PHENO2017 - Pittsburgh

PyR@TE2 : new developments

Comput.Phys.Commun. 213 (2017) 181-196
Comput.Phys.Commun. 185 (2014) 1130-1152
Phys.Rev. D94 (2016) no.7, 076008

Florian Lyonnet

with Ingo Schienbein

Southern Methodist University

SMU

8-10 May 2017

Motivations

Description

- Generate the **Renormalization Group Equations** for non-supersymmetic theories @ 2-loop

Motivations

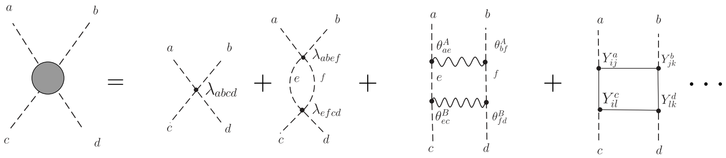
Description

- Generate the **Renormalization Group Equations** for non-supersymmetic theories @ 2-loop

- No evidence of SUSY so far :
  - collider experiments
  - $B_s \to \mu^+\mu^-,\ b \to s\gamma, \ldots$
  - direct DM detection experiments
- Systematic studies of non-SUSY models as well as SUSY broken at higher scale require the RGEs
- E.g. improved effective potential in minimal extensions of the SM, DM, inflation, gauge couplings unification . . .

- RGEs for general gauge theories known for a long time:
  - *I. Jack and H. Osborn, Nucl.Phys.B207 (1982), J.Phys.A16 (1983), Nucl.Phys.B249 (1985)*
  - *M. Machacek and M. T. Vaughn, 1983 Nucl.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.

E.g.:The Quartic Terms



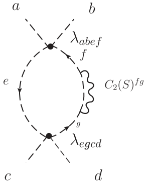
$\Downarrow$ $\Downarrow$ $\Downarrow$

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

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

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

$+$



$\cdots$

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

New Features

- Extended group Theory: **PyLie**
  - We have developped a `Python` module to deal with the Lie Algebra calculations (Python rewrite of the relevant methods of Susyno)
  - $\mathrm{SU}(n),\ n = 2, \ldots, 6 \Rightarrow$ any $\mathrm{SU(n)}$ and $\mathrm{SO}(2n), \mathrm{SO}(2n+1)$
  - Arbitrary irrep
  - All invariants of up to four fields are now supported
- **Kinetic Mixing** implemented at two-loop for all beta functions
- Anomalous dimensions

Multiple gauge invariants

- Possible to use different invariants

E.g.

A complex triplet of $\mathrm{SU}(2)$, $\Delta, \Delta^\dagger$:
$\rightarrow$ 2 invariants for quartic terms involving Δ and $\Delta^\dagger$ i.e.:

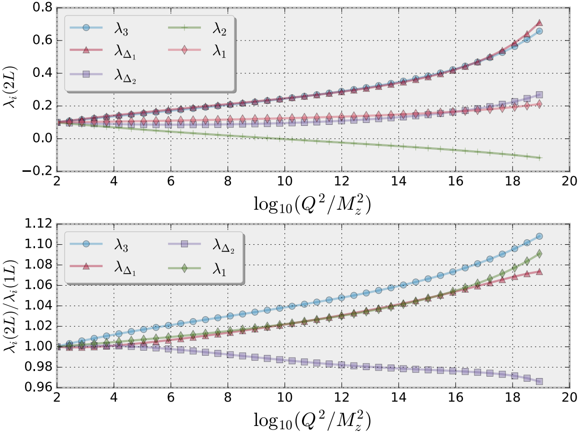
$$\mathrm{Tr}(\Delta\Delta^\dagger\Delta\Delta^\dagger),\ \left(\mathrm{Tr}(\Delta\Delta^\dagger)\right)^2$$

Toy model: SM + complex Triplet

- We consider the SM extended with a complex triplet $T = (\Delta^{++}, \Delta^{+}, \Delta^{0})$: $H \sim (2, 1/2)$, $T \sim (3, 1)$
- Potential :

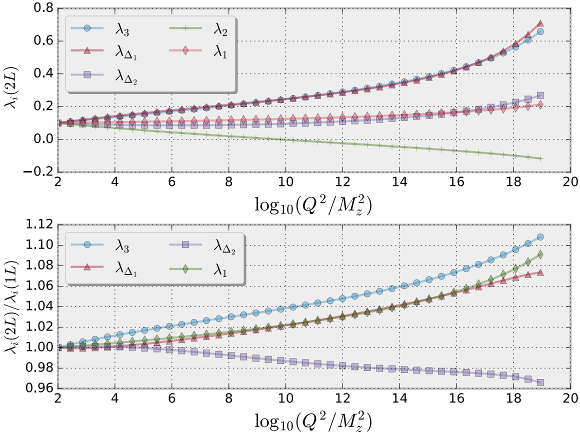
$$\begin{aligned}
\mathcal{V} &= \lambda_1 H^\dagger H H^\dagger H + \lambda_{\Delta_1} \mathrm{Tr}\left(\Delta^\dagger \Delta\right) H^\dagger H \\
&+ \lambda_{\Delta_2} \mathrm{Tr}\left(\Delta^\dagger \Delta\right) \mathrm{Tr}\left(\Delta^\dagger \Delta\right) \\
&+ \lambda_2 H^\dagger \Delta \Delta^\dagger H + \lambda_3 \mathrm{Tr}\left(\Delta^\dagger \Delta \Delta^\dagger \Delta\right)
\end{aligned}$$

Results



- Implement all the couplings in PyR@TE
- Solve using the provided wrapper
- All intitial values taken to be 0.1
- Toy example exhibits modifications of the order $\sim 5\%$ at the GUT scale

Results



- Implement all the couplings in PyR@TE
- Solve using the provided wrapper
- All intitial values taken to be 0.1
- Toy example exhibits modifications of the order $\sim 5\%$ at the GUT scale

- Two-loop effect can be sizeable !
- With PyR@TE it is easy to take them into account.

Kinetic Mixing at two-loop

$$\mathcal{L}_{kin.} \supset -\frac{1}{4} F^{T}_{\mu\nu} \xi F^{\mu\nu}$$

- Follow the method of R. Fonseca, M. Malinsky, F. Staub in arxiv:1308.1674
- Kinetic Mixing taken into account via an extended non diagonal gauge coupling Matrix G:

$$G = \tilde{G}\xi^{-1/2}\,,\ \tilde{G} = diag(g_1, g_2, \ldots, g_n)$$

- Leads to simple replacement rules such that
  - $\beta^{full} = \beta + \beta^{kin}$
  - Implemented all the rules at 1- and 2-loop

Kinetic Mixing at two-loop

- Defining $W_p^R = G^T Q_p^R$

Gauge Coupling

- At one loop only one rule: $g^3 S(R) \to G \sum_p W_p^R (W_p^R)^T$
- At two-loop the non abelian gauge coupling gets also modified: $g^5 C(R) S(R) \to$
$g_A^3 \sum_p S_A(R) \left[\sum_B g_B^2 C_B^{pp}(R) + (W_p^R)^T W_p^R \right]$

Kinetic Mixing at two-loop

Other terms

- Gets messy for the other parameters:

$$
\begin{gathered}
g^4\{\Theta^\alpha,\Theta^\beta\}_{ab}t^\alpha_{ij}t^\beta_{kl} \rightarrow \sum_A\sum_B\{\Theta^\alpha_A,\Theta^\beta_B\}_{ab}t^\alpha_{A,ij}t^\beta_{B,kl} \\
+2\delta_{ab}\delta_{ij}\delta_{kl}(W^S_a)^T W^F_i (W^S_b)^T W^F_k \\
+\sum_{A,p} g_A^2 \left[\tilde{\delta}_{ap}(W^S_a)^T\Theta^\alpha_{A,pb}+\tilde{\delta}_{pb}(W^S_b)^T\Theta^\alpha_{ap}\right] \\
\times\left(\delta_{ij}W^F_i t^\alpha_{A,kl}+\delta_{kl}W^F_k t^\alpha_{A,ij}\right)
\end{gathered}
$$

$\mathrm{U}(1)_{B-L}$

- We can revisit the $\mathrm{U}(1)_{B-L}$ model including the kinetic mixing at two-loop in all the beta functions, see Phys.Rev. D.94 (2106) no.7 076008

$$\mathrm{G} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L},\ \mathcal{G} = \begin{pmatrix} g & \tilde{g} \\ 0 & g' \end{pmatrix}$$

Field	Quantum Numbers
Q_L	$(\mathbf{3},\mathbf{2},\mathbf{1/6},\mathbf{1/3})$
u_R	$(\mathbf{3},\ \mathbf{1},\ \mathbf{2/3},\ \mathbf{1/3})$
d_R	$(\mathbf{3},\ \mathbf{1},\ \mathbf{-1/3},\ \mathbf{1/3})$
L_L	$(\mathbf{1},\ \mathbf{2},\ \mathbf{-1/2},\ \mathbf{-1})$
e_R	$(\mathbf{1},\ \mathbf{1},\ \mathbf{-1},\ \mathbf{-1})$
ν_R	$(\mathbf{1},\ \mathbf{1},\ \mathbf{0},\ \mathbf{-1})$
H	$(\mathbf{1},\mathbf{2},\ \mathbf{1/2},\ \mathbf{0})$
χ	$(\mathbf{1},\ \mathbf{1},\ \mathbf{0},\ \mathbf{2})$

- One can write the following potential

$$V(H,\chi) = \mu_H H^\dagger H + \mu_\chi \chi^\dagger \chi + \lambda_1 \left(H^\dagger H\right)^2 + \lambda_2 \left(\chi^\dagger \chi\right)^2 + \lambda_3 \left(H^\dagger H\right)\left(\chi^\dagger \chi\right) \quad (1)$$

with stability conditions:

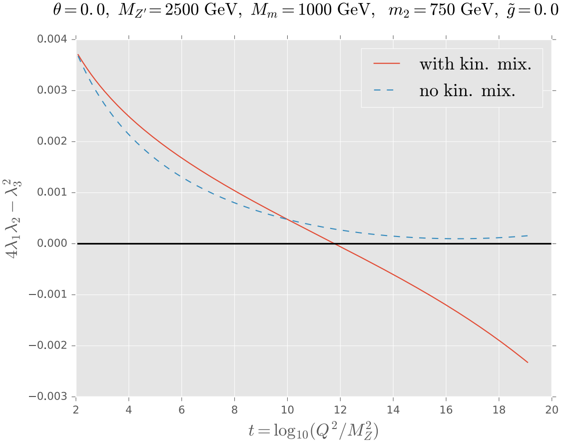
$$\lambda_1 > 0,\ \lambda_2 > 0,\ 4\lambda_1\lambda_2 - \lambda_3^2 > 0$$

Point in parameter space defined by $\mathcal{B} \equiv \{\theta, M_{Z'}, M_m, \tilde{g}, m_2\}$:

- $M_{Z'}$: mass of the Z' gauge boson,
- θ: mixing angle between the two scalars,
- M_m: mass of the heavy neutrinos,
- m_2: mass of the heavy scalar
- $\tilde{g}$: "amount of kinetic mixing"

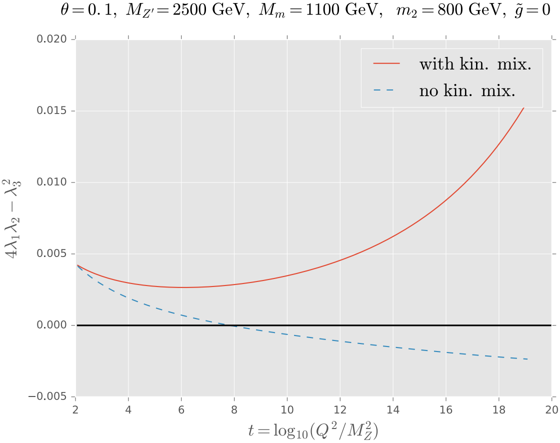
Kinetic Mixing vs No Kinetic Mixing

- Kin mixing can lead to vary different results

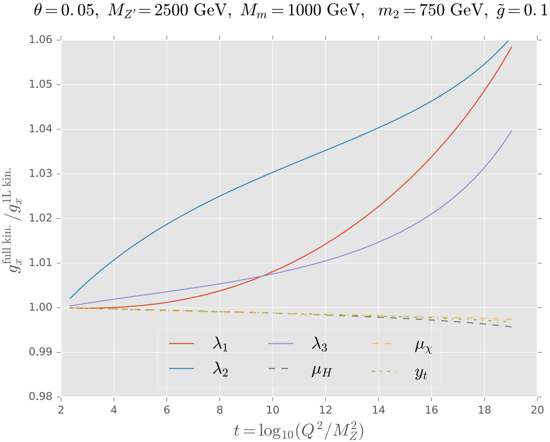


Kinetic Mixing vs No Kinetic Mixing

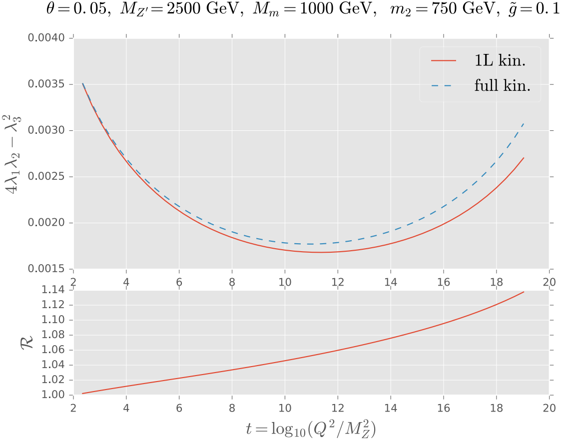
- Kin mixing can lead to vary different results



Kinetic Mixing @ 1L vs 2L



Kinetic Mixing @ 1L vs 2L



- Even the two-loop corrections can lead to a couple percent modifications!

Summary

- PyR@TE 2 is now available !
- Kinetic Mixing for all the couplings at two-loop has been implemented
- anomalous dimension for scalar and fermion fields
- Extended the theory part, more irreps, more groups
- Different gauge singlets are supported
- Full two-loop effects can now be included without effort

- visit our hepforge web page:

  http://pyrate.hepforge.org
- Have fun !