Automatizing validation of Higgs sectors - the case study of 95 GeV resonance

Scalars 2023

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FlexibleSUSY in a nutshell

- There are codes like 2HDMC, SPheno, SOFTSUSY or SuSpect that calculate mass spectra and various observables for a predefined model (THDM in case of 2HDMC and MSSM/NMSSM in remaining cases).
- FlexibleSUSY is a spectrum-generator generator - creates a code analogue to abovementioned programs but for an arbitrary BSM model.
- Use known results for a generic QFT. Don't recalculate what you don't have to from the ground.
- Streamlining study of BSM phenomenology, reducing time needed to study a new model from years to weeks. No hand written code, less place for errors.

What you get (singlet+SM example)

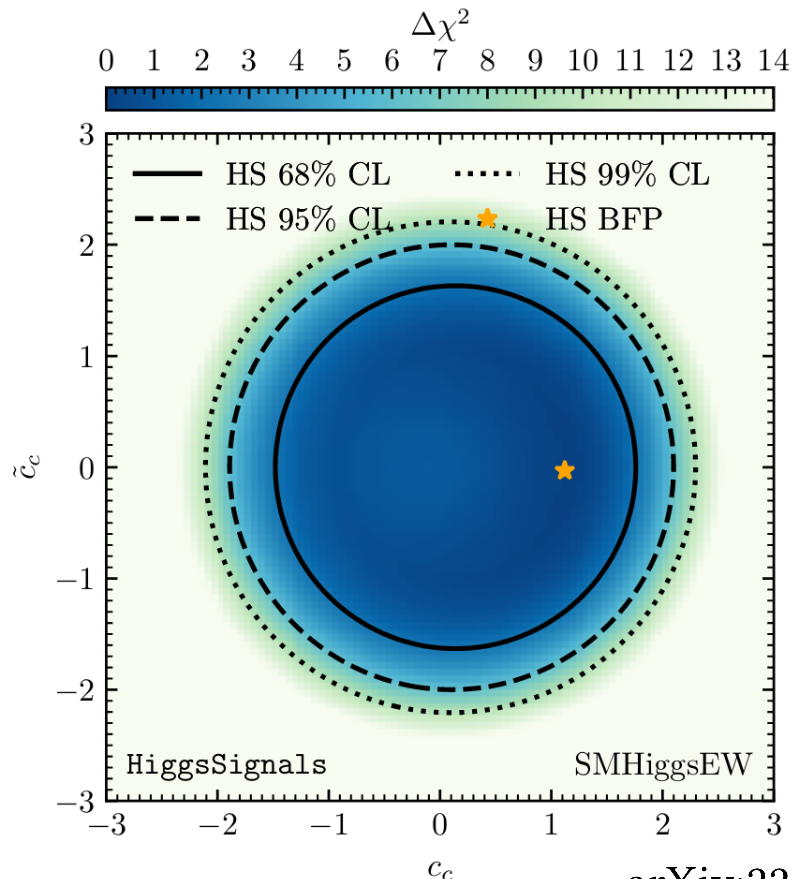
```
...
Block DCINFO
     1   FlexibleSUSY
     2   2.6.1
     5   SSMMhInput
     9   4.14.3
DECAY         25     3.20846016E-03   # hh(1) decays
     5.82089643E-01   2           -5          5  # BR(hh(1) -> barFd(3) Fd(3))
     2.10479150E-01   2          -24         24  # BR(hh(1) -> conjVWp VWp)
     8.56684916E-02   2           21         21  # BR(hh(1) -> VG VG)
     6.19432803E-02   2          -15         15  # BR(hh(1) -> barFe(3) Fe(3))
     2.87673651E-02   2           -4          4  # BR(hh(1) -> barFu(2) Fu(2))
     2.67950080E-02   2           23         23  # BR(hh(1) -> VZ VZ)
     2.29059815E-03   2           22         22  # BR(hh(1) -> VP VP)
     1.48172847E-03   2           22         23  # BR(hh(1) -> VP VZ)
     2.64726402E-04   2           -3          3  # BR(hh(1) -> barFd(2) Fd(2))
     2.19292886E-04   2          -13         13  # BR(hh(1) -> barFe(2) Fe(2))
DECAY         35     8.56617420E-01   # hh(2) decays
...
```

HiggsTools

Bahl, Biekötter, Heinemeyer, Li, Paasch, Weiglein, Wittbrod

- Succesor of HiggsBounds and HiggsSignals
- Consists of two parts:
  - HiggsSignals: checks SM-like Higgs
  - HiggsBounds: checks BSM Higgses
- Example: SM-like Higgs with perturbed coupling to charm quarks
- Some care needed in interpreting χ^2 from HiggSignals

CP–odd



arXiv:2210.09332

CP–even

HiggsTools interface

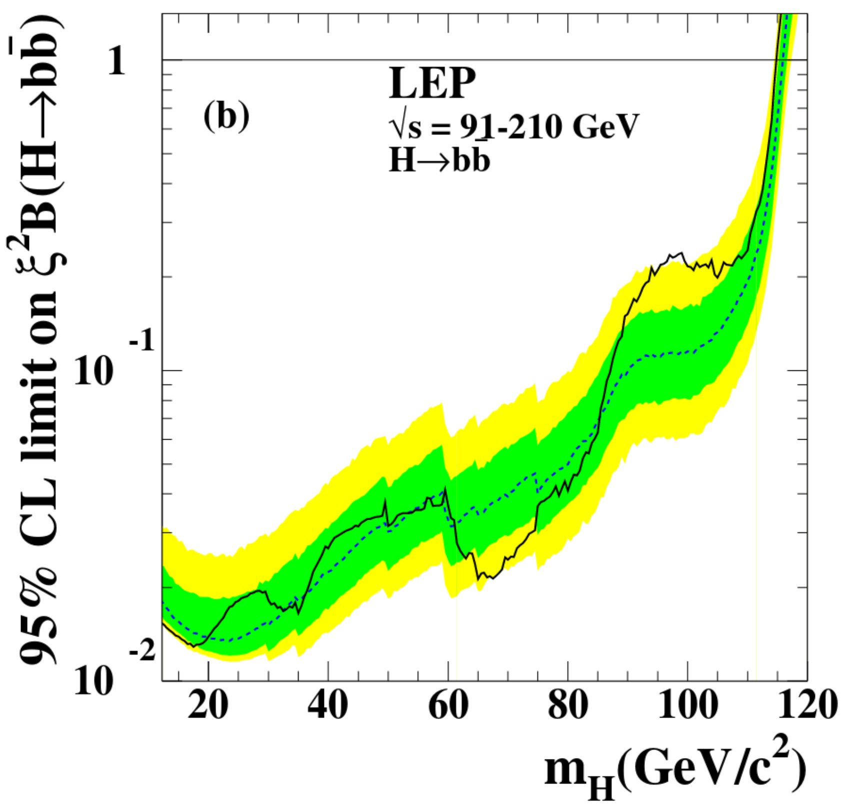
- Using HiggsTools from FlexibleSUSY is totally transparent to the user
- Howto:
  - install HiggsTools
  - point FlexibleSUSY to it's location during configuration
  - you're good to go

```
Block HIGGSSIGNALS
     1      1.59000000E+02   # number of degrees of freedom
     2      1.57662766E+02   # χ²
     3      1.51551655E+02   # SM χ² for mh = 125.250000 GeV
     4      4.70965484E-02   # p-value
Block HIGGSBOUNDS
 25  1      2.38307377E-01   # LHC13 [vbfH,HW,Htt,H,HZ]>[gamgam] from 1811.08459 ...
 25  2      5.84526557E-01   # expRatio
 35  1      7.11468251E-01   # LHC8 [vbfH,HW,Htt,H,HZ]>[bb,tautau,WW,ZZ,gamgam] ...
 35  2      3.57914871E+00   # expRatio
```

LEP hints of a 95 GeV scalar

- Higgsstrahlung excess in the $b\bar{b}$ channel [arXiv:0306033]
- Can be accommodate by a intermediate state H [arXiv:1612.08522]

$$\mu_{b\bar{b}}^{\text{LEP}} = \frac{\sigma^{exp}(e^+e^- \to Z\phi \to Zb\bar{b})}{\sigma^{\text{SM}}(e^{+-} \to ZH \to Zb\bar{b})} = 0.117 \pm 0.057$$



LHC hints of a 95 GeV scalar

- Recent ATLAS result based on the full Run 2 data set

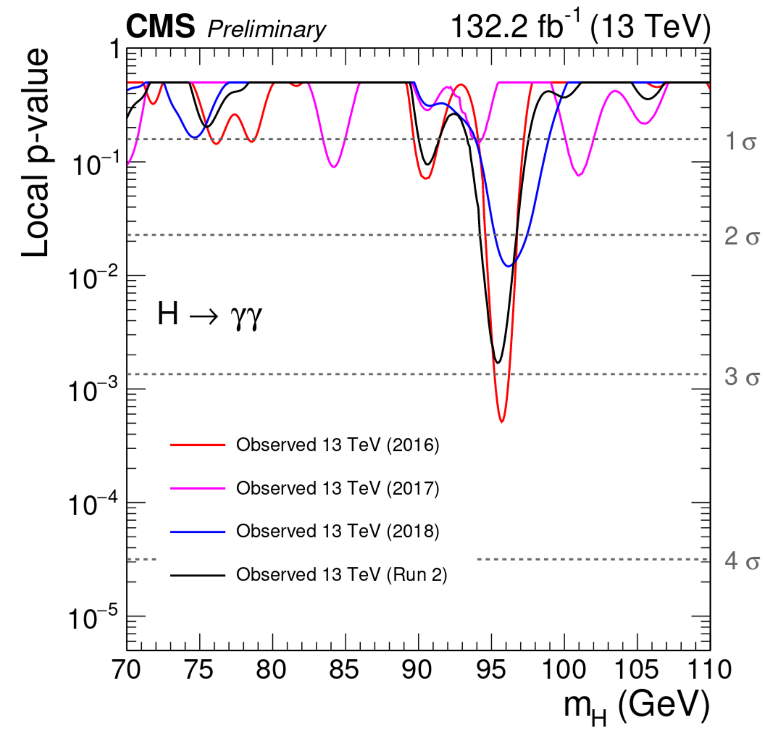
$$\mu_{\gamma\gamma}^{\text{ATLAS}} = \frac{\sigma^{\text{exp}}(pp \to \phi \to \gamma\gamma)}{\sigma^{\text{SM}}(pp \to H \to \gamma\gamma)} = 0.18^{+0.10}_{-0.10}$$

- Consistent with the already existing CMS excess

$$\mu_{\gamma\gamma}^{\text{CMS}} = \frac{\sigma^{\text{epx}}(pp \to \phi \to \gamma\gamma)}{\sigma^{\text{SM}}(pp \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

- Combined (Biekotter, Heinemeyer, Weiglein [arXiv:2306.03889])

$$\mu_{\gamma\gamma}^{\text{ATLAS + CMS}} = 0.24^{+0.09}_{-0.08}$$



Generic setup

- Mostly gauge singlet state

$$h_1^2 = \tfrac{1}{10} s^2 + \ldots$$

with mass 95.4 GeV. Such composition solves this

$$\mu_{b\bar{b}}^{\mathrm{LEP}} = \frac{\sigma^{\mathrm{BMS}}(e^+e^- \to Zh_1 \to Zb\bar{b})}{\sigma^{\mathrm{SM}}(e^+e^- \to ZH \to Zb\bar{b})} \approx 0.1$$

- But it equally (by a factor 1/10) suppreses

$$\mu_{\gamma\gamma} = \frac{\sigma^{\mathrm{BSM}}(pp \to h_1 \to \gamma\gamma)}{\sigma^{\mathrm{SM}}(pp \to H \to \gamma\gamma)} \approx 0.1$$

- You need a way to enhance

$$\mathrm{BR}(\phi \to \gamma\gamma) \approx (2 - 2.5)\mathrm{BR}(H \to \gamma\gamma)$$

R-symmetry

- R-symmetry is an additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem
- For N=1 SUSY it is a global $U(1)_R$ symmetry under which the SUSY generators are charged
- implies that the spinorial coordinates are also charged

$$Q_R(\theta) = 1,\ \theta \to e^{\imath\alpha}\theta$$

- Lagrangian invariance
  - Kähler potential K term is automatically invariant
  - R-charge of the superpotential W must be 2

$Q_R(d^2\theta)$=-2

$Q_R(\mathcal{L})$=0 $\longrightarrow$ $\mathcal{L} \ni \int d^2\theta\, W$

$Q_R(W)$=+2

  - soft-breaking terms must have R-charge 0

Particle content summary: MSSM vs. MRSSM

different number of physical state completely new states

	Higgs				R-Higgs		
	CP-even	CP-odd	charged	charginos	neutral	charged	sgluon
MSSM	2	1	1	2	0	0	0
MRSSM	4	3	3	2+2	2	2	2

	neutralino	gluino
MSSM	4	1
MRSSM	4	1

Majorana fermions

Dirac fermions

Light singlet setup

- Two lightest Higgses are a mixture of H_u and S

$$\mathcal{M}^{\phi}_{u,S} = \begin{pmatrix} m_Z^2 + \Delta m_{rad}^2 & v_u\left(\sqrt{2}\lambda_u \mu_u^{\text{eff},-} + g_1 M_B^D\right) \\ v_u\left(\sqrt{2}\lambda_u \mu_u^{\text{eff},-} + g_1 M_B^D\right) & 4(M_B^D)^2 + m_S^2 + \frac{\lambda_u^2 v_u^2}{2} \end{pmatrix}$$

- Obvious constraints:
  - mixing has to be small
  - $4(M_B^D)^2 + m_S^2 \approx (95\text{GeV})^2 \Longrightarrow$ this setup enforces light DM candidate
  - $|\lambda|_u \ll 1$

Example solution

- Reminder: we've identified

$$\lambda_d \hat{S}\hat{R}_d\hat{H}_d$$

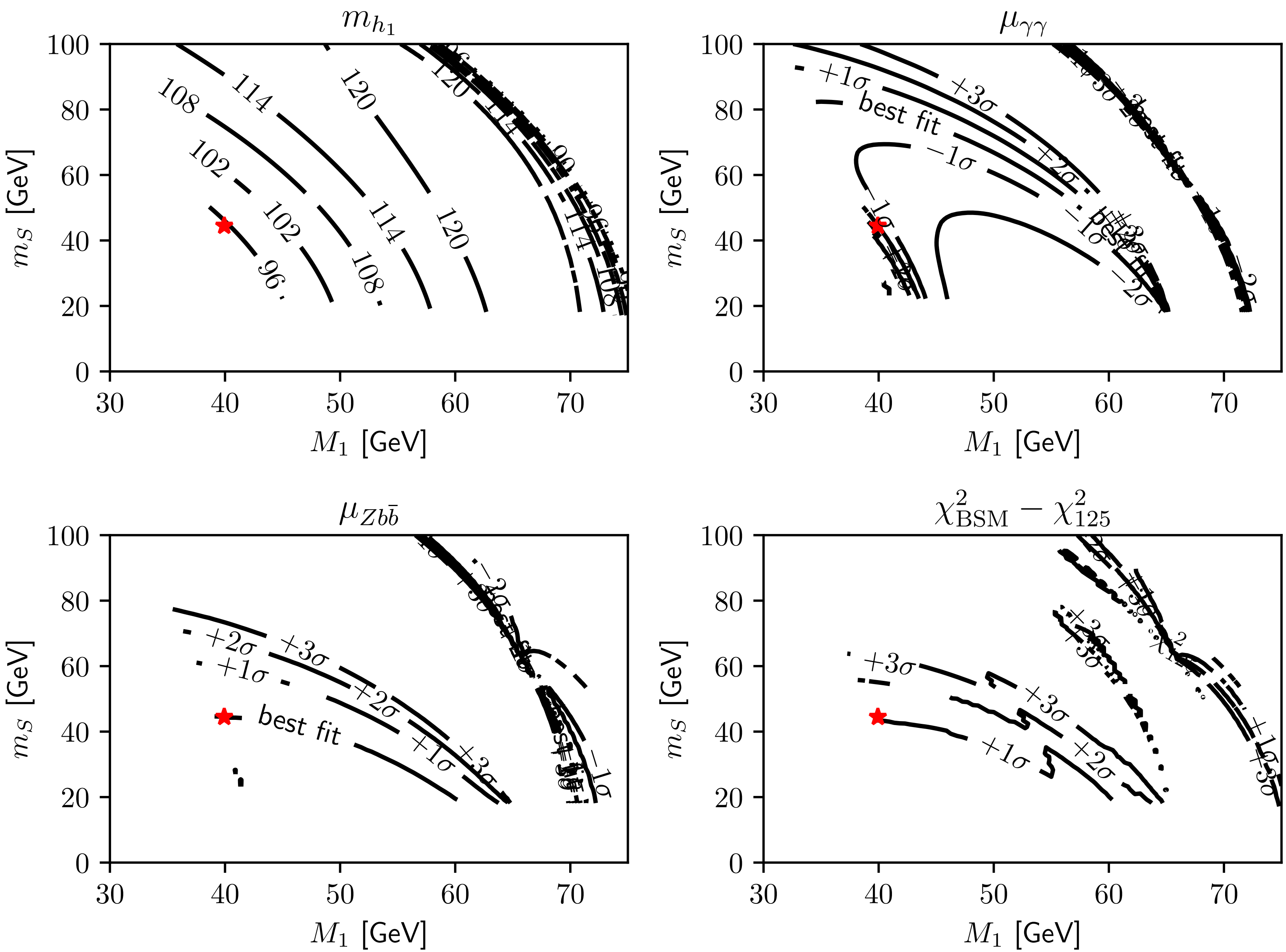
  as a crucial term to enhance $\mathrm{BR}(h_1 \to \gamma\gamma)$
- Parameters: M_1 = 40 GeV, m_S = 45 GeV, λ_d = -1
- Masses: h_1 = 95.4 GeV, h_2 = 125.25 GeV, A_1 = 38 GeV
- Properties:

$$\mu_{b\bar{b}}^{\mathrm{LEP}} = 0.117$$

$$\frac{\sigma(gg \to h_1)}{\sigma^{\mathrm{SM}}(gg \to H)} = 0.102 \qquad \times \qquad \frac{\mathrm{BR}(h_1 \to \gamma\gamma)}{\mathrm{BR}(H \to \gamma\gamma)} = 2.354 \qquad = 0.24$$

- both CP-even Higgses follow typical SM-like decay patters with small invisible decay widths. SM Higgs p-value 0.283.
- A_1 is extreamly narrow (10^{-10} GeV) pseudoscalar A_1 with almost 100% BR to $\gamma\gamma$

Numerics



m_{h_1}
$\mu_{\gamma\gamma}$
$\mu_{Zb\bar{b}}$
$\chi^2_{\mathrm{BSM}} - \chi^2_{125}$
m_S [GeV]
M_1 [GeV]
0
20
40
60
80
100
30
40
50
60
70
96
102
108
114
120
$+1\sigma$
$+2\sigma$
$+3\sigma$
-1σ
-2σ
best fit

DM constraints

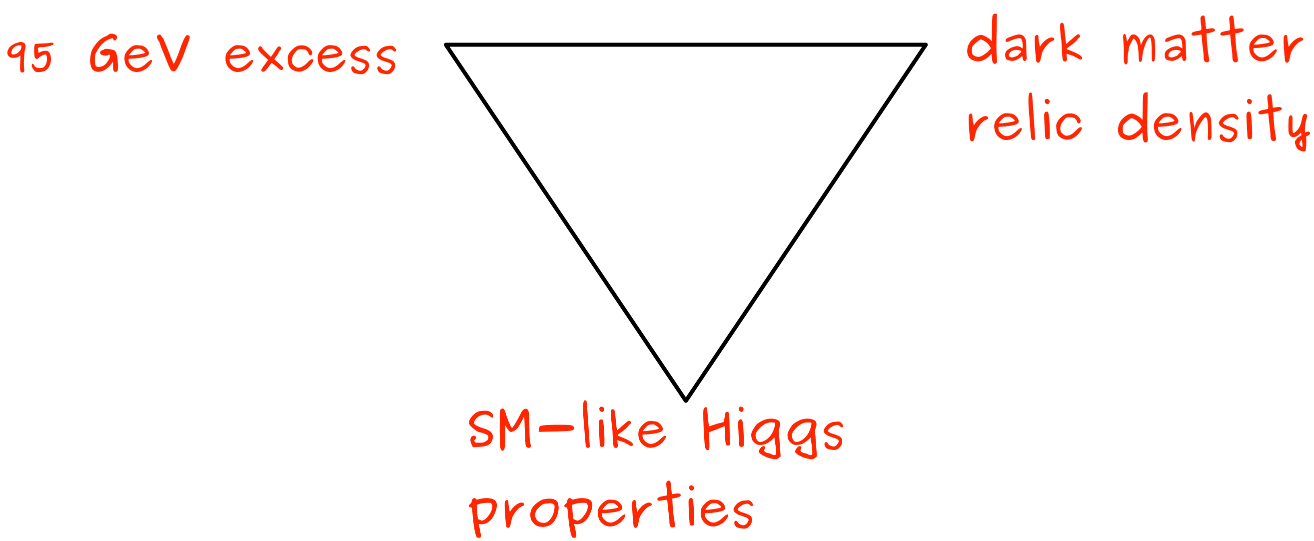
- Including DM as a contraint worsens the fit. You can get point with

$$\Omega h^2 = 0.128$$

  and allowed by direct detection
- with LEP & CMS excess strengths of

$$\mu_{\gamma\gamma} = 0.217 \qquad \mu_{b\bar{b}} = 0.077$$

- but with a SM-like Higgs p-value of 0.05
- There seems to be a trade off in this setup between



Conclusions and outlook

- Streamlining comparison of Higgs sector of **your** favourite model with experimental data
- Example aplication: fitted MRSSM to the 95 GeV excess
- There's no publication for the associated code but it is public. You can grab it from here.

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Norway grants

R-symmetry vs. matter parity

- Consider R-symmetric transformation of a generic supermultiplet

$$R : \Phi(x, \theta, \bar{\theta}) \to \Phi'(x, e^{\imath\varphi}\theta, e^{-\imath\varphi}\bar{\theta}) = e^{\imath\varphi R_\Phi}\Phi(x, \theta, \bar{\theta})$$

- In the MSSM one imposes the so-called matter parity

$$M_p = (-1)^{3(B-L)}$$

  - this is equivalent to R-pairity which is defined on components of a supermultiplet as $P_R = (-1)^{3(\mathrm{B-L})+2s}$
  - This is also equivalent to R-symmetry $R = e^{\imath\varphi R_\Phi}$ with $\varphi = \pi$ and $R_\Phi = 3(B-L)$
- R-charges
  - MSSM: $R_\Phi = 0, 1$
  - MRSSM: $R_\Phi = 0, 1, 2$
- R-symmetry is more restrictive than matter parity

Program flow

SARAH
(F. Staub, M. Goodsell, W. Porod)

↓

FlexibleSUSY

↓

C++ code

↓ solve BVP

calculate m_h, m_W, BSM masses, $(g-2)_\mu$, EDMs, …

- Analytic calculation: particle content + Lagrangian ⟹ tadpole equations, self-energies, mass matrices, RGEs, vertices etc.

- Creates code for numerical evaluation of various observables
  - 1-loop pole masses and mixing matrices (in specific models higher corrections are available)
  - observables: muon $(g\text{-}2)_\mu$, lepton's EDMs, $l \to l'\gamma$, $b \to s\gamma$, scalar decays
  - soon: $l \to l'$ conversion in nuclei, $l \to 3l$

Low-energy R-symmetry realization

- Charges of component fields

$$\begin{array}{ccccccccc} e^{\imath\alpha Q_R} & & e^{\imath\alpha Q_R} & & e^{\imath\alpha (Q_R-1)} & & \\ \Phi & = & \phi(y) & + & \sqrt{2}\theta\psi(y) & + & \theta\theta F(y) \end{array}$$

- “Natural” choice

Higgs	$Q_R = 1$	$Q_R = 1$	$Q_R = 0$
leptons and quarks	$Q_R = 0$	$Q_R = 0$	$Q_R = -1$

- Good: no barion and lepton number violating terms
- Bad: No Majorana masses for higgsinos and gauginos

One way to fix it: Dirac masses

Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)

Kribs et.al. arXiv:0712.2039

			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
Additional fields:	Singlet	$\hat{S}$	1	1	0	0
	Triplet	$\hat{T}$	1	3	0	0
	Octet	$\hat{O}$	8	1	0	0
	R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
		$\hat{R}_d$	1	2	$1/2$	2

$$\begin{aligned} W = & \mu_d \, \hat{R}_d \, \hat{H}_d + \mu_u \, \hat{R}_u \, \hat{H}_u \\ & + \Lambda_d \, \hat{R}_d \, \hat{T} \, \hat{H}_d + \Lambda_u \, \hat{R}_u \, \hat{T} \, \hat{H}_u + \lambda_d \, \hat{S} \, \hat{R}_d \, \hat{H}_d + \lambda_u \, \hat{S} \, \hat{R}_u \, \hat{H}_u \\ & - Y_d \, \hat{d} \, \hat{q} \, \hat{H}_d - Y_e \, \hat{e} \, \hat{l} \, \hat{H}_d + Y_u \, \hat{u} \, \hat{q} \, \hat{H}_u \end{aligned}$$

MSSM vs. MRSSM

- MSSM superpotencial

$$\mu \hat{H}_u \hat{H}_d$$

$$-Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d\;-Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d\;+Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u$$

- MSSM soft-SUSY breaking terms
  - B_μ - term
  - soft scalar masses
  - Majorana gaugino masses
  - A - terms

- MRSSM superpotencial

$$\mu_d\,\hat{R}_d\,\hat{H}_d\;+\mu_u\,\hat{R}_u\,\hat{H}_u$$

$$-Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d\;-Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d\;+Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u$$

$$\Lambda_d\,\hat{R}_d\,\hat{T}\,\hat{H}_d\;+\Lambda_u\,\hat{R}_u\,\hat{T}\,\hat{H}_u\;+\lambda_d\,\hat{S}\,\hat{R}_d\,\hat{H}_d\;+\lambda_u\,\hat{S}\,\hat{R}_u\,\hat{H}_u$$

- MRSSM soft-SUSY breaking terms
  - B_μ- term (though no B_{μ_u}, B_{μ_d})
  - soft scalar masses
  - Dirac gaugino masses
  - no A-terms

One way to fix it: Dirac masses
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		$\hat{R}_d$	1	2	$1/2$	2