Introduction to SARAH and related tools

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Download & Documentation: http://sarah.hepforge.org

Corfu2015, 03. September 2015

Outline

Introduction: going beyond the (MS)SM

BSM Models and SARAH

Output of SARAH and interface to other tools

Summary and practical introduction

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
- ... $\rightarrow$ see Wolfgang's Lectures

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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.

Steps to study a new model

collider phenomenology | dark matter | check constraints | ...

↑ ↑ ↑ ↑

Add loop corrections to masses

↑

Calculate the mass spectrum and parameters

↑

Embed model in GUT theory: **RGEs needed**

↑

Derive expressions for masses, vertices, ...

↑

Idea for a new model

looks like a long and exhaustive way

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Idea for a new model

is covered in a completely automatized way

Linking Model Building and Phenomenology using SARAH

1. Build and understand your model

Check model for consistency, get the Lagrangian, derive masses, vertices, RGEs.

→ Strength of SARAH

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Calculate the mass spectrum based on GUT or low scale input

→ interface to SPheno

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3. Constraints

Check constraints from dark matter, precision observables and vacuum stability.

→ interface to SPheno, MicrOmegas, Vevacious, HiggsBounds/HiggsSignals

Linking Model Building and Phenomenology using SARAH

4. Make your Collider study

Use your favorite MC tool and make some nice study.
$\rightarrow$ interface to CalcHep, CompHep, MadGraph, WHIZARD,. . .

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You might want to check loop corrections or do other calculations.
→ interface to FeynArts/FormCalc

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6. Save time and work

Combine all tools in an automatized way
→ try the BSM Toolbox
(sarah.hepforge.org/Toolbox.html)

BSM Models and SARAH

Implement models in 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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SARAH

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- gauge & global symmetries
- particle content
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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

  $(m^2\phi\phi^*,\ M_\lambda\lambda\lambda,\ T\phi_i\phi_j\phi_k,\ B\phi_i\phi_j,\ L\phi_i)$
- Field rotations to mass eigenbasis are performed by SARAH

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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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.

Supported gauge groups

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

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

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]}
};
```

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.

Analytical information derived by SARAH I

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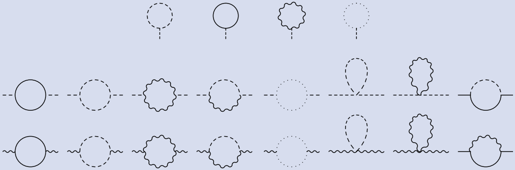
General QFT: Full CP and flavour structure [Luo,Wang,Xiao,hep-ph/0211440]
+ Support of kinetic mixing [Fonseca,Malinsky,FS,1308.1674]
+ Running VEVs in R_ξ gauge [Sperling,Stöckinger,Voigt,1305.1548,1310.7629]

One-loop corrections

All corrections to tadpoles and self-energies are calculated:



→ 1-loop corrections to **all** masses

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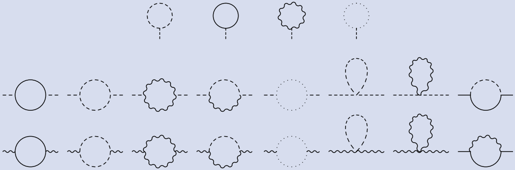

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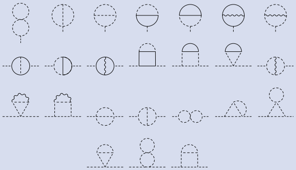
Two-loop corrections

Two-loop corrections to neutral scalars in gaugeless limit:



→ 2-loop corrections to Higgs states

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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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 both looks very promising

SARAH and SPheno

'Spectrum Generator Generator'

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

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Features of 'SPheno by SARAH' versions

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

Mass calculation with SARAH and SPheno

Thresholds corrections

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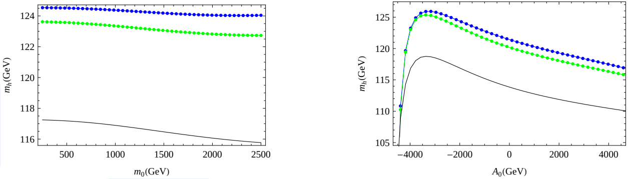
Two-loop contributions

[Goodsell,Nickel,FS,1411.0675,1503.03098]

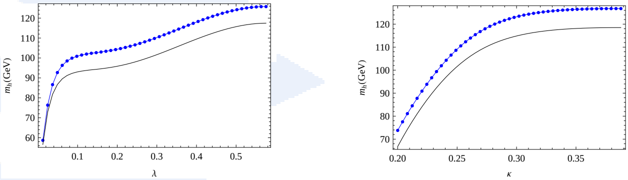
Generic two-loop contributions are implemented in gaugeless limit $\rightarrow$ pushes all models to MSSM precision when using SoftSUSY, Suspect or SPheno out-of-the box

Two-loop Corrections: Validation I

MSSM:



NMSSM:



full lines: SARAH, dots: Brignole,Dedes,Degrassi, Slavich, Zwirner

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

Two-loop Corrections: Validation II and Applications

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

[Goodsell,Slavich]

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Functionality used to get new two-loop Higgs results

- Contributions of trilinear RpV [Dreiner,Nickel,FS,1411.3731]
- Missing corrections for NMSSM [Goodsell,Nickel,FS,1411.4665]
- Contributions from non-holomorphic soft-terms [Ün, Tanyildizi,Kerman Solmaz,1412.1440]
- MRSSM at full two-loop [Diessner,Kalinoswki,Kotlarski,Stöckinger,1504.05386]
- Contributions from vectorlike stops [Nickel,FS,1505.06077]

Decay widths and branching ratios

New matter and heavy gauge boson decays

- All 2-body decays of scalars, fermions and vector bosons
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Higgs decays

- All 2-body decays into BSM particles and leptons at tree-level
- 2-body decays into quarks with gluonic NLO corrections
- 2-body decays in off-shell vector bosons included
- Loop induced decays in two photons and gluons at LO; NLO QCD corrections from SM added

Implemented observables

Many flavour observables are calculated out-of-box at full one-loop:

- Lepton flavour violation:
  - 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')
- Quark flavour violation:
  - 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($D_s \to l\nu$)

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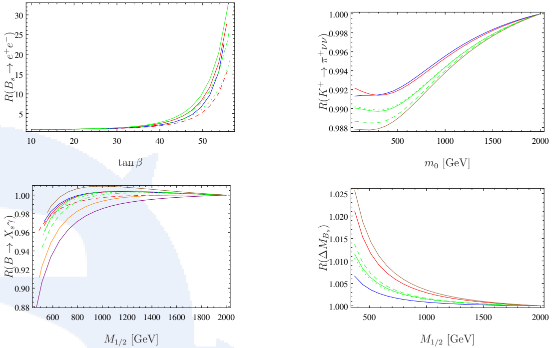
  - Br($B \to l\nu$), Br($D_s \to l\nu$)

FlavorKit [Porod,FS,Vicente,1405.1434]

The FlavorKit functionality can be used to add more observables.

Comparison with other codes for the MSSM



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

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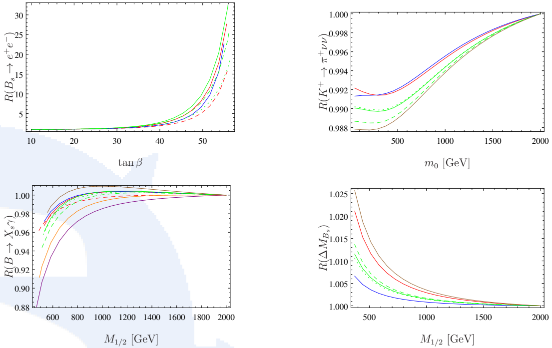

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Differences

Caused by chiral resummation, higher order corrections, handling of scales, ...

Checking Higgs constraints

SPheno modules write all necessary input files for HiggsBounds and HiggsSignals

HiggsBounds/HiggsSignals [Bechtle et al.,0905.2190,1102.1898,1305.1933]

HiggsBounds tests models against the exclusion bounds obtained by LEP, the Tevatron and the LHC.

HiggsSignals performs a χ^2 test of the Higgs sector predictions against the measured signal rates and masses.

- Up to nine neutral scalars possible
- With a small hack of HiggsBounds/HiggsSignals even more

MC Tools and SARAH

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- SLHA+ functionality: CalcHep reads SPheno spectrum files
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UFO output

SARAH writes model files in the UFO format which can be used by:

- MadGraph, Herwig++, Sherpa
- SPheno file can be used as parameter card for MadGraph

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WHIZARD model files

SPheno modules of SARAH write additional input file to pass parameter values to WHIZARD

SARAH + SPheno + MC tools

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→ Spectrum calculator and Monte Carlo tool use for sure the same conventions

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SPheno provides also the width of all particles

→ not needed to be obtained by MC code

Other outputs of SARAH

FeynArts/FormCalc

SARAH writes model files for FeynArts/ FormCalc.

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FormCalc

- Makes use of Feynman diagram generated by FeynArts and Form for analytical manipulations
- Calculates tree-level and one-loop amplitudes
- Squares amplitudes; performs colour simplifications, polarisation sums, . . .
- Writes Fortran or C code for numerical calculations

Vevacious

SARAH can write the input file for Vevacious

Vevacious

- Finds the global minimum of the one-loop effective potential
- Approach:
  - Find all tree-level minima via homotopy method (HOM4PS2)
  - Use minuit to roll down the one-loop effective potential
  - Include finite temperature effects

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Possible Applications:

- Find other VEV combinations of Higgs states in models beyond the MSSM (e.g. NMSSM with large A-terms)
- Check for charge and colour breaking minima
- Check for spontaneous R-parity violation
- ...

LaTeX

LaTeX files

- Includes analytical expressions for:
  - Field rotations and mass matrices
  - Tadpole equations
  - All vertices
  - One-loop self-energies and tadpoles
  - Two-loop RGEs
- FeynMP can be included to draw Feynman diagrams for all vertices

Summary and practical introduction

collider pheno	dark matter	Higgs constraints	...	CalcHep, WHIZARD, HB, HS, MG5, MicrOmegas, FeynArts,...
↑	↑	↑	↑	

calculate observables; decays of sparticles and Higgs

↑

calculate running parameters; loop corrected masses; fine-tuning

(SPheno)

↑

create model files for MC tools and Fortran code for `SPheno`

↑

derive expressions for masses, vertices, RGEs, ...

(SARAH)

↑

create `SARAH` **input file**

↑

Idea for a new model

(User)

How to use SARAH?

Short practical introduction to SARAH:

Today, 19:20

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Possible topics of tutorials for interested students:

- Using SARAH to get analytical information about your model
- Implementing new models in SARAH
- Interface to SPheno
- Interface to MC-Tools and MicrOmegas
- Interface to HiggsBounds/HiggsSignals via SPheno
- New observables with FlavorKit
- ...

→ Let me know if you are interested!

List of SUSY models delivered with SARAH

- MSSM: with/without FV or CPV
- Low scale extensions of the MSSM:
  - Singlet extensions: NMSSM, nMSSM, SMSSM (GNMSSM)
  - Triplet extensions: TMSSM, TNMSSM
  - RpV: bilinear RpV, Lepton/Baryon number violation, $\mu\nu$SSM
  - Additional $U(1)'s$: UMSSM, sMSSM, B-L-SSM, $U(1)_R \times U(1)_{B-L}$
  - inverse seesaw, linear seesaw
  - MSSM with color sextet
- Models with Dirac gauginos:
  - MDGSSM
  - MRSSM
- High scale extensions
  - Seesaw 1 - 3 ($SU(5)$ version)
  - Left/right model (ΩLR)
- Others:
  - Models with vectorlike (s)tops
  - Models with $SU(3)$ sexplets