Séminaire des doctorants

PyR@TE: Python Renormalization Group Equations @ Two-loop

Florian Lyonnet

Theory Group

under the supervision of Ingo Schienbein

Laboratoire de Physique Subatomique et de Cosmologie
Université Joseph Fourier, Grenoble

June, 12 2013

PyR@TE-Motivations

Description

- Python RGEs @ Two-loop
- Goal: Generate the **Renormalization Group Equations** for non-supersymmetic theories @ 2-loop

PyR@TE-Motivations

Description

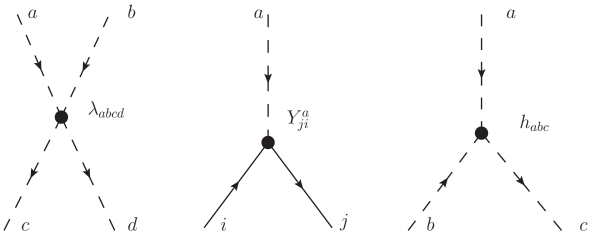
- Python RGEs @ Two-loop
- Goal: Generate the **Renormalization Group Equations** for non-supersymmetic theories @ 2-loop

Why ?

- No evidence of SUSY so far
- Systematic studies of non-SUSY models require the RGEs
- One possible application: constraining non-SUSY BSM models via the stability bound

Renormalization Group Equations

- Renormalization scale μ
  $\Rightarrow g_{10}, \alpha_{S0}, \lambda_0 \cdots \Rightarrow \tilde{g}_1(\mu), \tilde{\alpha}_S(\mu), \tilde{\lambda}(\mu)$.
- RGEs : ensure the invariance of the observables.
  - e.g. : $\mu \frac{d}{d\mu}\tilde{\alpha}_S(\mu) = \beta_{\alpha_S}$



- β functions depend on the theory i.e. **particles and gauge groups**.
- Can be calculated in perturbation theory.

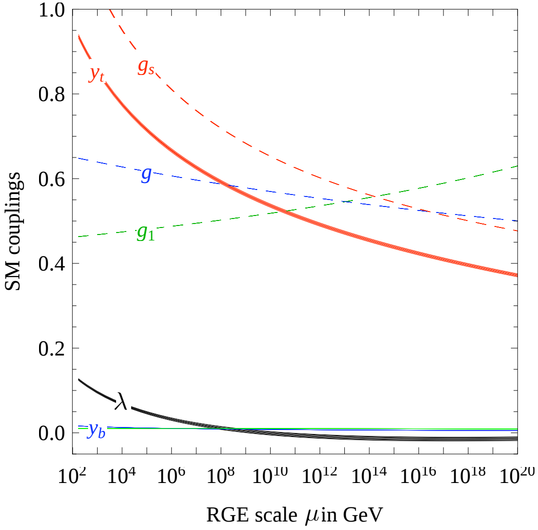


Fig: Higgs mass and vacuum stability in the SM at NNLO, *G. Degrassi et al.*

- 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 $\Rightarrow$ 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
  - ...

Definition

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

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

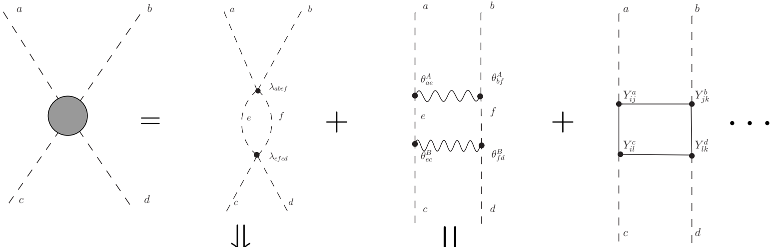
$\Rightarrow$ 6 types of beta functions to calculate:

- $\beta(g) \Rightarrow$ 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

e.g. SM

- $SU(3) \times SU(2) \times U(1) \Rightarrow \beta_{g_1}, \beta_{g_2}, \beta_{g_3}$
- $Y_u \bar{Q} H^c u_R \Rightarrow \beta_{Y_u} (\beta_{Y_d}, \beta_{Y_l})$
- $\lambda (H^\dagger H)^2 \Rightarrow \beta_\lambda$
- $\mu (H^\dagger H) \Rightarrow \beta_\mu$

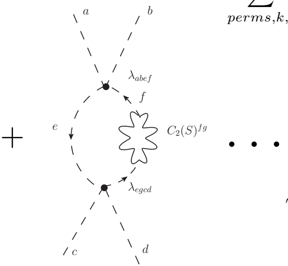
The Quartic Terms



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

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

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



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

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 ⇒ Trilinear terms
  SM + t' vector like quark ⇒ Fermion mass terms
- Collaborator F. Staub implemented same RGEs in SARAH 4 (unpublished) ⇒ independent cross check.

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.

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

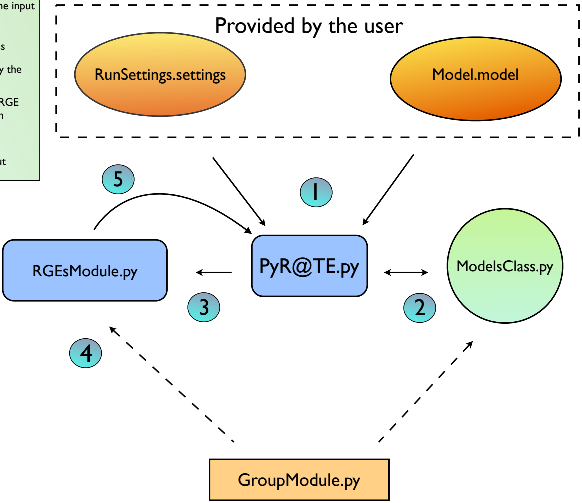
1 : read the settings from the input files

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.

.model

- we are using text files from the input (YAML)
- keys :
  - Author Date Name

    e.g. Name : SMtp

Input files

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

.model

- we are using text files from the input (YAML)
- keys :
  - Author Date Name

    e.g. Name : SMtp
  - *Groups* : GroupName: Group

    e.g. SU2L: SU2

Input files

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

.model

- we are using text files from the input (YAML)
- keys :
  - Author Date Name

    e.g. Name : SMtp
  - *Groups* : GroupName: Group

    e.g. SU2L: SU2
  - *Fermions*: Label: Gen: ng, Qnb:{GroupName:value}

    e.g. Q: Gen: ng, Qnb:{ U1: 1/3, SU2L: 2, SU3c: 3}

Input files

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

.model

- we are using text files from the input (YAML)
- keys :
  - Author Date Name

    e.g. Name : SMtp
  - *Groups* : GroupName: Group

    e.g. SU2L: SU2
  - *Fermions*: Label: Gen: ng, Qnb:{GroupName:value}

    e.g. Q: Gen: ng, Qnb:{ U1: 1/3, SU2L: 2, SU3c: 3}
  - Potential $\Rightarrow$ is given in a similar way.

    e.g. $\mathrm{Y}_t : \{Fields : [tpR, Q, H], Norm : 1, latex : Y_t\}$

Higgs Potential

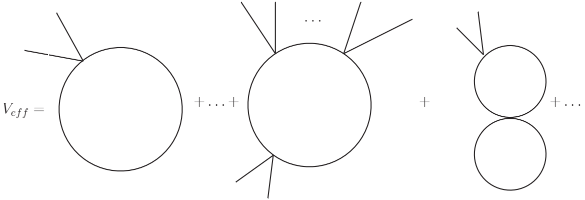
- At the classical level ⇒ $V_{SM}(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$
  - "Higgs Miracle" ⇒ allow us to give mass to the vector bosons
  - Include all the terms that are gauge invariant and renormalizable
  - Potential gives the energy density of the field.

- Equivalent of $V(\phi)$ which takes into account all the radiative processes ⇒ $V_{eff}(\phi_c)$
  - The effective potential will give the energy density of $\phi_c = \langle\phi\rangle$ **including the quantum effects**
  - Needs to take into account all the possible processes !

Higgs Potential

- At the classical level $\Rightarrow V_{SM}(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$
  - "Higgs Miracle" $\Rightarrow$ allow us to give mass to the vector bosons
  - Include all the terms that are gauge invariant and renormalizable
  - Potential gives the energy density of the field.

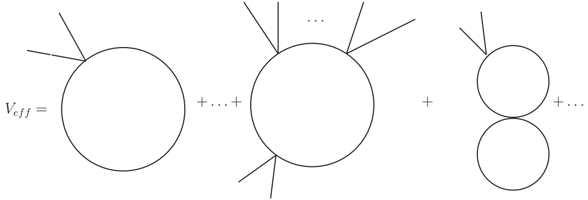
- Equivalent of $V(\phi)$ which takes into account all the radiative processes $\Rightarrow V_{eff}(\phi_c)$
  - The effective potential will give the energy density of $\phi_c = \langle\phi\rangle$ **including the quantum effects**
  - Needs to take into account all the possible processes !



Higgs Potential

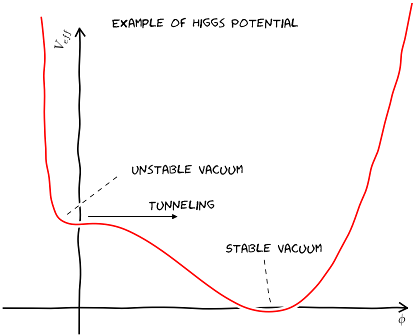
- At the classical level $\Rightarrow V_{SM}(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$
  - "Higgs Miracle" $\Rightarrow$ allow us to give mass to the vector bosons
  - Include all the terms that are gauge invariant and renormalizable
  - Potential gives the energy density of the field.

- Equivalent of $V(\phi)$ which takes into account all the radiative processes $\Rightarrow V_{eff}(\phi_c)$
  - The effective potential will give the energy density of $\phi_c = \langle\phi\rangle$ **including the quantum effects**
  - Needs to take into account all the possible processes !



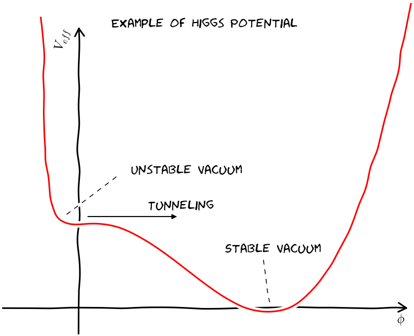
Stability bound

- Our existence demands that the minimum of the EW potential be stable !
  - Stable : Only one minimum
  - Potential Stable up to scale $\Lambda \Leftrightarrow \lambda(\Lambda) > 0$



Stability bound

- Our existence demands that the minimum of the EW potential be stable !
  - Stable : Only one minimum
  - Potential Stable up to scale $\Lambda \Leftrightarrow \lambda(\Lambda) > 0$
- $\lambda(\mu)$ calculated from β_λ, depends on $m_H, m_t, \ldots$
- Stability bound :
  - Curve $\Lambda(m_H) \Rightarrow$ gives $m_{H_{max}}$ so that the theory be valid up to Λ



Calculating the Stability bound

Take a value of $m_H(m_Z)$

↓ Fix the other parameters

RGEs with Pyr@te

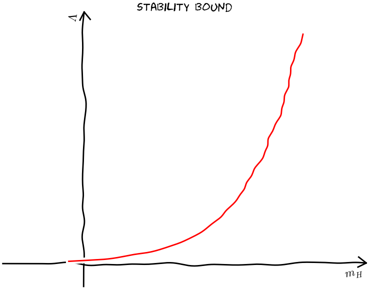
↓ Use β_λ

Find $\Lambda_{max} \,!\, \lambda(\Lambda_{max}) = 0$

↓

Store $(\Lambda_{max}, m_H(m_Z))$

Iterate



Stability bound SM

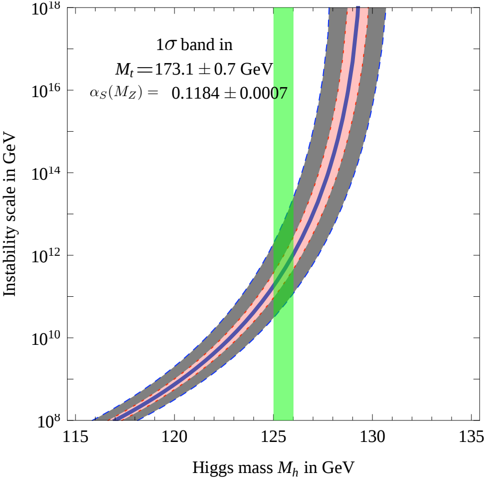


Fig: Higgs mass and vacuum stability in the SM at NNLO, *G. Degrassi et al.*

Vector like t' model

Vector like quarks

L, R components $\Rightarrow$ same transformation

One of the simplest extension of the SM

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

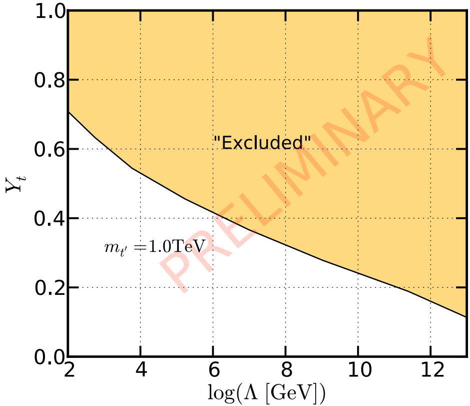
Lagrangian

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

- 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 $m_{t'} \simeq 500$ GeV $\Rightarrow Y_t \sim 0.8$ excluded

Stability Bound

- For a given $Y_t(m_{t'})$
  - Estimate the stab. bound.
  - Intersection with $m_H = 125\ \mathrm{GeV} \Rightarrow (\Lambda, Y_t(m_{t'}))$
- Possibility of extracting constrains in the plane (Y_t, Λ).
- Very small dependence on m'_t



Conclusion

- 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 !

Other Projects

- Heavy new resonances with Auger
  - Calculate the event rate of downward-going neutrinos @PAO.
  - SM + extensions of the SM with W', Z'.
- $Z/\mathrm{Z}' \rightarrow t\bar{t}$ (Tomas) and $W/\mathrm{W}' \rightarrow t\bar{b}$ @ NLO