Automatisation of two-loop Higgs mass calculations with SARAH and SPheno

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CERN

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Outline

Going beyond the SM

Supersymmetry is the best studied extension of the SM

- 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 $\rightarrow$ F- or D-term enhanced tree mass?
- Missing signals for SUSY at LHC

  $\rightarrow$ compressed spectra? R-parity violation? split-SUSY? ...
- Neutrino masses $\rightarrow$ R-parity violation? Seesaw mechanism?
- The μ problem $\rightarrow$ effective μ term?
- Strong CP problem $\rightarrow$ (gauged?) Peccei-Quinn symmetry?
- R symmetry $\rightarrow$ Dirac Gauginos?
- GUT/String model $\rightarrow$ extended gauge sector? Z', W' in reach?
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Generic tools needed

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

The Higgs mass as precision observable

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(At least) two-loop precision is necessary to be able to confront B(MS)SM models with the measurements

The SARAH framework

SARAH and supported models

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
- field rotations

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- Gauge kinetic mixing fully supported
- An arbitrary number of matter states is possible
- All irreducible representations are supported

Example: MSSM model file

```
Off[General::spell]

Model`Name = "MSSM";
Model`NameLaTeX ="MSSM";
Model`Authors = "F.Staub";
Model`Date = "2012-09-01";

(* 2013-09-01: changing to new conventions for Superfields, Superpotential and global symmetries *)


(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Global symmetries *)

Global[[1]] = {Z[2],RParity};
RpM = {-1,-1,1};
RpP = {1,1,-1};

(* Vector Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False,RpM};
Gauge[[2]]={WB, SU[2], left,        g2,True, RpM};
Gauge[[3]]={G,  SU[3], color,       g3,False,RpM};


(* Chiral Superfields *)

SuperFields[[1]] = {q,  3, {uL,  dL},    1/6, 2, 3, RpM};
SuperFields[[2]] = {l,  3, {vL,  eL},   -1/2, 2, 1, RpM};
SuperFields[[3]] = {Hd, 1, {Hd0, Hdm},  -1/2, 2, 1, RpP};
SuperFields[[4]] = {Hu, 1, {Hup, Hu0},   1/2, 2, 1, RpP};

SuperFields[[5]] = {d, 3, conj[dR],  1/3, 1, -3, RpM};
SuperFields[[6]] = {u, 3, conj[uR], -2/3, 1, -3, RpM};
SuperFields[[7]] = {e, 3, conj[eR],    1, 1,  1, RpM};


(*------------------------------------------------------*)
(* Superpotential *)
(*------------------------------------------------------*)

SuperPotential = Yu u.q.Hu - Yd d.q.Hd - Ye e.l.Hd + \[Mu] Hu.Hd;
```

```
(*----------------------------------------------*)
(*   ROTATIONS                                  *)
(*----------------------------------------------*)

NameOfStates={GaugeES, EWSB};


(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector] =
{
  {{VB,VWB[3]},{VP,VZ},ZZ},
  {{VWB[1],VWB[2]},{VWm,conj[VWm]},ZW},
  {{fWB[1],fWB[2],fWB[3]},{fWm,fWp,fW0},ZfW}
};


(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid,1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu,1/Sqrt[2]}}};


(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
         {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}       };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}
    };


DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  FDL, conj[FDR]},
 Fe ->{  FEL, conj[FER]},
 Fu ->{  FUL, conj[FUR]},
 Fv ->{  FvL, 0},
 Chi ->{ L0, conj[L0]},
 Cha ->{ Lm, conj[Lp]},
 Glu ->{ fG, conj[fG]}
};
```

Analytical information derived by SARAH

Calculated Lagrangian

- SARAH derives all gauge and matter interactions
- The gauge fixing terms and ghost interactions are added
- For SUSY models, the soft-breaking terms are added
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- Expressions for loop-diagrams (more later)

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

- FeynArts/FormCalc [Hahn,hep-ph/0012260],[Hahn,Victoria,hep-ph/9807565]
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Spectrum generators:

- SPheno [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- Third-party interface to C++ code: FlexibleSUSY
  [Athron, Park, Stöckinger, Voigt, 1406.2319; flexiblesusy.hepforge.org]

Linking SPheno and SARAH

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Status before 2011

SPheno	SARAH
Restricted mostly to MSSM	Supports many models
RGEs, vertices, ... hardcoded	Calculates everything by its own
Routines for loop integrals, phase space,...	Nothing like that
Numerically fast (Fortran)	Numerically slow (Mathematica)

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→ A combination of both looked very promising

SARAH and SPheno

'Spectrum Generator Generator'

SARAH writes source-code which can be compiled with SPheno.

→ Implementation of new models in SPheno in a modular way without the need to write source code by hand.

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Running time and lines of SPheno code:

- MSSM: $\sim$8min, $\sim$280k lines
- NMSSM: $\sim$10min, $\sim$330k lines
- B-L-SSM: $\sim$35min, $\sim$550k lines

Features

The generated SPheno version provides all features of
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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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Adjustable SPheno properties

- What are the input parameters?
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→ Handy possibility to get a spectrum generator for the MSSM with a new SUSY breaking mechanism

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

↑ ↑ ↑ ↑

Flavour observables, Sparticle and Higgs decays

↑

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 masses at two-loop

in collaboration with
Mark D. Goodsell & Kilian Nickel

Inside the black box: loop corrections with SARAH/SPheno

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1. Hardcode generic expressions for the amplitude of all necessary loop diagrams:

$$\mathcal{M} = \text{Symmetry} \times \text{Colour} \times \text{Couplings} \times \text{Loop-Function}$$

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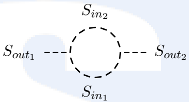

$$= c_S \times c_C \times C(S_{out1}, S_{in_1}, S_{in_2}) C(S_{out_2}, S^*_{in_1}, S^*_{in_2}) \times B_0(p^2, m^2_{S_{in_1}}, m^2_{S_{in_2}})$$

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$(S_{out_1}, S_{out_2}) = (h_a, h_b)$ in the MSSM:

$\to (S_{in_1}, S_{in_2}) = (h_i, h_j), (A^h_i, A^h_j), (H^+_i, H^-_j), (\tilde{d}_i, \tilde{d}^*_j), (\tilde{u}_i, \tilde{u}^*_j), (\tilde{e}_i, \tilde{e}^*_j), (\tilde{\nu}_i, \tilde{\nu}^*_j)$

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$(S_{in_1}, S_{in_2}) = (\tilde{u}_i, \tilde{u}_j^*)$:

$\mathcal{M} = \sum_{i=1}^{6} \sum_{j=1}^{6} 1 \times 3 \times C(h_a, \tilde{u}_i, \tilde{u}_j^*) C(h_b, \tilde{u}_i^*, \tilde{u}_j) \times B_0(p^2, m^2_{\tilde{u}_i}, m^2_{\tilde{u}_j})$

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2. Po
   in
3. M
4. Tr

```
!-----------------------
! conj[Su], Su
!-----------------------
sumI = 0._dp
Do i1 = 1, 6
   Do i2 = 1, 6
    B0m2 = B0(p2,MSu2(i1),MSu2(i2))
     Do gO1 = 1, 2
      Do gO2 = gO1, 2
       coup1 = cplUhhSucSu(gO1,i2,i1)
       coup2 = Conjg(cplUhhSucSu(gO2,i2,i1))
       SumI(gO1,gO2) = coup1*coup2*B0m2
      End Do
     End Do
     res = res +3._dp* SumI
  End Do
End Do
```

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7. Combine self-energies and tree-level masses:

$$m_S^{2,(1L)}(p^2) = m_S^{2,(T)} - \Pi_S^{(1L)}(p_i^2)$$

$$m_\Psi^{(1L)}(p^2) = m_\Psi^{(T)} - \Sigma_S^{+}(p^2) - \Sigma_R^{+}(p^2) m_\Psi^{(T)} - m_\Psi^{(T)} \Sigma_L^{+}(p^2)$$

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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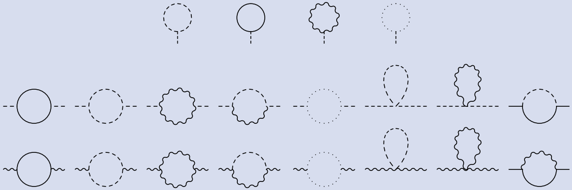
One-loop corrections

All one-loop diagrams contributing to mass corrections of any particle in the model including full p^2 dependence



Two-loop contributions

Dominant two-loop contributions to CP even Higgs.

Approximations:

- Gaugeless limit ($g_1 = g_2 = 0$)
- $p^2 = 0$

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

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Two calculations are implemented in `SARAH`/`SPheno`:

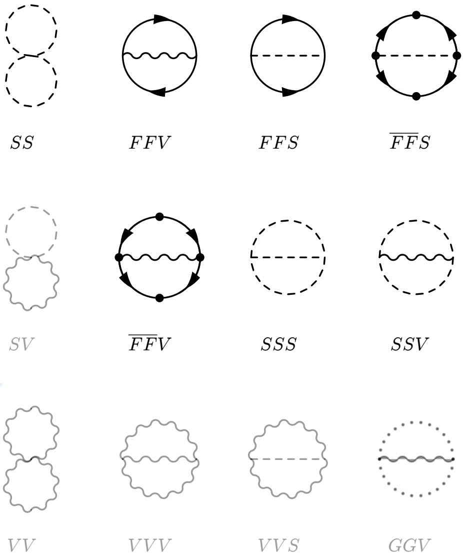
- Effective potential calculation
- Diagrammatic calculation

- 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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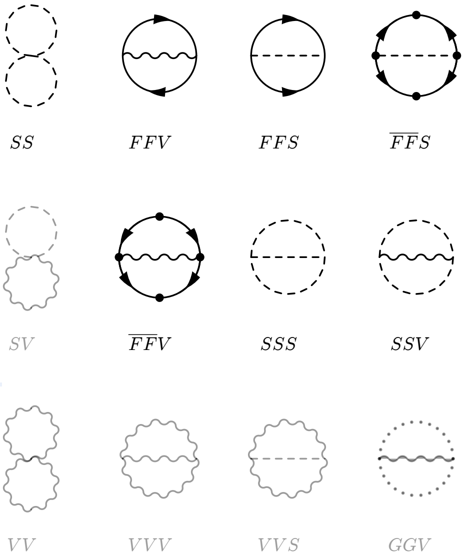

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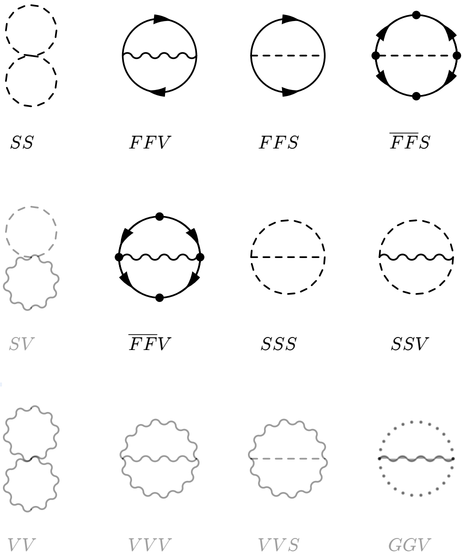
- Two-loop corrections calculated by

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

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



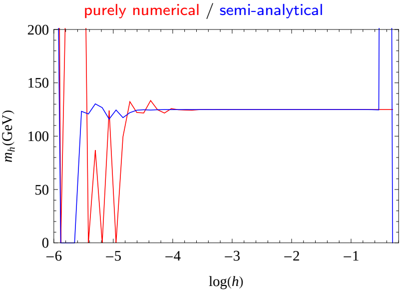
Higgs masses from the Effective potential

[Goodsell,Nickel,FS,1411.0675]

Self-energies / tadpoles are calculated numerically:

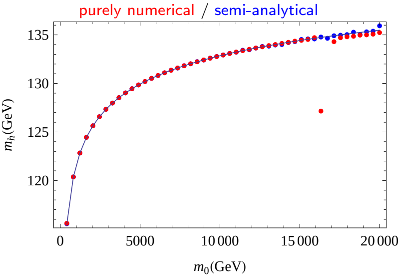
1. Numerical derivation of the entire two-loop effective potential with respect to VEVs
2. Chain rule: Analytical derivation of loop-functions which respect to masses; derivative of masses/couplings with respect to VEVs numerically

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

Numerical stability



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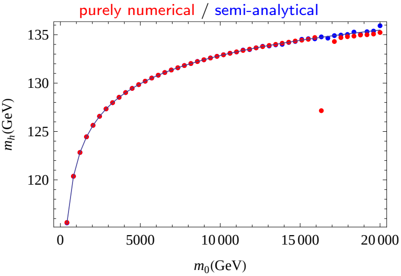

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- Problems can appear for models with small VEVs (e.g. RpV)

Intrinsic problem of 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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Possible solution: include p^2 dependence

Diagrammatic calculation

Fully analytically expressions

[Goodsell,Nickel,FS,1503.03098]

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

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

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

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

- We derived a new set of generic expressions

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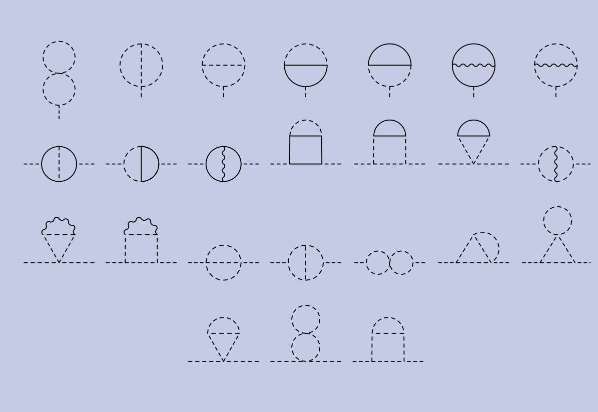

$\Big)_{k'j}$

$S_k S_l$

→ eac … & vertex

→ equ … : $p^2 \to 0$.

- W…

Diagrammatic calculation

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→ equivalent to a diagrammatic calculation in the limit $p^2 \to 0$.

- We derived a new set of generic expressions
- No numerical derivation!
- Current extensions:
  - support of CP violation (under validation at the moment → release soon! ☺)
  - including momentum dependence (linking `TSIL` possible, but very slow ☹)

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
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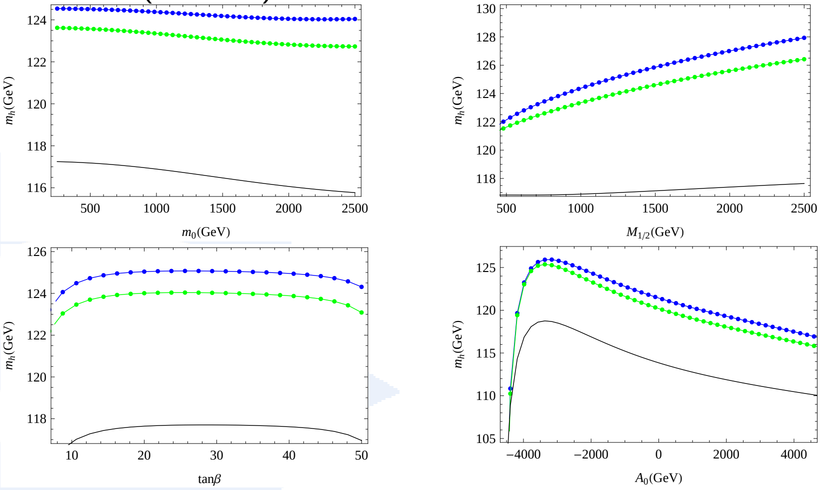
However, a few are there ...

Validation I (MSSM)

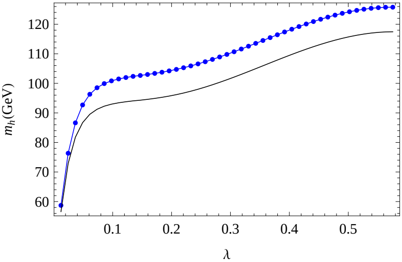


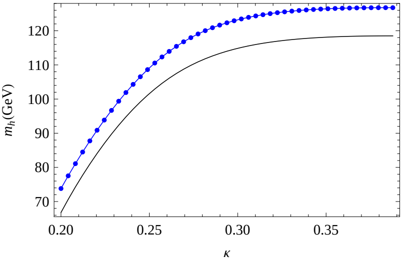
full lines: `SARAH`, dots: Brignole,Dedes,Degrassi, Slavich, Zwirner ([hep-ph/0112177,0206101,0212132,0305127])

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

Validation II

NMSSM:





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

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

Validation II

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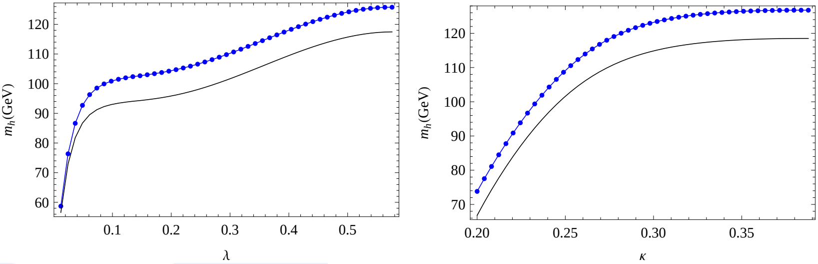

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1–loop / $\alpha_S(\alpha_b + \alpha_t)$

Dirac Gauginos:

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

[Goodsell,Slavich]

Some Results

New two-loop results

The setup was used to obtain new two-loop Higgs corrections:

- Contributions from trilinear RpV [Dreiner,Nickel,FS,1411.3731]
- Missing corrections in the NMSSM [Goodsell,Nickel,FS,1411.4665]
- Contributions from non-holomorphic soft-terms [Ün, Tanyildizi,Kerman Solmaz,1412.1440]
- MRSSM [Diessner,Kalinoswki,Kotlarski,Stöckinger,1504.05386]
  - Stop contributions very suppressed
  - Many other, non-MSSM-like contributions
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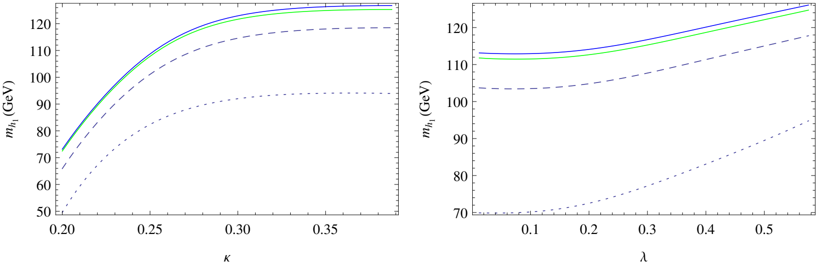
NMSSM results I: heavy singlet & moderate λ

[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

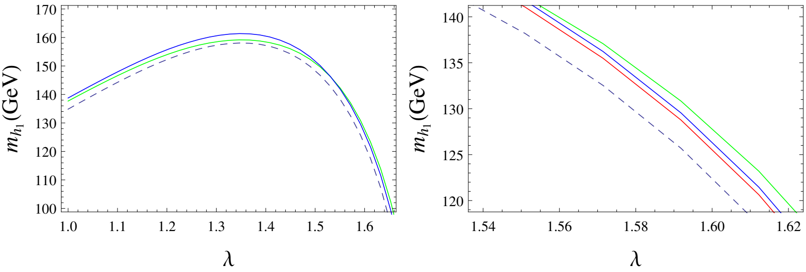
- Corrections beyond $\alpha_S(\alpha_t + \alpha_b)$ give negative contribution of a few GeV
- Corrections often MSSM-like and dominated by (s)quarks

NMSSM results II: heavy singlet & large λ

[Goodsell,Nickel,FS,1411.4665]

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

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



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

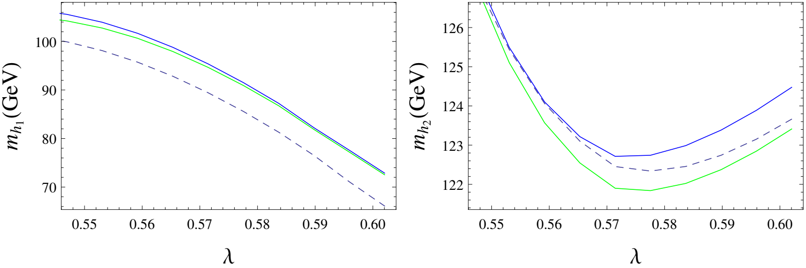
- Additional corrections can be positive for very large λ
- Using MSSM results not a good approximation any more

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

Spectrum generators for singlet extensions

Two-loop corrections available for the NMSSM in public codes

- $\alpha_S \alpha_t$: `NMSSMCALC`
- $\alpha_S(\alpha_t + \alpha_b)$ & MSSM approx. for $\alpha_t(\alpha_t + \alpha_b)$, $(\alpha_b + \alpha_\tau)^2$: `NMSSMTools`, `FlexibleSUSY`, `SoftSUSY`
- $\alpha_s(\alpha_b + \alpha_t)$, $(\alpha_t + \alpha_b + \alpha_\lambda)^2$, $\alpha_\tau(\alpha_\tau + \alpha_b)$, $\alpha_\kappa(\alpha_\kappa + \alpha_\lambda)$: `SPheno`

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Other singlet extensions (e.g. nMSSM, GNMSSM)

- Not supported by NMSSMCALC
- NMSSMTools, FlexibleSUSY, SoftSUSY use approximations also for $\alpha_S(\alpha_t + \alpha_b)$
- SPheno/SARAH provides the same accuracy as for the NMSSM

Higgs mass predictions in the NMSSM of public codes

[FS,Ahtron,Ellwanger,Gröber,Mühlleitner,Slavich,Voigt,1507.05093]

Differences fully understood and due to

- threshold corrections
- renormalisation scheme
- Two-loop calculations

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	Q	$\tan\beta$	λ	κ	A_λ	A_κ	μ_{eff}	M_1	M_2	M_3	A_t	A_b	$m_{\tilde{t}_L}$	$m_{\tilde{t}_R}$
TP1	1500.	10.	0.1	0.1	-10.	-10.	900.	500.	1000.	3000.	3000.	0.	1500.	1500.
TP2	1500.	10.	0.05	0.1	-200.	-200.	1500.	1000.	2000.	2500.	-2900.	0.	2500.	500.
TP3	1000.	3.	0.67	0.1	650.	-10.	200.	200.	400.	2000.	1000.	1000.	1000.	1000.
TP4	750.	2.	0.67	0.2	405.	0.	200.	120.	200.	1500.	1000.	1000.	750.	750.
TP5	1500.	3.	0.67	0.2	570.	-25.	200.	135.	200.	1400.	0.	0.	1500.	1500.
TP6	1500.	3.	1.6	1.61	375.	-1605.	614.	200.	400.	2000.	0.	0.	1500.	1500.

SM-like Higgs mass:

	TP1	TP2	TP3	TP4	TP5	TP6
FlexibleSUSY	123.55	122.83	126.58	127.62	125.08	126.46
NMSSMCalc	120.34	118.57	124.86	126.37	123.14	123.45
NMSSMTOOLS	123.52	121.83	127.28	127.30	126.95	126.63
SOFTSUSY	123.84	123.08	126.59	127.52	125.12	126.67
SPHENO	124.84 ($\sim$0.0)	124.74 ($\sim$0.0)	126.77 (-0.5)	126.62 (-1.2)	125.61 (-0.3)	131.29 (+3.3)

Shift from additional two-loop corrections in SPheno/SARAH

Flavour-effects at two-loop

[Goodsell,Nickel,FS,in prep.]

`SARAH`/`SPheno` include all generations of (s)fermions at two-loop

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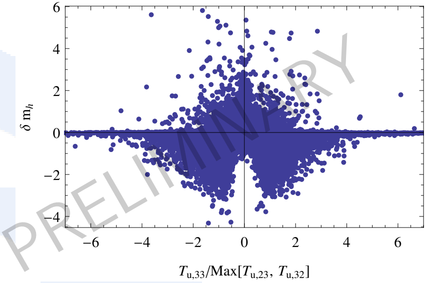

Important effects of several GeV in case of ...

- ... large $|T_{u,32}|$, $|T_{u,23}|$

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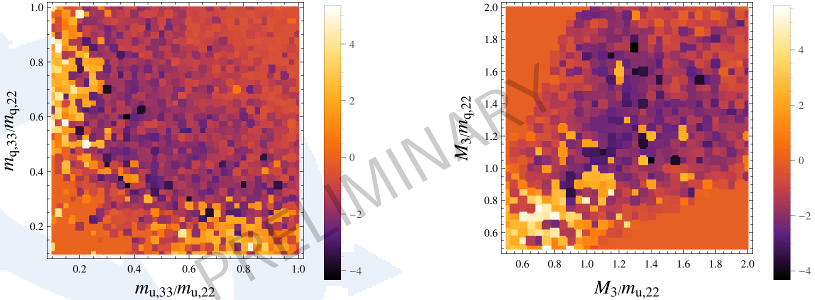

Important effects of several GeV in case of . . .

- . . . large $|T_{u,32}|$, $|T_{u,23}|$
- . . . hierarchy between soft-terms

Summary

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- I have discussed the automatisation of two-loop Higgs mass calculations with SARAH and SPheno
- This new functionality reduces significantly the theoretical uncertainty in the Higgs mass prediction in many SUSY models
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- In the case of large squark flavour violation, large deviations to standard calculations in the MSSM are possible
- Future extensions:
  - CP violation
  - Momentum dependence
  - Long-term aim: electroweak corrections at two-loop

Backup

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.

Vectorlike top partners

[Goodsell,Nickel,FS,in prep.]

MSSM with vectorlike top partners

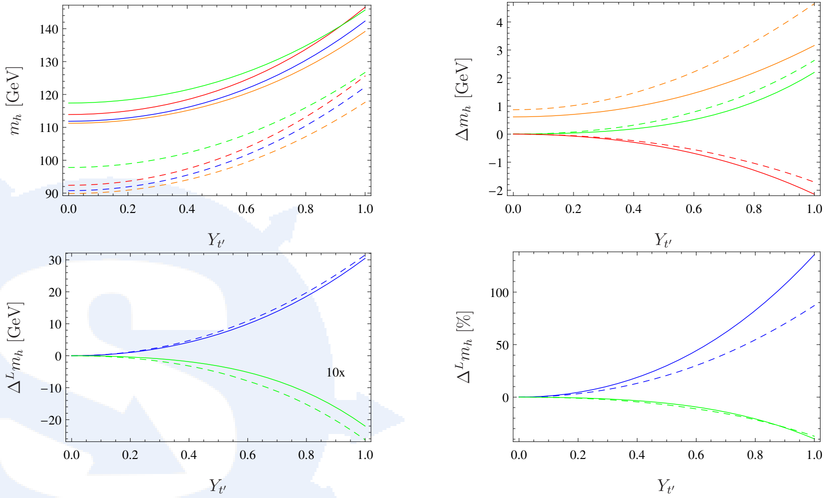
$$W = W_{MSSM} + Y^i_{t'}\hat{Q}_i\hat{T}'\hat{H}_u + M_{T'}\hat{T}'\hat{\bar{T}}' + m^i_{t'}\hat{U}_i\hat{\bar{T}}'.$$

$\rightarrow$ 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)

MSSM with trilinear $\not{R}$pV

[Dreiner,Nickel,FS,1411.3731]

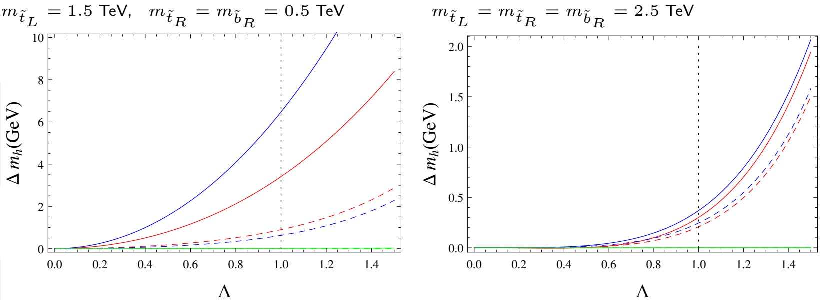
MSSM with trilinear $\not{R}$pV

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

- $\not{R}$pV contributions to Yukawas at one-loop
- $\not{R}$pV 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

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[1]
3. Expressions for observables
4. Numerical values for everything

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Let's combine the different tools!

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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

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  gives Fortran code to combine form factors to observables

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

→ 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

```
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)

Coefficients of new operators

Input files for form factors look much more complicated:

```
Switch[prop,
V, (* Vector penguins *)
 Switch[top,  (* Check topology *)
  1,
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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," PVOddlIVRR=PVOddlIVRR+ 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)

→ 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`):

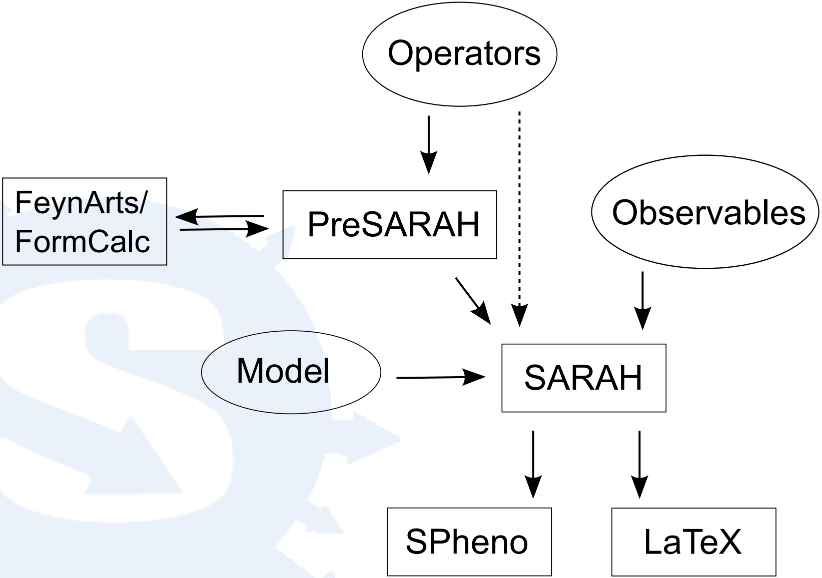
- Easy way to define operators and colour flow
- Uses `FeynArts`/`FormCalc` to calculate generic expressions
- Writes all necessary files for `SARAH`

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

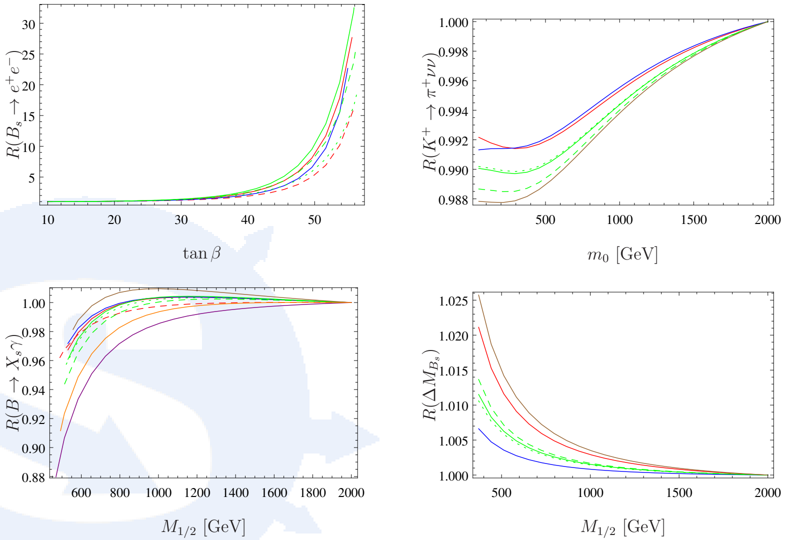
```
NameProcess="2d2L";

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

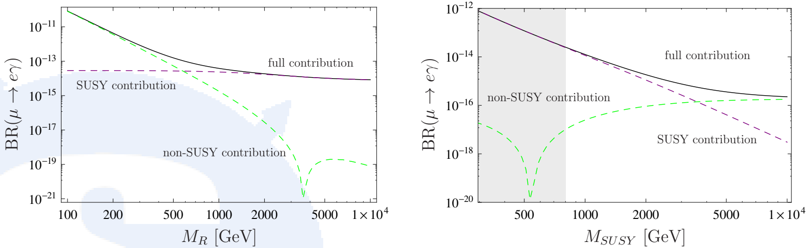
MSSM extended by 3 generations of right-handed neutrinos ($\widehat{\nu}^C$) and gauge singlets ($\widehat{X}$)

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

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

$\mu \to e\gamma$

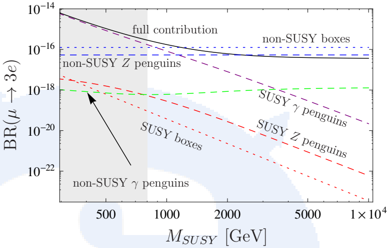
$m_0 = M_{1/2} = 1$ TeV, $A_0 = -1.5$ TeV, $M_R = 2$ TeV, $\tan\beta = 10, \mu > 0$

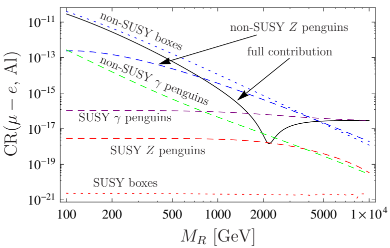


- Limits: 5.7×10^{-13} (present), 6×10^{-14} (future)
- light right-handed neutrinos can give dominant contributions
- Dependence of non-SUSY contributions on SUSY scale because of charged Higgs mass

$\mu \to 3e$ and μ–e conversion

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





- 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