Precise predictions in (non-minimal) SUSY models

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TU Dresden

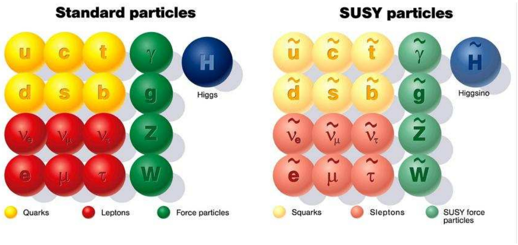
Planck Conference, May 2017, Warsaw

Outline

1. Motivation: SUSY and non-minimal SUSY
2. R-symmetric SUSY as a concrete example
3. Higgs mass and muon $(g-2)$
4. Summary

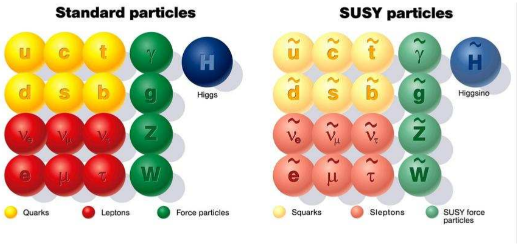
Outline

SUSY



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

SUSY



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- Relation to gravity, string theory
- Fine tuning problem/stabilization of EW scale
- Unification of gauge couplings
- Dynamic generation of mexican hat potential
- Dark matter

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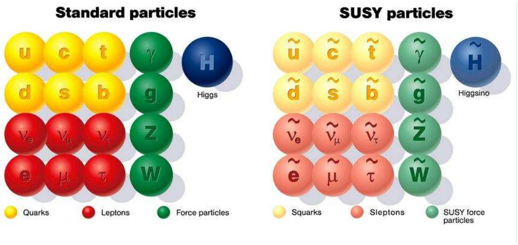

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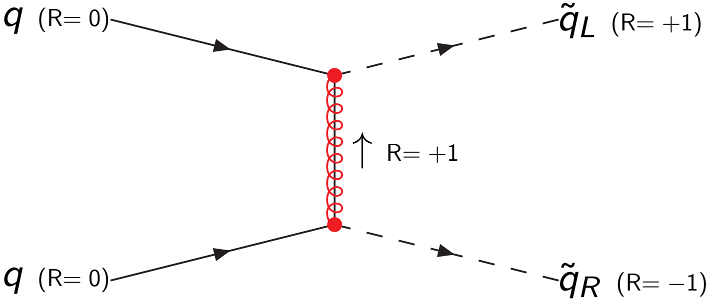
- Dynamic generation of mexican hat potential
- Dark matter
- Minimality was never an argument! Most motivations hold equally well in minimal and non-minimal SUSY!

Outline

2. R-symmetric SUSY as a concrete example
   - Higgs, W, dark matter vs. LHC data in MRSSM

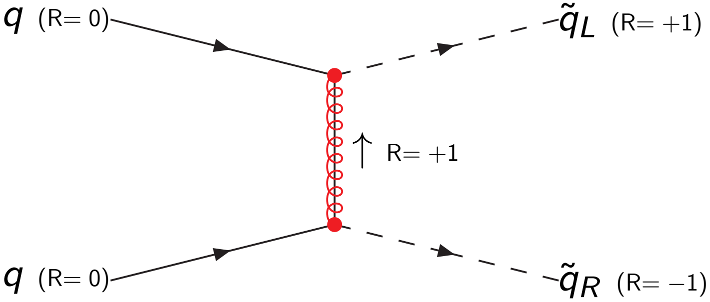
R-symmetric model MRSSM [Kribs, Poppitz, Weiner]



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

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

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



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

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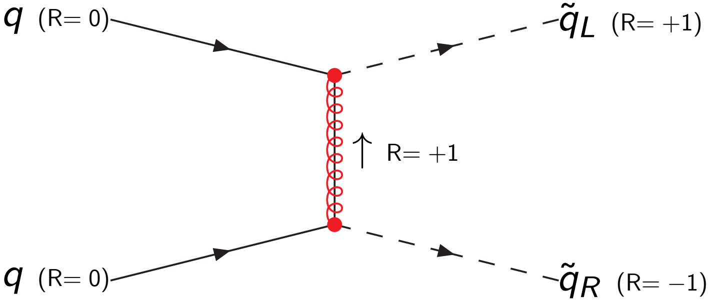

- gluino (and other gauginos/Higgsinos) = Dirac-fermion
  - gluon: 2 d.o.f.
  - gluino: 4 d.o.f.
  - new scalar sgluon: 2 d.o.f

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

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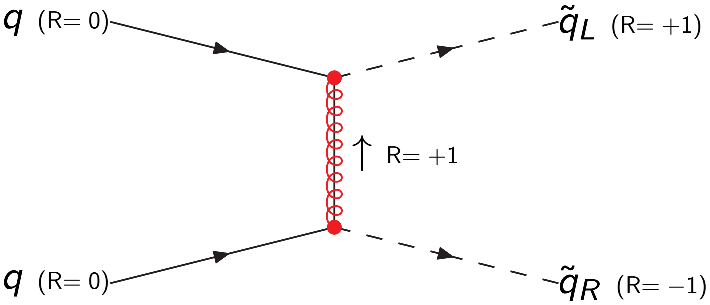


Same for all gauginos ⇒ new scalars

- 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 $\hat{O}$, $\hat{T}$, $\hat{S}$

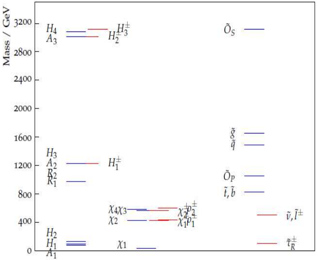
- Dirac gluinos
- new scalars: sgluons, Higgs triplet, Higgs singlet

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

Interesting properties of MRSSM, sample scenarios



[Diessner]

- M_h: motivates rather light charginos
- ... and large "Yukawa coupling" Λ_u
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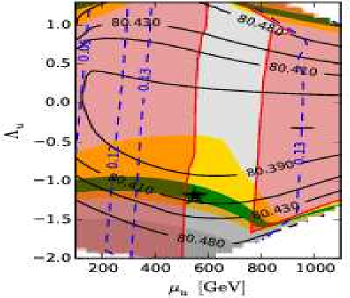
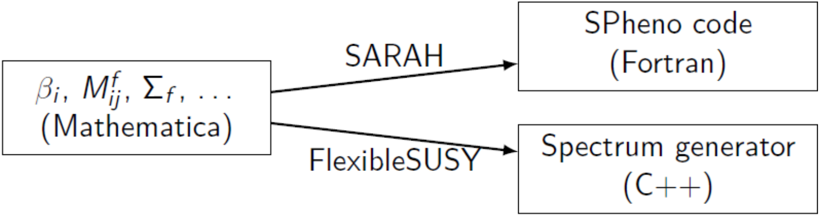


Technical remarks: Tools for non-minimal SUSY

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



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

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

(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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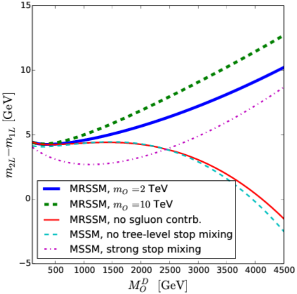
Additionally: positive two-loop corrections from sgluons



However, danger for M_W:

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

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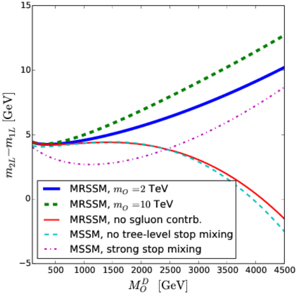

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Answer 1: There is viable parameter space! [Diessner, Kalinowski, Kotlarski, DS '14, '15]

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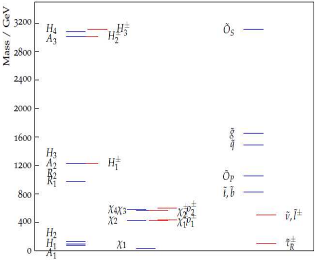

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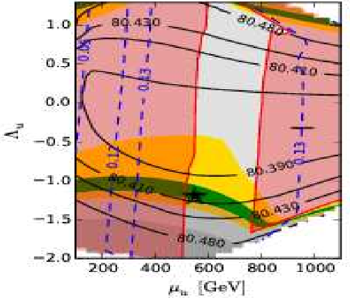

Question 2: light singlet possible/helpful?

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

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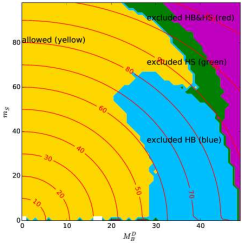
Answer 2:
Yes! Light bino Dirac mass possible!

[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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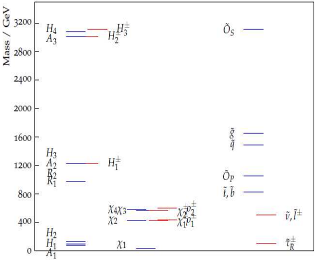

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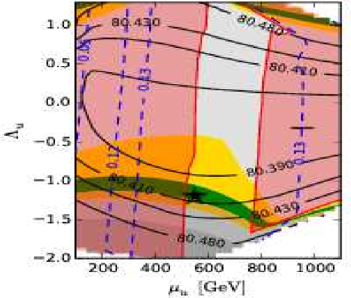

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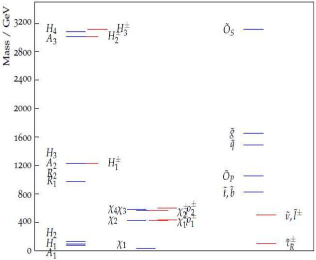

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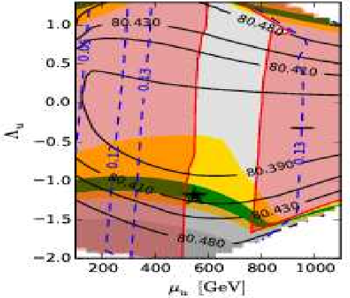

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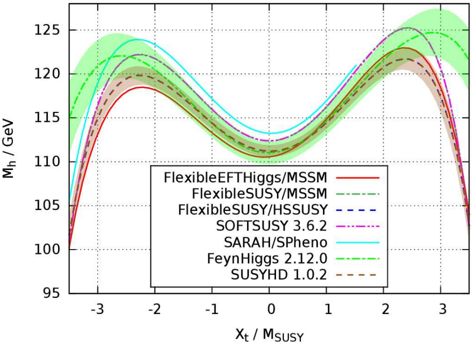
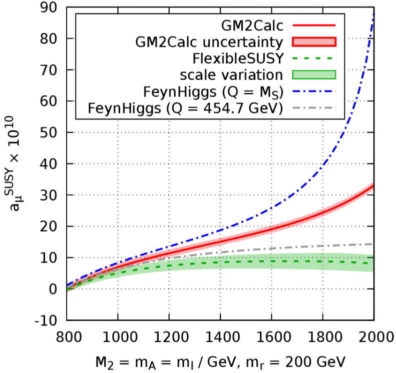
3. Higgs mass and muon $(g-2)$

Compare computations of Higgs mass and muon $(g-2)$





[plot from A. Voigt]

$$M_h^{\text{exp}} = 125.09 \pm 0.24 \text{ GeV} \qquad \Delta a_\mu \approx (30 \pm 8) \times 10^{-10}$$

Higgs mass

Higgs mass $\propto$ quartic scalar coupling predictable

- leading 2-loop corrections essential, many MSSM programs available
- for heavy SUSY particles, loops dominated by $L \equiv \log \frac{M_{\text{SUSY}}}{M_{\text{weak}}}$

Two basic approaches

$$\text{standard P.T.} = \text{tree} + \mathcal{O}(\alpha) + \mathcal{O}(\alpha^2) + \mathcal{O}(\alpha^3) + \ldots$$
$$\text{EFT} = \text{tree'} + \mathcal{O}(\alpha^n L^n) + \mathcal{O}(\alpha^n L^{n-1}) + \ldots + \mathcal{O}(1/M_{\text{SUSY}})$$

Combined/hybrid approaches:

resummed logs + full M_{SUSY}-dependence at fixed order

FeynHiggs for fixed models;

FlexibleEFTHiggs for all models [Athron,Park,Steudtner,DS,Voigt '16], now also in SARAH/Spheno [Porod,Staub '17]

EFT-type calculation in detail: matching at SUSY scale

$\geq M_{\text{SUSY}}$:	SUSY model
at M_{SUSY}:	match to SM (fixed order)
$< M_{\text{SUSY}}$:	run in SM (resum large logs)
at M_{weak}:	compute Higgs mass in SM

FlexibleEFTHiggs (hybrid approach): determine λ via pole mass

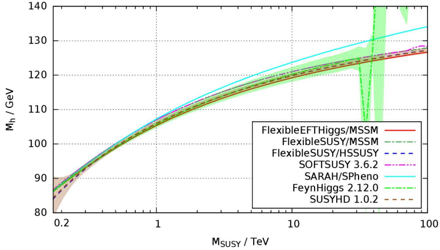
$$\lambda v^2 - \tilde{\Sigma}_h^{\text{SM}}((M_h^{\text{SM}})^2) = (M_h^{\text{MSSM}})^2$$

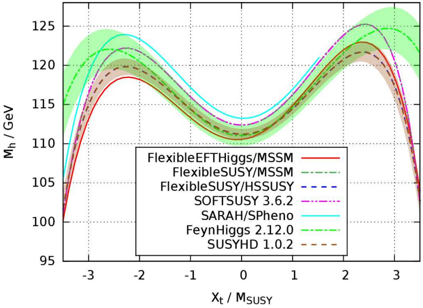
$y_t, m_Z, \ldots$ similar

Pro: exact at tree-level and 1-loop (2-loop can/will be included)

Pro: easier to automate for non-minimal SUSY

Con: tricky to avoid double counting of subleading multi-loop contributions

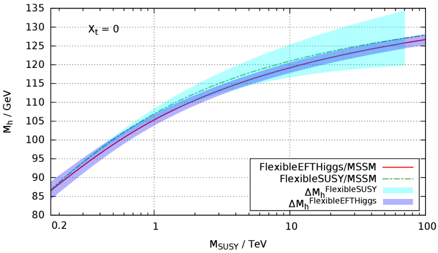




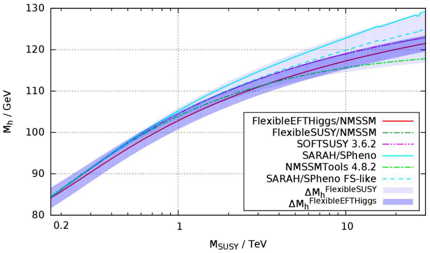
- FEFTHiggs agrees with pure EFT for large masses
- and agrees with fixed-order calculations for masses $\rightsquigarrow$ “interpolates”
- fixed-order calculations differ strongly at high M_{SUSY} $\rightsquigarrow$ theory uncertainty
- for $X_t \neq 0$: non-log 2-loop terms important — not yet included in FEFTHiggs

Can be applied to non-minimal models

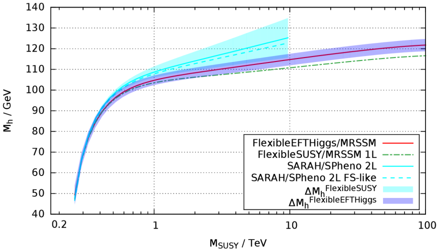
MSSM



NMSSM



MRSSM



Point	SPheno 1L	SPheno 2L	SPheno 1L, (*)	SPheno 2L, (*)	FlexibleSUSY 1L	FlexibleEFT-Higgs 1L
BM1′	120.4	125.6 ± 1.3	120.0	125.1 ± 1.3	120.6	122.1 ± 1.7
BM2′	120.8	126.0 ± 1.1	120.4	125.6 ± 1.1	120.2	121.7 ± 1.8
BM3′	121.0	125.7 ± 1.3	120.5	125.2 ± 1.3	120.4	121.9 ± 1.9

points from Diessner, Kalinowski, Kotlarski, DS
results from Athron, Park, Steudtner, DS, Voigt

Muon $(g-2)$

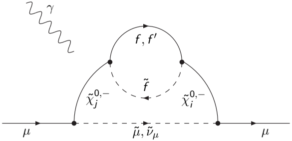
- Currently: discrepancy $\sim (30 \pm 8) \times 10^{-10}$
  $\rightsquigarrow$ Soon: new Fermilab experiment

- SUSY could naturally explain discrepancy

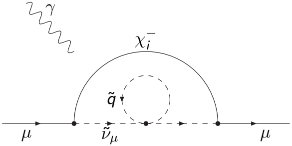
$$a_\mu^{\mathrm{SUSY}} \approx 12 \times 10^{-10} \tan\beta \,\mathrm{sign}(\mu) \left(\frac{100\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

- Mass splittings motivated

Potentially large corrections

- 

  $\to a_\mu^{1L} \times \log(m_{\tilde{f}})$

- 

  $+$ c.t.s

  $$\begin{cases} \approx 0 & \text{(on-shell)} \\ a_\mu^{1L} \times m_{\tilde{f}}^2 & (\overline{\text{DR}}) \end{cases}$$

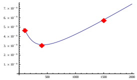
- on-shell 2-loop calculation ($\rightsquigarrow$ Gm2Calc): theory uncertainty from still missing two-loop contributions under control
- often: 1-loop, in $\overline{\text{DR}}$ parameters $\to$ unstable in some parameter regions

Reliable predictions in interesting corners of parameter space (Gm2Calc)

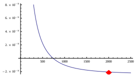
[Fargnoli,Gnendiger,Passehr,DS,Stöckinger-Kim '13]
[Bach,Park,DS,Stöckinger-Kim '15]
[... + FlexibleSUSY-team '15]

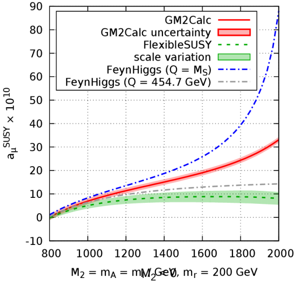
Mass splittings motivated, can lead to enhancements/opposite sign

small/large μ



small/large $M_{\tilde{\mu}_L}$

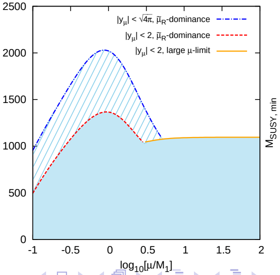




"Largest" possible $a_\mu^{\rm SUSY}$ for $\tan\beta \to \infty$

$$a_\mu^{\rm SUSY} = \frac{y_\mu v_u \; a_\mu^{\rm red}}{m_\mu^{\rm pole}}$$

$$m_\mu^{\rm pole} = \underbrace{y_\mu v_d}_{\text{usual approx.}} + \underbrace{y_\mu v_u \Delta_\mu^{\rm red}}_{\text{now important}}$$



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
- Precise & reliable computations
  - spectrum generators, e.g. FlexibleSUSY, SARAH
  - Progress on Higgs mass calculations
  - $(g-2)$ prediction Gm2Calc