scalars :

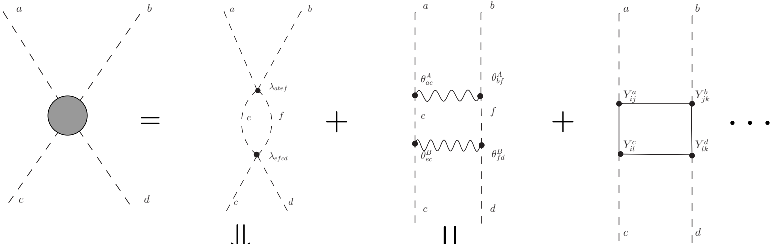
$$D_\mu \phi_a = \partial_\mu \phi_a - ig\theta^A_{ab} V^A_\mu \phi_b$$

- The θ^A_{ab} matrices are assumed to be purely imaginary and antisymmetric in the calculation. $\Rightarrow$ Hermitian Basis

$$L^1_{\phi_h} = \frac{i}{2}\begin{pmatrix} 0 & \tau^1 \\ -\tau^1 & 0 \end{pmatrix},\ L^2_{\phi_h} = \frac{1}{2}\begin{pmatrix} \tau^2 & 0 \\ 0 & \tau^2 \end{pmatrix},\ L^3_{\phi_h} = \frac{i}{2}\begin{pmatrix} 0 & \tau^3 \\ -\tau^3 & 0 \end{pmatrix}$$

$$\phi_h = (\phi_1, \phi_2, \phi_3, \phi_4)^T, \phi^+ = (\phi_1 + i\phi_2)/\sqrt{2}, \phi^0 = (\phi_3 + i\phi^4)/\sqrt{2}$$

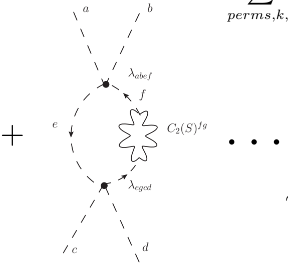
The Quartic Terms



$$\sim \sum_{perm} \lambda_{abef}\lambda_{efcd}$$

$$\sim \sum_{perms,k,l} g^{2k} g^{2l} \{\theta^A, \theta^B\}_{ab} \{\theta^A, \theta^B\}_{cd}$$

$$\sim \sum_{perms} \sum_{i,j,k,l} Y^a_{ij} Y^{b\dagger}_{jk} Y^c_{kl} Y^{d\dagger}_{li}$$



$$\sim \sum_{perm} g^2 C_2^{fg}(S) \lambda_{abef}\lambda_{cdeg}$$

Goal

- Public code for any non-SUSY theories at 2-loop
- Any gauge group (with single $U(1)$ factor)

Status

- beta version working with SM gauge groups
- LateX output ready
- SM + one real scalar field $\Rightarrow$ Trilinear terms
  SM + t' vector like quark $\Rightarrow$ Fermion mass terms
- Collaborator F. Staub implemented same RGEs in SARAH 4 (unpublished) $\Rightarrow$ independent cross check.

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TODO :

- Extend the group part i.e. get the CGCs as well as the matrix representation (following R. Fonseca, hep-ph/1106.5016)
- Interface to C++,. . .

Structure of PyR@TE

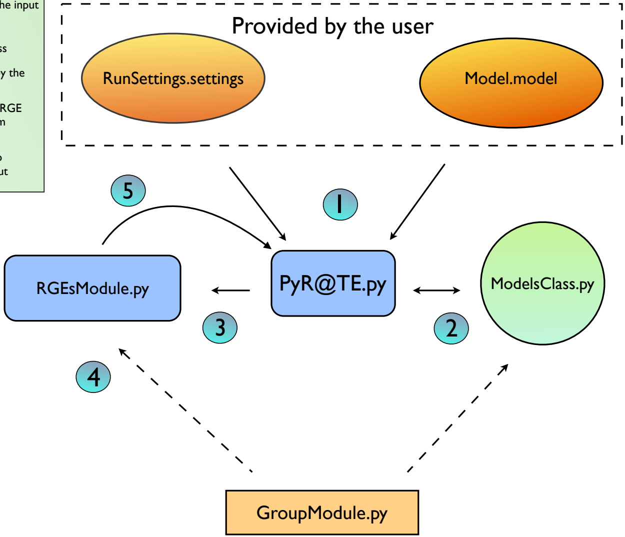
1 : read the settings from the input files

2 : construct the Model class

3 : each RGE is calculated by the RGEsModule

4 : the calculation of each RGE requires information from GroupModule.py

5 : the result is sent back to PyR@TE.py for final output



Input files

- *.model* and *.settings* files are required to run.

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  - Author Date Name

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  - Potential ⇒ is given in a similar way.

Vector like t' model

Vector like quarks

One of the simplest extension of the SM

- One vector like $t' \sim (3,1)_{4/3} \Rightarrow$ vector like mass.

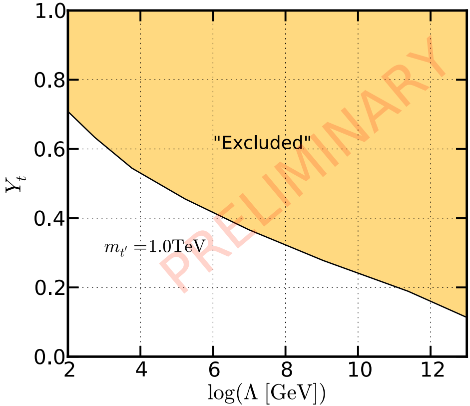
Lagrangian

$$\mathcal{L} \supset \quad \mathcal{L}_{SM} - \underbrace{m_t t_L'^{\dagger} t_R'}_{\beta_{m_t}} - \underbrace{Y_t^i \bar{Q}^i H t_R'}_{\beta_{Y_t}}$$

- t' modifies the RGEs $\Rightarrow Y_t$ enters β_λ at 1-loop.
- Constrains from *Wtb* and T parameter by G. Cacciapaglia et al. *JHEP11(2010)159*
  for $m_{t'} \simeq 500\ \mathrm{GeV} \Rightarrow Y_t \sim 0.8$ excluded

Stability Bound

- Estimated the stability bound for this model.
- No matching corrections for now.
- Possibility of extracting constrains in the plane (Y_t, Λ).
- Very small dependence on m_t'



Conclusion and outlook

- No experimental evidence for SUSY so far.
- For a more systematic study of non SUSY models RGEs are needed.
- We are working on a tool that generates RGEs @2-loop $\Rightarrow$ PyR@TE
- Group Theory part has to be finalized
- Have fun !