One-Loop Flavour Observables and Two-Loop Higgs Masses for *free*

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Disclaimer

The tools I'm speaking about are not restricted to supersymmetric models. Nevertheless, I'll focus mainly on supersymmetry!

Outline

Today:

1. Introduction: there is life beyond the MSSM
2. The SARAH framework to explore models
3. Flavour observables at one-loop

Tomorrow:

4. Higgs masses at two-loop

Supersymmetry

Supersymmetry is one of the best studied extensions of the SM.

Appealing features

- Solves the hierarchy problem
- Predicts gauge coupling unification
- Provides a dark matter candidate
- Relates EWSB and large top mass

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The focus was usually on the MSSM

Public tools

Widely used SUSY tools (`SoftSUSY`, `Suspect`, `Superiso`, `Susy_Flavor`, `FeynHiggs`,...) are restricted to the MSSM (and a few extensions).

Reasons to look beyond the MSSM

- Higgs mass/Naturalness $\to$ F- or D-term enhanced tree mass?
- Missing signals for SUSY at LHC
  $\to$ compressed spectra? R-parity violation? split-SUSY? ...
- Neutrino masses $\to$ R-parity violation? Seesaw mechanism?
- The μ problem $\to$ effective μ term?
- Strong CP problem $\to$ (gauged?) Peccei-Quinn symmetry?
- R symmetry $\to$ Dirac Gauginos?
- GUT/String model $\to$ extended gauge sector? Z', W' in reach?
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Generic SUSY tools needed

To confront many models with experimental data (e.g. Higgs mass measurement, flavour observables, dark matter relic density) a high level of automatization is needed.

The SARAH framework to explore models

SARAH

SARAH

[FS,0806.0538,0909.2863,1002.0840,1207.0906,1309.7223,1503.04200]

SARAH is a Mathematica package to get from a minimal input all important properties of SUSY and non-SUSY models. Models are defined by

- gauge & global symmetries
- particle content
- (super)potential

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- All gauge (and gaugino) interactions are automatically derived from quantum numbers
- Gauge fixing terms in R_ξ gauge are automatically derived
- Soft SUSY breaking terms are added automatically

  ($m^2\phi\phi^*$, $M_\lambda\lambda\lambda$, $T\phi_i\phi_j\phi_k$, $B\phi_i\phi_j$, $L\phi_i$)

Supported models

Matter and gauge sector

The gauge sector can consist of an arbitrary number of groups and all irreducible representations can be used for matter fields.

[1] Susyno supports also $SO(N)$, $SP(2N)$, $E_{6,7,8}$, G_2, F_4, but the link is not yet well tested

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Supported gauge groups

- Non-Abelian groups:
  SARAH links Susyno to calculate Clebsch-Gordan coefficients, generators and Casimir/Dynkin for non-fundamental irreps of unbroken $SU(N)$ [1] [Fonseca,1106.5016]
- Abelian groups:
  kinetic mixing for arbitrary numbers of $U(1)'s$ included

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Consistency check of a model

SARAH performs several checks

Physical properties

- Check for gauge and Witten anomalies
- Check if all terms in the (super)potential are in agreement with charge conservation
- Check if other (renormalizable) terms allowed in the (super)potential by (gauge) symmetries
- Check if other particles might mix
- ...

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Also formal checks (syntax, self-consistency,...) of the implementation in SARAH are done.

Information derived by SARAH

Tree-level Relations

- all Tadpole equations, Masses and Mass matrices
- all Vertices

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Two-Loop RGEs

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+ Support of kinetic mixing [Fonseca,Malinsky,Porod,FS,1107.2670]
+ Support of Dirac Gauginos [Goodsell,1206.6697]
+ Running VEVs in R_ξ gauge [Sperling,Stöckinger,Voigt,1305.1548,1310.7629]

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General QFT: Full CP and flavour structure [Luo,Wang,Xiao,hep-ph/0211440]
+ Support of kinetic mixing [Fonseca,Malinsky,FS,1308.1674]
+ Running VEVs in R_ξ gauge [Sperling,Stöckinger,Voigt,1305.1548,1310.7629]

The analytical expressions derived by SARAH can be exported:

Model files for Monte Carlo Tools

- CalcHep/CompHep (can be used with MicrOmegas) [Pukhov et al.],[Boos et al.],[Belanger et al.]
- WHIZARD [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
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Interface to other tools

SARAH writes also model files

- FeynArts/FormCalc [Hahn,hep-ph/0012260],[Hahn,Victoria,hep-ph/9807565]
- Vevacious [Camargo-Molina,O'Leary,Porod,FS,1307.1477]

and generates Fortran code for

- SPheno [Porod,hep-ph/0301101],[Porod,FS,1104.1573]

Third-party interface to SoftSUSY: FlexibleSUSY [Athron et al.,1406.2319]

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Interplay: Vevacious

Vevacious . . . [Camargo-Molina,O'Leary, Porod, FS,1307.1477]

. . . is a tool to find the global minimum of the 1-loop effective potential and checks the stability of the 'correct' vacuum.

- Written in Python and C++; includes LHPC [O'Leary]
- Makes use of HOM4PS, pyminuit and CosmoTransitions

[Lee, Yi, Tsai,Computing, 83, pp109-133],[Wainwright,1109.4189]]

vevacious.hepforge.org

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If you use it, you'll see that thumb rules like

$$A_t^2 < 3(m_{H_u}^2 + m_{\tilde{t}_l}^2 + m_{\tilde{t}_R}^2)$$

are not sufficient to identify CCB vacua in the MSSM! [1309.7212,1405.7376]

SARAH and SPheno

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Features of 'SPheno by SARAH' versions

- Full 2-loop running of all parameters and all masses at 1-loop
- Complete 1-loop thresholds at M_Z
- two-loop corrections to Higgs masses
- calculation of flavour and precision observables
- calculation of decay widths and branching ratios
- interface to HiggsBounds and HiggsSignals
- estimate of electroweak Fine-Tuning

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collider pheno	dark matter	Higgs constraints	Vacuum stability	CalcHep, HB, WHIZARD, MG5, MicrOmegas, Vevacious
↑	↑	↑	↑	

Flavour observables, Sparticle and Higgs decays — SPheno

↑

Calculate running parameters, SUSY masses at one-loop, Higgs masses at two-loop, Fine-Tuning — SPheno

↑

Create model files for MC tools & Vevacious as well as Fortran code for SPheno — SARAH

↑

Derive expressions for masses, vertices, RGEs, . . . — SARAH

↑

Create SARAH input file — User

↑

Idea for a new model — User

Flavour observables at one-loop

in collaboration with
Werner Porod & Avelino Vicente

Calculation of Flavour observables in a nutshell

To calculate flavour observables in a given model one needs

1. Expressions for vertices and masses
2. Expressions for Wilson coefficients[2]
3. Expressions for observables
4. Numerical values for everything

[2] a.k.a. formfactors for LFV

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Let's combine the different tools!

[2] a.k.a. formfactors for LFV

FlavorKit

[Porod,FS,Vicente,1405.1434]

1. SARAH calculates the necessary vertices & masses and includes them in the SPheno output
2. SPheno provides routines for the numerical evaluation of Passarino-Veltman integrals
3. The necessary expressions for the form factors and observables are still needed

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FlavorKit

The calculation of flavour observables is based on external files parsed by SARAH which ...

- ...provide the generic expressions of form factors (function of masses, vertices, loop integrals)
- ...the formulae for the observables (function of form factors, masses, (hadronic) parameters, constants)

New observables

To calculate new observables the user has to provide two files

- A steering file:
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  defines the necessary form factors and the desired position in the SPheno output
- A Fortran file:
  gives Fortran code to combine form factors to observables

Both files have to be put into the FlavorKit subdirectory of SARAH

$\rightarrow$ The observables are included automatically in the SPheno output.

Example $l \to l_j\gamma$: Steering file

The Steering file reads

```
NameProcess = "LLpGamma";

NameObservables = {{muEgamma, 701, "BR(mu->e gamma)"},
                   {tauEgamma, 702, "BR(tau->e gamma)"},
                   {tauMuGamma, 703, "BR(tau->mu gamma)"}};

NeededOperators = {K2L, K2R};

Body = "LLpGamma.f90";
```

K2L, K2R are the coefficients of the dipole operator

$$\mathcal{L}_{\ell\ell\gamma} = e\,\bar{\ell}_\beta \left[i m_{\ell_\alpha} \sigma^{\mu\nu} q_\nu \left(K_2^{L,\beta\alpha} P_L + K_2^{R,\beta\alpha} P_R \right) \right] \ell_\alpha A_\mu + h.c.$$

which are known by SARAH.

Example $l \to l_j \gamma$: Fortran file

```fortran
Real(dp) :: width
Integer :: i1, gt1, gt2

Do i1=1,3
If (i1.eq.1) Then              ! mu -> e gamma
 gt1 = 2
 gt2 = 1
Elseif (i1.eq.2) Then          !tau -> e gamma
 ...
End if

width=0.25_dp*mf_l(gt1)**5*(Abs(K2L(gt1,gt2))**2 &
           & +Abs(K2R(gt1,gt2))**2)*Alpha

If (i1.eq.1) Then
  muEgamma = width/(width+GammaMu)
Elseif (i1.eq.2) Then
 ...
End if
End do
```

Example $l \to l_j \gamma$: Result

After running SARAH and compiling the SPheno module the spectrum files produced by SPheno include the new observable:

```
# SUSY Les Houches Accord 2 - NMSSM
# SPheno module generated by SARAH
...
Block FlavorKitLFV # lepton flavor violating observables
      701     1.61451131E-14  # BR(mu->e gamma)
      702     5.67628390E-16  # BR(tau->e gamma)
      703     2.15514014E-17  # BR(tau->mu gamma)
...
```

Coefficients of new operators

Input files for form factors look much more complicated:

```
Switch[prop,
V, (* Vector penguins *)
 Switch[top,  (* Check topology *)
  1,
  Switch[type,  (* Check the generic type of the diagram *)
SFF,
    WriteString[file,"   int1=B0(0._dp, mF12, mF22)\n" ];
    WriteString[file,"   int2=C00(mF22, mF12, mS12)\n" ];
    WriteString[file,"   int3=C0(mF22, mF12, mS12)\n" ];
    WriteString[file,"   PVOddllVRR=PVOddllVRR+ ↪
        ↩ chargefactor*coup1R*coup2L*coup4R*IMP2* ↪
        ↩ (-1.*coup3R*int3*mF1*mF2 + coup3L*(int1 - ↪
        ↩ 2.*int2 + int3*mS12))\n" ];
    ...
```

(the files for $(\bar{d}\Gamma d)(\bar{\ell}\Gamma\ell)$ have about 5000 lines like this)

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     ...
```

(the files for $(\bar{d}\Gamma d)(\bar{\ell}\Gamma\ell)$ have about 5000 lines like this)

→ Nothing you want to implement by hand!

PreSARAH

The generic expressions for the coefficients of new operators can be calculated with an additional package (PreSARAH):

- Easy way to define operators and colour flow
- Uses FeynArts/FormCalc to calculate generic expressions
- Writes all necessary files for SARAH

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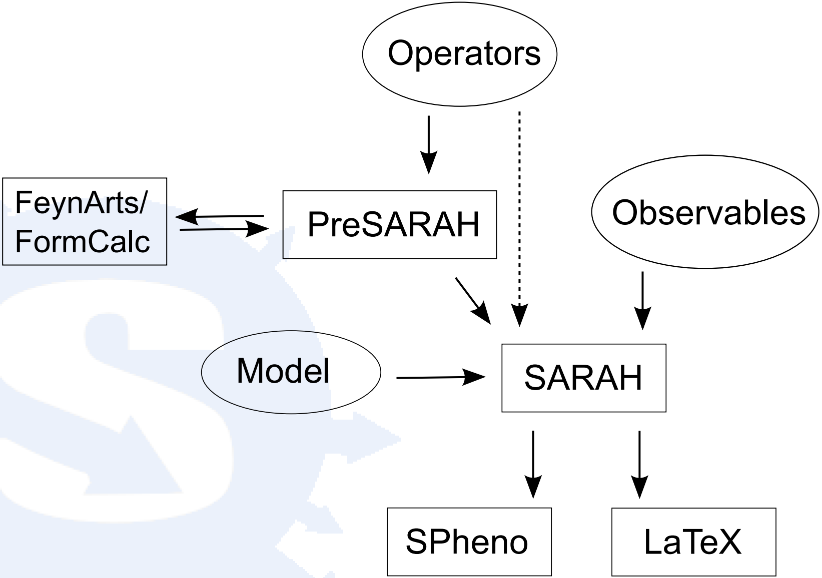
```
NameProcess="2d2L";

ConsideredProcess = "4Fermion";
FermionOrderExternal={2,1,4,3};
NeglectMasses={1,2,3,4};

ExternalFields= {DownQuark,bar[DownQuark],
                                    ChargedLepton,bar[ChargedLepton]};

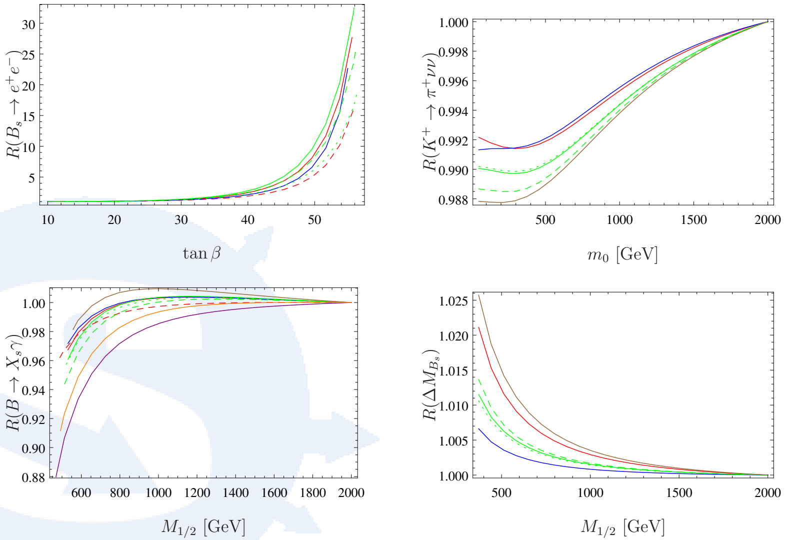
AllOperators={{OddllSLL,Op[7].Op[7]}, (* [d PL d][l PL l] *)
                  {OddllSRL,Op[6].Op[7]}, (* [d PR d][l PL l] *)
...
};
```


Operators
FeynArts/
FormCalc
PreSARAH
Observables
Model
SARAH
SPheno
LaTeX

Implemented observables

We made use of this to (re-) implement in SARAH

- Br($l_i \to l_j \gamma$), Br($l \to 3l'$), Br($Z \to ll'$)
- CR($\mu - e, N$) (N=Al,Ti,Sr,Sb,Au,Pb), Br($\tau \to l + P$) (P=π, η,η')
- Br($B \to X_s \gamma$), Br($B^0_{s,d} \to l\bar{l}$), Br($B \to sl\bar{l}$), Br($K \to \mu\nu$)
- Br($B \to q\nu\nu$), Br($K^+ \to \pi^+\nu\nu$), Br($K_L \to \pi^0\nu\nu$)
- $\Delta M_{B_s,B_d}$, ΔM_K, ϵ_K, Br($B \to K\mu\bar{\mu}$)
- Br($B \to l\nu$), Br($D_s \to l\nu$)



FlavorKit, SPhenoMSSM (dashed), SPheno 3.3, SUSY_Flavor 1, SUSY_Flavor 2, MicrOmegas, SuperIso

LFV in low-scale Seesaw models

[Abada,Krauss,Porod,FS,Vicente,Weiland,1408.0138]

inverse Seesaw

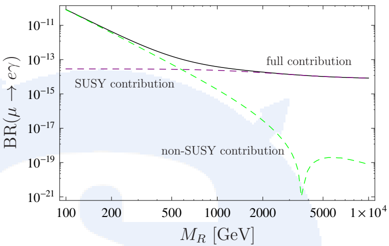
MSSM extended by 3 generations of right-handed neutrinos ($\widehat{\nu}^C$) and gauge singlets ($\widehat{X}$)

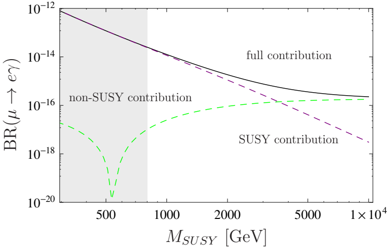
$$W = W_{\mathrm{MSSM}} + \varepsilon_{ab} Y_\nu^{ij} \widehat{\nu}_i^C \widehat{L}_j^a \widehat{H}_u^b + M_{R_{ij}} \widehat{\nu}_i^C \widehat{X}_j + \frac{1}{2} \mu_{X_{ij}} \widehat{X}_i \widehat{X}_j \, .$$

$\rightarrow$ Neutrino masses $M_\nu \simeq \frac{v_u^2}{2} Y_\nu^T M_R^{T^{-1}} \mu_X M_R^{-1} Y_\nu \, ,$

$\mu \to e\gamma$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -1.5$ TeV, $M_R = 2$ TeV, $\tan\beta = 10, \mu > 0$





- Limits: 5.7×10^{-13} (present), 6×10^{-14} (future)
- light right-handed neutrinos can give dominant contributions
- Dependence of non-SUSY contributions on SUSY scale because of charged Higgs mass

$\mu \to 3e$ and μ–e conversion

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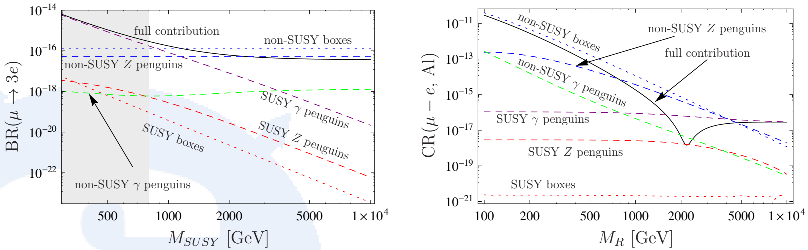

- Limits
  - $\mu \to 3e$: 1.0×10^{-12} (present), 10^{-16} (future)
  - CR(μ–e, Al): 10^{-15}–10^{-18} (future)
- non-SUSY box contributions can dominate
- Higgs penguins contributions usually negligible

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  - SPheno version created by SARAH provide many flavour observables out of the box
  - The user can easily extend the list of observables by combining the existing Wilson coefficients
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- I discussed today how SARAH in combination with SPheno and FeynArts/FormCalc automatizes the calculation of flavour observables at one-loop:
  - SPheno version created by SARAH provide many flavour observables out of the box
  - The user can easily extend the list of observables by combining the existing Wilson coefficients
  - Also new coefficients at full one-loop can be included
- I have shown at the example of the inverse seesaw that new/different features compared to standard seesaw scenarios can show up

Higgs masses at two-loop

in collaboration with
Mark D. Goodsell & Kilian Nickel

collider pheno	dark matter	Higgs constraints	Vacuum stability	CalcHep, HB, WHIZARD, MG5, MicrOmegas, Vevacious

↑ ↑ ↑ ↑

Flavour observables, Sparticle and Higgs decays

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Calculate running parameters, SUSY masses at one-loop, Higgs masses at two-loop, Fine-Tuning

(SPheno)

↑

Create model files for MC tools & `Vevacious` as well as Fortran code for `SPheno`

↑

Derive expressions for masses, vertices, RGEs, . . .

(SARAH)

↑

Create `SARAH` input file

↑

Idea for a new model

(User)

Higgs mass calculations 2015

- All BSM models have to be confronted today with the Higgs mass measurements.
- However, including only new effects compared to the MSSM in an one-loop effective potentiall approach introduces are very large uncertainty.

→ It is necessary to push non-minimal models to the MSSM precision!

Higgs mass calculation with SARAH and SPheno

Thresholds corrections

Full one-loop thresholds at M_Z to get running SM gauge and Yukawa couplings, in particular Y_{top}

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Two-loop contributions

[Goodsell,Nickel,FS,1411.0675]

Dominant two-loop contributions to CP even Higgs via effective potential approach

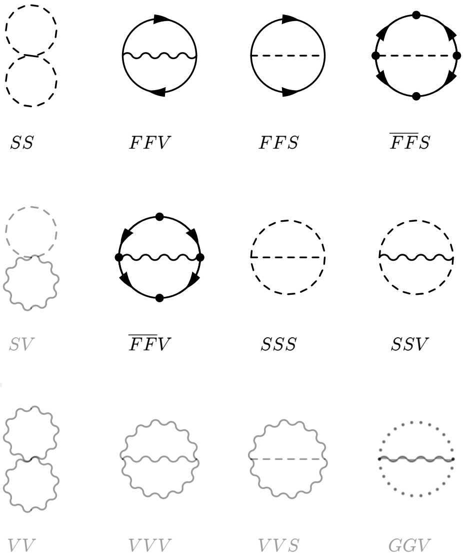
$\rightarrow$ corresponds to precision available for the MSSM when using SoftSUSY, Suspect or SPheno

- Generic expressions for all two-loop diagrams are known

  [Martin,hep-ph/0111209]

- Expressions have been translated into 4-component notation

  [Goodsell,Nickel,FS,1411.0675]



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  [Martin,hep-ph/0111209]

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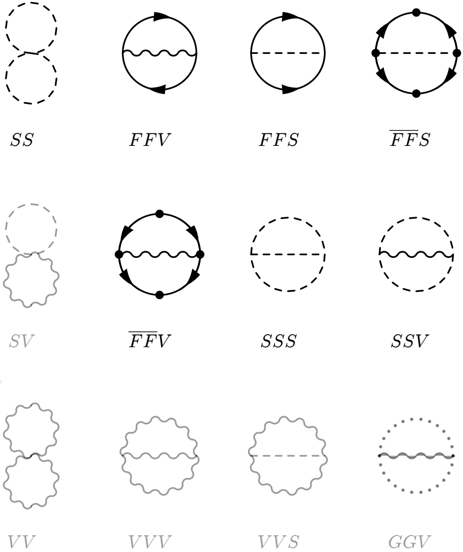

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  [Martin,hep-ph/0111209]

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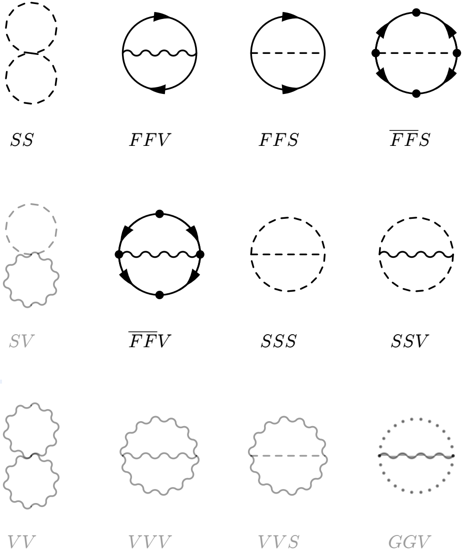
  [Goodsell,Nickel,FS,1411.0675]

- ew gauge contributions usually neglected
- Two-loop corrections calculated by

$$\delta t_i^{(2)} = \frac{\partial V^{(2)}}{\partial v_i}$$

$$\Pi_{ij}^{(2)} = \frac{\partial^2 V^{(2)}}{\partial v_i \partial v_j}$$

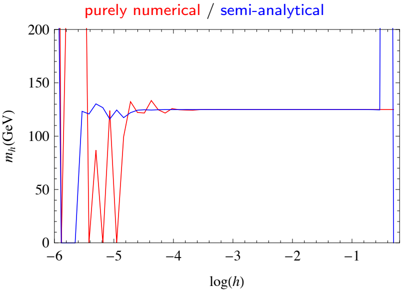


First implementation in SARAH/SPheno

[Goodsell,Nickel,FS,1411.0675]

1. Generic expressions are implemented in SARAH
2. SARAH generates all possible diagrams for included topologies in SPheno output
3. Self-energies / tadpoles are calculated numerically:
    3.1 Numerical derivation of the entire two-loop effective potential with respect to VEVs
    3.2 Chain rule: Analytical derivation of loop-functions which respect to masses; derivative of masses/couplings with respect to VEVs numerically

Numerical stability



- Numerical derivation dependence on initial step-size
  - There is a large plateau which can be used
  - we implemented a 'safe mode' which varies the step-size and checks the stability

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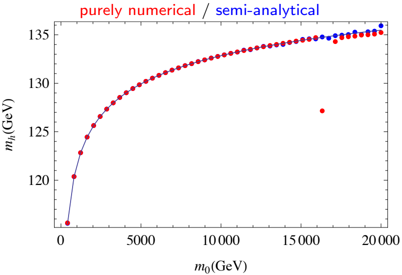

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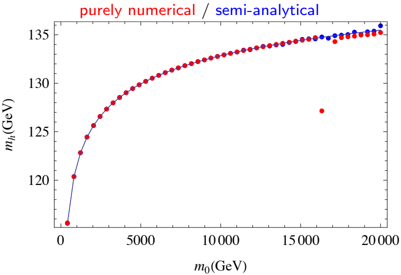

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  - we implemented a 'safe mode' which varies the step-size and checks the stability
- Numerics worse for $M_{SUSY} \gg v$ No SUSY calculation should be used anyway!)
- Problems can appear for models with small VEVs (e.g. RpV)

Diagrammatic calculation

Fully analytically expressions

[Goodsell,Nickel,FS,1503.03098]

One can take *all* derivatives of the eff. pot. analytically using e.g.

$$\frac{\partial}{\partial S_r}\left(\frac{1}{q^2+\mathbf{m^2}}\right)_{ij} = -\left(\frac{1}{q^2+\mathbf{m^2}}\right)_{ik}\frac{\partial m^2_{kk'}}{\partial S_r}\left(\frac{1}{q^2+\mathbf{m^2}}\right)_{k'j}$$

$$m^2_{ij}(S) = \frac{\partial^2}{\partial S_i \partial S_j}V = m^2_i\delta_{ij} + \lambda^{ijk}S_k + \frac{1}{2}\lambda^{ijkl}S_kS_l$$

$\rightarrow$ each derivative introduces an additional propagator
$\rightarrow$ equivalent to a diagrammatic calculation in the limit $p^2 \rightarrow 0$.

- We derived a new set of generic expressions
- The expressions are equivalent to S. Martin results in the limit $p^2 \rightarrow 0$ but sometimes significantly shorter
- Results have been implemented in `SARAH` as third option to calculate two-loop masses

Two-loop masses with SARAH/SPheno

There are three options to calculate the two-loop masses in SARAH/SPheno which can easily be switched in the numerical session:

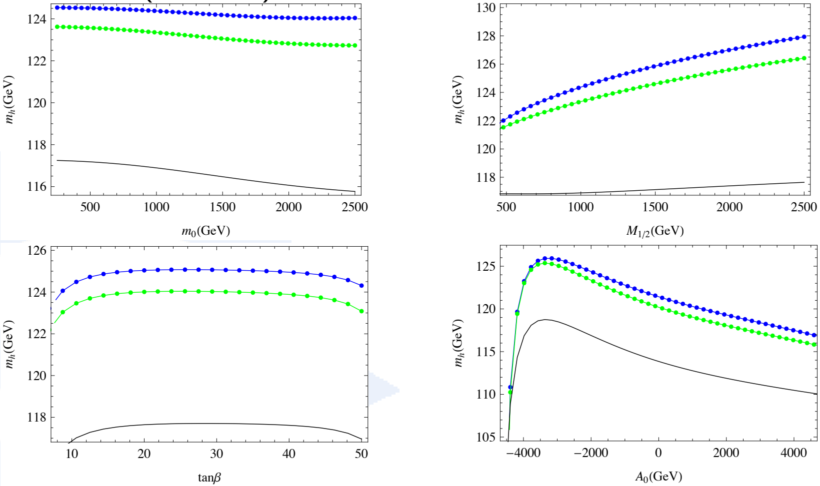
1. Effective potential with fully numerical derivation
2. Effective potential with semi-analytical derivation
3. Diagrammatic approach in the limit $p^2 \to 0$

Double check

The third option uses a different ansatz and was completely independently implemented as the other two
$\to$ possibility to internally double checks results by just using SARAH/SPheno!

That's necessary because there are hardly other two-loop results to compare with. However, a few are there ...

Validation I (MSSM)

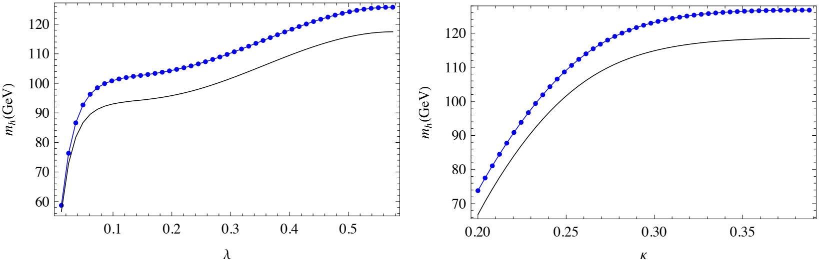


full lines: SARAH, dots: Brignole,Dedes,Degrassi, Slavich, Zwirner ([hep-ph/0112177,0206101,0212132,0305127])

1–loop / $\alpha_S(\alpha_b + \alpha_t)$ / full 2-loop

Validation II

NMSSM:



full lines: `SARAH`, dots: Degrassi, Slavich ([0907.4682])

1–loop / $\alpha_S(\alpha_b + \alpha_t)$

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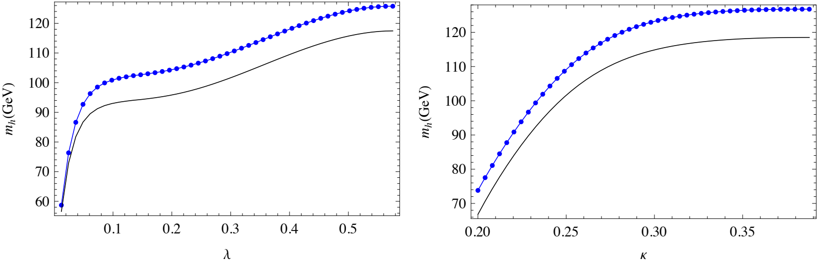

full lines: `SARAH`, dots: Degrassi, Slavich ([0907.4682])

1–loop / $\alpha_S(\alpha_b + \alpha_t)$

Dirac Gauginos:

full agreement with non-public code for $\alpha_S(\alpha_b + \alpha_t)$ corrections

[Goodsell,Slavich]

Problems with massless states

There is an intrinsic problem in the eff. pot. in Landau gauge

Goldstone boson catastrophe

The second derivative of the one-loop effective potential

$$V^{(1)} \sim (m^2)^2 \left[\log(m^2/Q^2) + c\right]$$

diverges for massless particles

$$\Pi^{(1)} \equiv \frac{\partial^2 V^{(1)}}{\partial m^2 \partial m^2} \to \infty \quad \text{for} \quad m^2 \to 0$$

At two-loop already the first derivative diverges for $m^2 \to 0$

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- Problematic are the Goldstones of broken groups
  $\rightarrow$ ew corrections are not considered in the MSSM at 2-loop
- In BMSSM also other very light scalars can cause similar problems

Outlook

The diagrammatic calculation gives not only a very important cross check, but allows for future improvements:

- Corrections to CP odd states can be included
- Full coverage of CP violation at two-loop
- To include momentum dependence, only the loop functions but not the generic structures have to be changed

We hope that we can release improvements in these directions in the not too far future!

Vectorlike top partners

[Goodsell,Nickel,FS,in prep.]

MSSM with vectorlike top partners

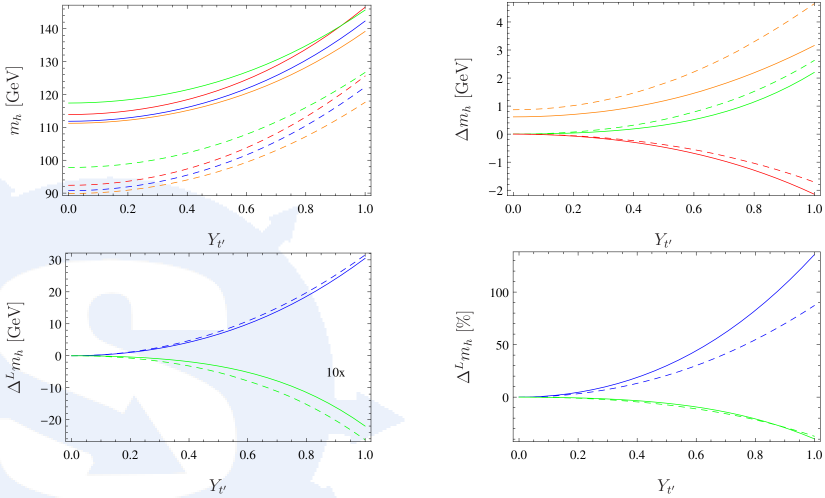
$$W = W_{MSSM} + Y^i_{t'}\hat{Q}_i\hat{T}'\hat{H}_u + M_{T'}\hat{T}'\hat{\bar{T}}' + m^i_{t'}\hat{U}_i\hat{\bar{T}}'.$$

$\rightarrow$ it is well know that $Y^3_{t'} \equiv Y_{t'}$ can give a large push to the Higgs mass.

Using SARAH/SPheno one can easily improve existing calculations in three aspects:

1. one-loop thresholds to calculate Y_{top} at M_Z
2. momentum dependence at one-loop
3. dominant two-loop corrections

$\tan\beta = 10$ (full), $\tan\beta = 2$ (dashed), $M_{T'} = 1.0$ TeV, $B_{T'} = 0$



top left: 1-loop eff.pot, 1-loop with p^2, 1-loop p^2 and thresholds, two-loop

top right: shift by momentum dependence, thresholds, two-loop

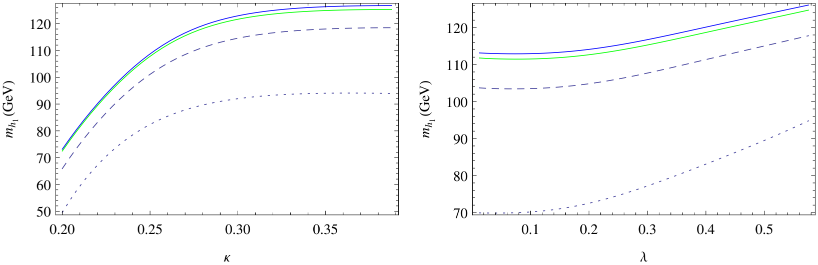
bottom: absolute shifts (left) by 1- and 2-loop corrections, and normalized to MSSM contributions (right)

NMSSM results I: heavy singlet & moderate λ

[Goodsell,Nickel,FS,1411.4665]

$m_0 = 1.4$ TeV $\quad M_{1/2} = 1.4$ TeV $\quad \tan\beta = 2.9 \quad A_0 = -1.35$ TeV

$\kappa = 0.33 \quad A_\lambda = -390$ GeV $\quad A_\kappa = -280$ GeV $\quad \mu_{eff} = 200$ GeV



1–loop / $\alpha_S(\alpha_b + \alpha_t)$ / full

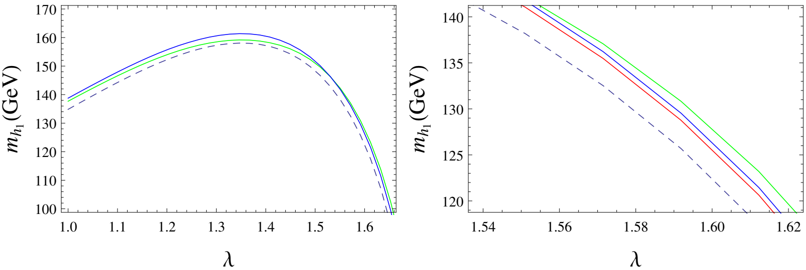
- Corrections beyond $\alpha_S(\alpha_t + \alpha_b)$ give negative contribution of a few GeV
- Corrections often MSSM-like and dominated by (s)quarks

NMSSM results II: heavy singlet & large λ

[Goodsell,Nickel,FS,1411.4665]

$\kappa = 1.6 \quad \tan\beta = 3 \quad T_\lambda = 600$ GeV $\quad T_\kappa = -2650$ GeV $\quad \mu_{eff} = 614$ GeV

$m^2_{\tilde{f}} = 2 \cdot 10^6$ GeV^2 $\quad T_i = 0 \quad M_1 = 200$ GeV $\quad M_2 = 400$ GeV $\quad M_3 = 2000$ GeV



1–loop / $\alpha_S(\alpha_b + \alpha_t)$ / full / MSSM approx.

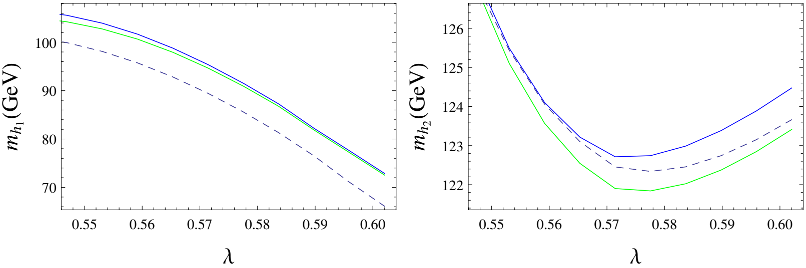
- Additional corrections can be positive for very large λ
- Using MSSM results not a good approximation any more

NMSSM results III: light singlet

[Goodsell,Nickel,FS,1411.4665]

$\kappa = 0.596 \quad T_\lambda = -27$ GeV $\quad T_\kappa = -240$ GeV $\quad \mu_{eff} = 130$ GeV

$T_t = -3050$ GeV $\quad T_b = T_\tau = -1000$ GeV $\quad m^2_{\tilde{t}_L} = 9.0 \cdot 10^5$ GeV^2 $\quad m^2_{\tilde{t}_R} = 1.05 \cdot 10^6$ GeV^2



1–loop / $\alpha_S(\alpha_b + \alpha_t)$ / full

- Corrections can be larger than the ones $\sim \alpha_S$
- Again, using MSSM results not a good approximation any more

MSSM with trilinear RpV

[Dreiner,Nickel,FS,1411.3731]

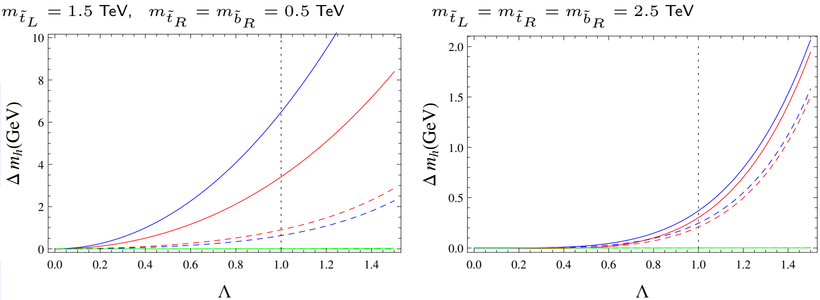
MSSM with trilinear RpV

$$W = W_{MSSM} + \frac{1}{2}\lambda_{ijk}\mathbf{L}_i\mathbf{L}_j\bar{\mathbf{E}}_k + \lambda'_{ijk}\mathbf{L}_i\mathbf{Q}_j\bar{\mathbf{D}}_k + \frac{1}{2}\lambda''_{ijk}\bar{\mathbf{U}}_i\bar{\mathbf{D}}_j\bar{\mathbf{D}}_k\,.$$

- RpV contributions to Yukawas at one-loop
- RpV contributions to effective potential at two-loop

MSSM with trilinear RpV

[Dreiner,Nickel,FS,1411.3731]



$T_t = -2.5$ TeV, $T_\Lambda = -2.5\Lambda$ TeV

λ''_{313}, λ''_{312}, λ''_{213}, λ'_{333} (dashed), λ'_{331} (dashed), λ'_{313} (dashed)

- Corrections only important if stops are involved
- For light stops the corrections can be several GeV
- Often couplings beyond the perturbativity limit needed

Summary Part II

- The precise measurement of the Higgs mass is a challenge for many BSM models
- To confront models with this measurement a precise prediction of the Higgs mass in a given model is necessary
- The combination SARAH/SPheno provides a prediction for a wide range of SUSY models which is comparable with the MSSM precision of standard spectrum generators by including:
  - All new effects in the one-loop thresholds to determine the running gauge and Yukawa couplings
  - The full momentum dependence at one-loop
  - The (most likely!) dominant two-loop corrections
- By providing $O((\alpha_\lambda + \alpha_\kappa)\alpha_x)$ $(x = s, t, b, \tau, \lambda, \kappa)$ corrections, the NMSSM version of SPheno generated by SARAH is even more precise than dedicated tools