(Non-minimal) SUSY Phenomenology of the minimal R-symmetric SUSY model

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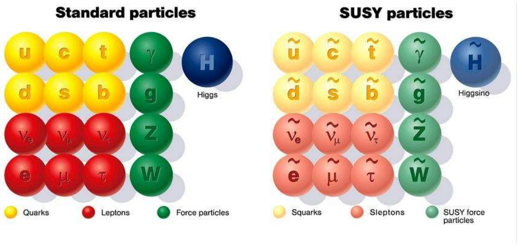
KIAS Workshop, October 2016

based on work with: [Philip Diessner, Jan Kalinowski, Wojciech Kotlarski, and Sebastian Liebschner '14, '15, '16]

Outline

SUSY



- Fundamental new symmetry, unique extension of Poincaré
- Relation to gravity, string theory

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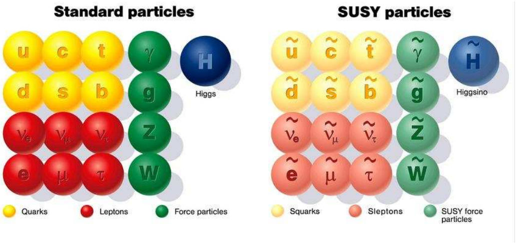

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- Unification of gauge couplings
- Dynamic generation of mexican hat potential
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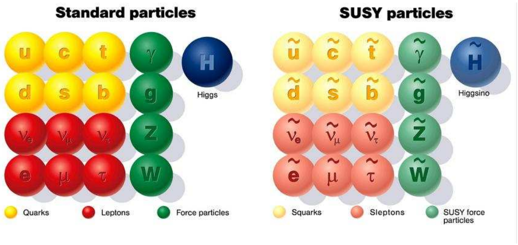

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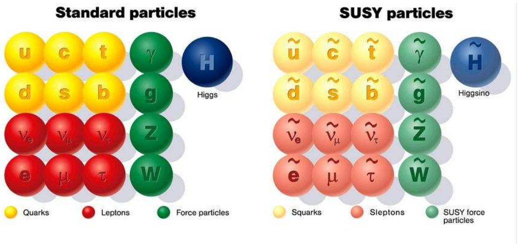
- Minimality was never an argument! These motivations hold equally well in minimal and non-minimal SUSY!

SUSY



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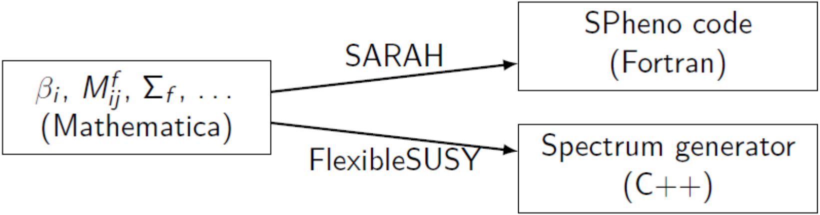
- Dark matter
- some non-minimal models even better motivated than MSSM (improve μ-problem, flavor problem, allow lighter/heavier sparticles)

Tools for non-minimal SUSY (advertisement/warning)

Model	Spectrum generator
MSSM	Softsusy, Spheno, Isasusy, SuseFlav, Suspect
NMSSM	NMSpec, Softsusy
any SUSY model	Sarah [F. Staub], **FlexibleSUSY** [Athron, JH Park, DS, Voigt]



FlexibleSUSY properties:

- simple def. of model ($\to$ Sarah)/boundary condition
- c++ code modular, readable, can be reused, customized, extended!

  "hacking vs. programming" (Jae-hyeon Park)

Later calculations based on both codes + selected by-hand one-loop/two-loop calculations $\rightsquigarrow$ cross-checks very important!

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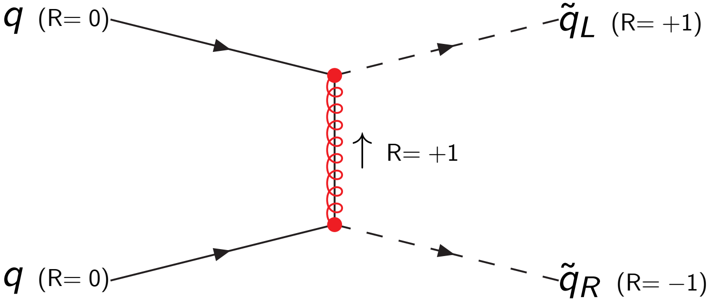
R-symmetric model MRSSM [Kribs, Poppitz, Weiner]



- Continuous, conserved R-charge. R-charges fixed by SUSY-algebra

(in superfields: $\theta \to e^{i\alpha}\theta$)

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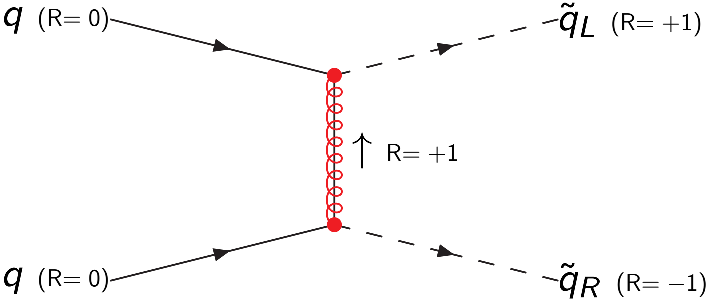

- some MSSM-processes forbidden
- surviving ones have stronger m_{gluino}-suppression

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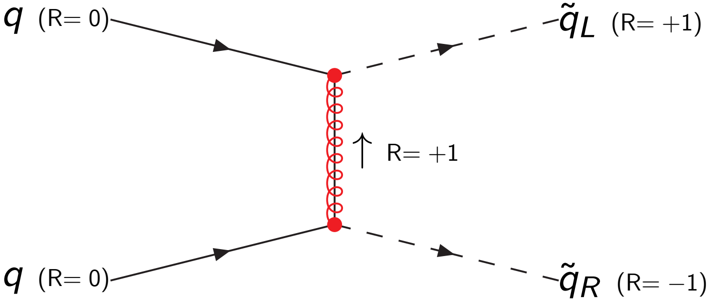

- gluino (and other gauginos/Higgsinos) = Dirac-fermion
  - gluon: 2 d.o.f.
  - gluino: 4 d.o.f.
  - new scalar sgluon: 2 d.o.f

(SU(3)×SU(2)×U(1) requires new chiral superfields (adjoint) $\hat{O}$, $\hat{T}$, $\hat{S}$)

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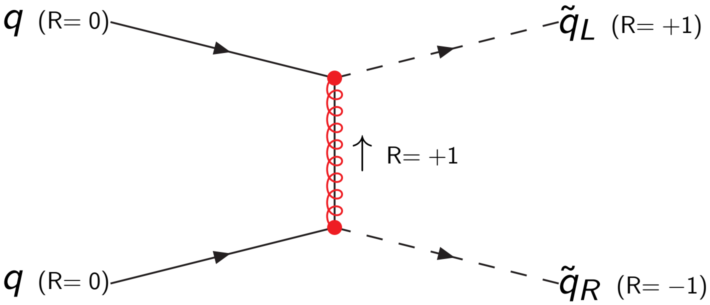

Same for all gauginos $\Rightarrow$ new scalars

- colour octet scalars (sgluons)
- SU(2) triplet scalar (Higgs Triplet!)
- Higgs singlet

Technical summary of MRSSM

New symmetry, $\theta \to e^{i\alpha}\theta$

- $\tilde{q}_L$: R=+1, $\tilde{q}_R$: R= -1, no LR-mixing!

Dirac gauginos, new superfields $\hat{O}$, $\hat{T}$, $\hat{S}$

- Dirac gluinos
- new scalars: sgluons, Higgs triplet, Higgs singlet

Dirac Higgsinos, new superfields $\hat{R}_u$, $\hat{R}_d$

- New superpotential terms
  $W_{\text{MRSSM}} = \ldots + \mu_u \hat{H}_u \hat{R}_u + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u + \lambda_u \hat{H}_u \hat{S} \hat{R}_u + y_u \hat{Q} \hat{H}_u \hat{U}$

$\Rightarrow$ Mass eigenstates: 4 Dirac neutralinos, 4 Dirac charginos

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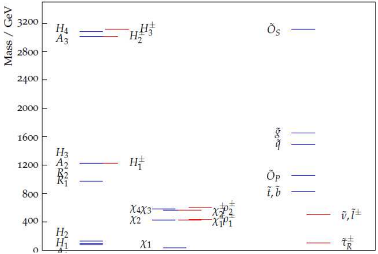

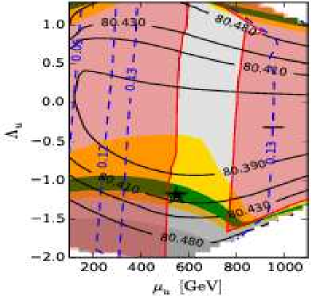

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   - $M_h^{\text{Exp}} = 125.09 \pm 0.24$ GeV, $M_W^{\text{Exp}} = 80.385 \pm 15$ GeV
   - $\Omega h^2 = 0.1199 \pm 0.0027$, no dark matter direct detection
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Question 1: MRSSM compatible with Higgs, W mass measurements? [Diessner, Kalinowski, Kotlarski, DS '14, '15]

Bad/difficulty for M_h: more scalars S, T^0 mix, reduced tree-level mass

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(for $v_{S,T} \ll v$, $m_D^2 \ll m_{\text{soft}}^2$:)

- off-diag. elements=Higgsino/gaugino masses shouldn't be too large, loop corrections very important

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- Top Yukawa: $y_u \hat{Q}\hat{H}_u\hat{U}$:

$$(\Delta m_h)^2 \propto y_u^4 \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

- New Yukawa: $\Lambda_u \hat{H}_u \hat{T} \hat{R}_u$:

$$(\Delta m_h)^2 \propto \frac{4\lambda^4 + 4\lambda^2\Lambda^2 + 5\Lambda^4}{4} \log \frac{m_{\text{scalar}}^2}{m_D^2}$$

(additional positive two-loop contributions from sgluons!)

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- motivates large "Yukawa coupling" Λ_u and mass splitting $m_D \ll m_{\text{scalar}}$

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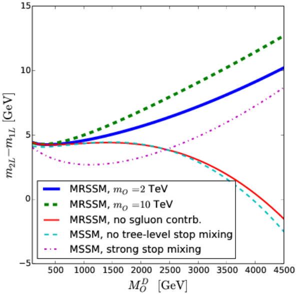
Additionally: positive two-loop corrections from sgluons



However, danger for M_W:

- Yukawas shouldn't be too large!
- Higgs Triplet VEV must be small!

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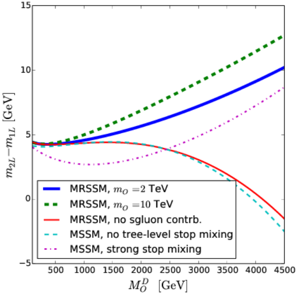

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Answer 1: There is viable parameter space! [Diessner, Kalinowski, Kotlarski, DS '14, '15]

Interesting properties of MRSSM, sample scenarios

- R-charges forbid some processes
- Dirac gauginos, and Dirac Higgsinos
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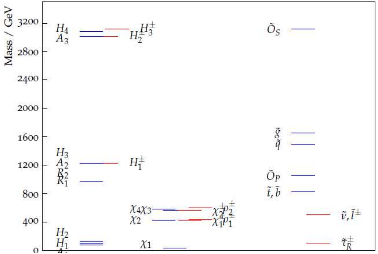
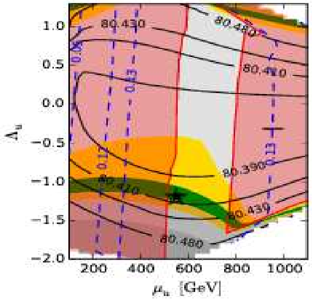
- M_h: motivates rather light charginos
- ...and large "Yukawa coupling" Λ_u





Question 2: light singlet possible/helpful?

- Should be an advantage:
- No tree-level reduction for SM-like Higgs
- relevant H_u–S mass matrix shows the requirements:

$$\mathcal{M}^{\text{limit}}_{\text{phi};2,3} = \begin{pmatrix} m_Z^2 & v_u(\sqrt{2}\lambda_u\mu_u^{\text{eff-}} + g_1 m_D^B) \\ v_u(\sqrt{2}\lambda_u\mu_u^{\text{eff-}} + g_1 m_D^B) & 4(m_D^B)^2 + m_S^2 + \frac{\lambda_u^2 v_u^2}{2} \end{pmatrix} .$$

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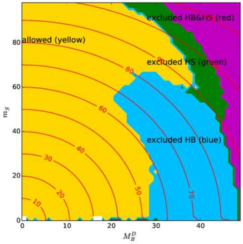
- small m_D^B, m_S, $\lambda_u v_u$ $\to$ is this viable?

Answer 2:
Yes! Light bino Dirac mass possible!

[Diessner,Kalinowski,Kotlarski,DS '15]

Now study dark matter and LHC data!



allowed region for $\lambda_u = 0$:

(used HiggsBounds/HiggsSignals)

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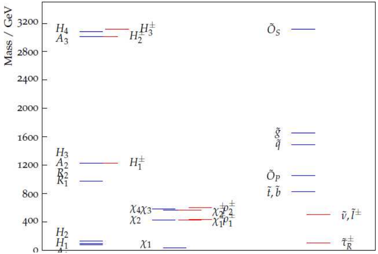

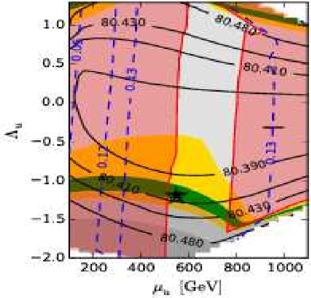

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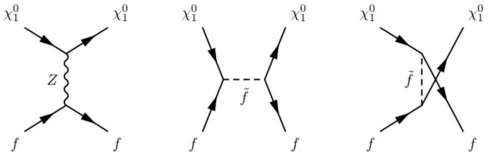

Relic density ($f = \tau$):

- LSP = Dirac Bino
- $m_{\text{LSP}} < 60 \ldots 300\text{GeV}$
- annihilates into τ
- light stau mass fixed, $m_{\tilde{\tau}} - m_{\text{LSP}} < 100\text{GeV}$

Direct detection limits ($f = q$):

- Interference between terms $\propto \frac{1}{\mu_u^2}, \frac{1}{m_{\tilde{q}}^2}$
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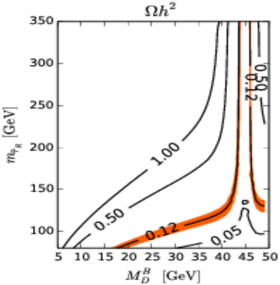

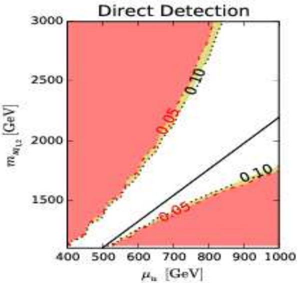

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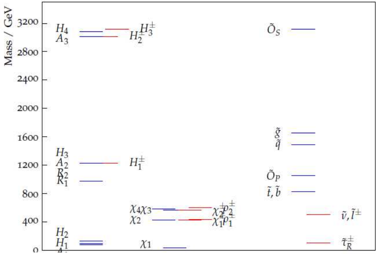

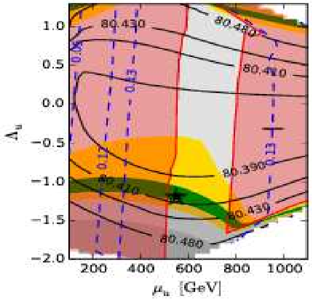

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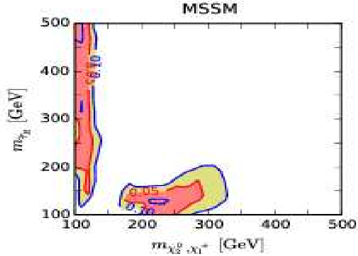
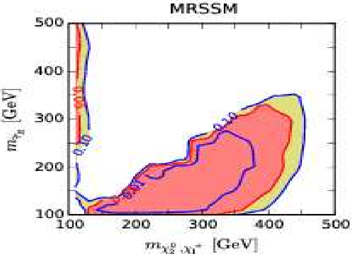
Recast LHC limits for MSSM to MRSSM:
Assume very light singlet and LSP $\sim$ 50 GeV; light stau $\sim$ 100 GeV;
discuss limits on one degenerate neutralino/chargino $\chi^{0,\pm}$





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Answer 3/4: Dark matter can be explained in this scenario!

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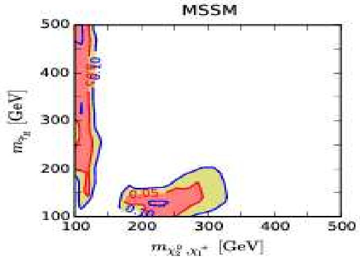

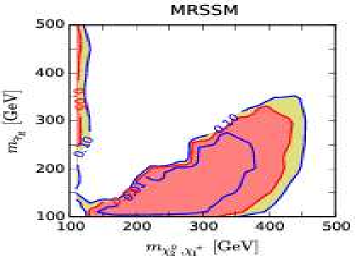

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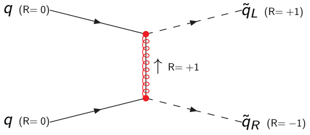
Hope: total cross section reduced, lighter masses possible!



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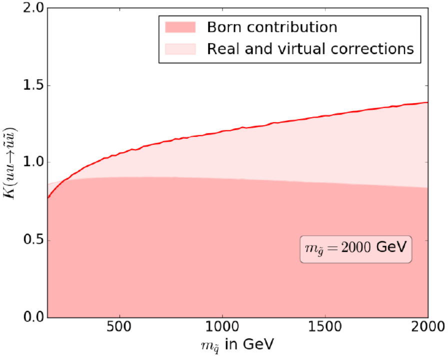
- preliminary result for NLO corrections [Diessner, Kalinowski, Kotlarski, Liebschner, DS]: K-factor in MRSSM is higher than in MSSM! Depends e.g. on sgluon mass



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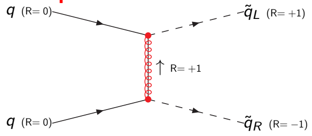

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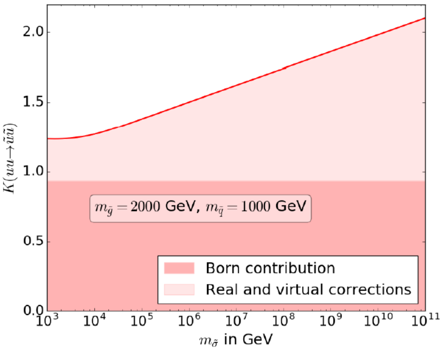
- outlook: compare to LHC data!



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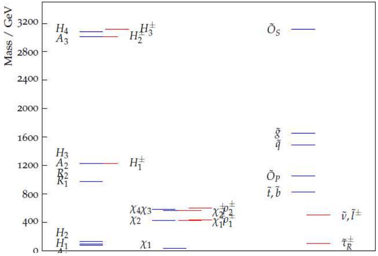
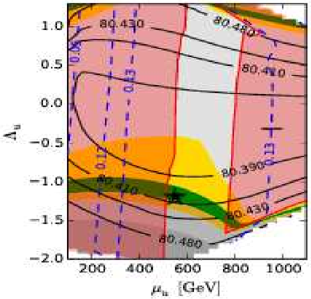
- dark matter: LSP=Dirac Bino, light stau; $\sim$ 500GeV Higgsino μ_u preferred
- LHC EW searches: ok
- LHC squark searches: to do precisely





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	BMP4	BMP5	BMP6
$\tan\beta$	40	20	6
B_μ	200^2	200^2	500^2
λ_d, λ_u	$0.01, -0.01$	$0.0, -0.01$	$0.0, 0.0$
Λ_d, Λ_u	$-1, -1.2$	$-1, -1.15$	$-1, -1.2$
M_B^D	50	44	30
m_S^2	30^2	40^2	80^2
$m_{R_u}^2$, $m_{R_d}^2$		$1000^2, 700^2$	
μ_d, μ_u	130, 650	400, 550	550, 550
M_W^D	600	500	400
M_O^D		1500	
m_T^2, m_O^2		$3000^2, 1000^2$	
$m_{Q;1,2}^2$, $m_{Q;3}^2$	$1500^2, 700^2$	$1300^2, 700^2$	$1400^2, 700^2$
$m_{D;1,2}^2$, $m_{D;3}^2$	$1500^2, 1000^2$	$1300^2, 1000^2$	$1400^2, 1000^2$
$m_{U;1,2}^2$, $m_{U;3}^2$	$1500^2, 700^2$	$1300^2, 700^2$	$1400^2, 700^2$
$m_{L;1,2}^2$, $m_{E;1,2}^2$	$800^2,\ 800^2$	$1000^2,\ 1000^2$	$500^2,\ 350^2$
$m_{L;3,3}^2$, $m_{E;3,3}^2$	$800^2,\ 136^2$	$1000^2,\ 1000^2$	$500^2,\ 95^2$
m_{H_d}	1217^2	211^2	1042^2
m_{H_u}	$-(767^2)$	$-(207^2)$	$-(201)^2$
v_S	-64.9	-42.5	-56.1
v_T	-1.08	-1.2	-1.1

Outline

Summary and Outlook

- Non-minimal SUSY well motivated
  - general + model-specific motivations
  - model-specific LHC signals/limits
- Example R-symmetry: distinct, motivated model
  - M_W, m_h, dark matter can be explained
  - very light spectrum possible ($\tilde{B}$, S, $\tilde{\tau}$, $\chi^{0,\pm}$) (Heavy singlet scenario: LSP $\sim$ 250GeV)
  - Dirac fermions, new scalars
  - beautiful, more symmetry
- Other "non-minimal" SUSY models also of interest
  - e.g. E_6SSM unifies quarks–leptons–Higgs
    - ★ predicts observable leptoquark(ino)s
  - e.g. MSSM for $\tan\beta \to \infty$
    - ★ $(g-2)_\mu$ explained for $M_{\text{LSP}} \sim 1000$GeV!