SUSY with R-symmetry: confronting EWPO and LHC constraints

Jan Kalinowski
University of Warsaw
Fantastic first three years of LHC run 1 with plenty of data

- from the first $\pi \rightarrow \gamma\gamma$ reconstructed
- to "rediscovery" of the SM
  - precise SM measurements
    - culminated with the discovery of a Higgs $\sim 125$ GeV
Fantastic first three years of LHC run 1 with plenty of data

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A new era has begun

- already quite precise measurement of properties consistent with SM prediction within errors
- searches beyond the SM
- ultimately: understand the nature of EWSB
A great triumph of a weakly coupled SM

Although very successful, the SM is not the ultimate theory

- the Higgs sector unnatural
- matter-antimatter asymmetry
- dark matter/energy

hints for new physics at a TeV scale
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\[ \text{hints for new physics at a TeV scale} \]

- a light Higgs implies a new scale below $M_{\text{GUT}}$
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Supersymmetry – arguably the best proposition for beyond the SM physics
Arguments in favor for supersymmetry

- solves the SM hierarchy problem: bosons enjoy the same protection as fermions
- explains gauge coupling unification and EWSB via radiative corrections
- provides candidates for dark matter (e.g. neutralino)
In the simplest realisation each SM particle is paired with a sparticle that differs in spin by \( \frac{1}{2} \):

- fermions – sfermions
- gauge bosons – gauginos
- Higgses – higgsinos

\[ \text{gluinos, neutralinos are Majorana fermions to be checked experimentally!} \]

- Exact supersymmetry: no new parameters!
- but inconsistent with experiment
- Must be broken: this is where many arbitrary parameters enter
- Once parameters fixed: completely computable, mathematically consistent theory up to \( M_{\text{GUT}} \)
The mass of the Higgs boson $\sim 125$ GeV consistent with SUSY

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should we give up supersymmetry????

Even before the LHC the minimal SUSY was under severe pressure:
- dim-4 $B$- and $L$-violating operators $\rightarrow$ extra symmetry (e.g. $R$-parity)
- possible flavor and CPV $\rightarrow$ strong constraints on the parameter space
- already LEP2 limit on Higgs mass $>114$ GeV required fine tuning with $125$ GeV even more
Question: how many SUSY do we need?
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- N=1 (squashed, extra matter, NMSSM, extra gauge factors, ...)


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- $0<N<1$ (split SUSY, not-so split SUSY, natural SUSY, ...)
- $N=1$ (squashed, extra matter, NMSSM, extra gauge factors, ...)
- $N>1$ ??
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**Supersymmetry with R-symmetry**

Continuous **R-symmetry** can ameliorate the above problems by

- removing dim-4 B- and L-violating terms, and dim-5 in proton decay
- removing soft tri-linear scalar couplings
- suppressing large contributions to flavor-violating observables
- suppressing the production cross sections for squarks, relax search limits
R-symmetry

Structure of the minimal SUSY with R-symmetry (MRSSM)

Confronting the experiment

- Higgs mass
- electroweak precision observables
- constraints from LHC

based on:

- Diessner, JK, Kotlarski, Stockinger, JHEP12 (2014) 124

Summary
Supersymmetry: superspace \{x^\mu, \theta, \bar{\theta}\}

superfields

matter and Higgs – chiral \(\hat{\Phi}(x^\mu, \theta) = \{\phi, \psi^\alpha\}\)
gauge fields – vector \(\hat{G}(x^\mu, \theta, \bar{\theta}) = \{\tilde{G}^\alpha, G^\mu\}\)
Supersymmetry

Supersymmetry: superspace \( \{x^\mu, \theta, \bar{\theta}\} \)

superfields

matter and Higgs – chiral \( \hat{\Phi}(x^\mu, \theta) = \{\varphi, \psi^\alpha\} \)
gauge fields – vector \( \hat{G}(x^\mu, \theta, \bar{\theta}) = \{\hat{G}^\alpha, G^\mu\} \)

Lagrangian

- kinetic terms \( \int d^2\theta d^2\bar{\theta} \hat{\Phi}^\dagger e^{-2\hat{G}^\alpha \hat{G}_\alpha} \hat{\Phi} + (\int d^2\theta \hat{G}^\alpha \hat{G}_\alpha + h.c.) \)

  where \( \hat{G}^\alpha \equiv \lambda^\alpha + \theta^\alpha D \) field-strength superfield

- potential \( \int d^2\theta W \) where superpotential

  \( W \sim \mu \hat{H}_d \hat{H}_u + y_d \hat{H}_d \hat{Q} \hat{D}^c + \ldots \)

- soft-SUSY breaking: tri-linear scalar couplings and soft masses
R-symmetry

R-symmetry – a continuous U(1) global symmetry under \( \theta \rightarrow e^{i\alpha} \theta \)

[Fayet ‘76; Salam & Strathdee, ...]

Grassmann coordinates have non-trivial R-charge

\[
R(\theta) = +1, \quad R(d\theta) = -1, \quad R(\bar{\theta}) = -1, \quad R(d\bar{\theta}) = +1
\]

superfields \( \hat{X}_i(x^\mu, \theta, \bar{\theta}) \rightarrow e^{i\xi_i \alpha} \hat{X}_i(x^\mu, e^{i\alpha} \theta, e^{-i\alpha} \bar{\theta}) \)

\( \Rightarrow \) component fields have different R-charge
R-symmetry – a continuous U(1) global symmetry under $\theta \rightarrow e^{i\alpha} \theta$

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$\Rightarrow$ component fields have different R-charge

Consider kinetic terms

$$\int d^2\theta \ d^2\bar{\theta} \ \hat{\Phi}^\dagger e^{-2g\hat{G}} \hat{\Phi} + (\int d^2\theta \ \hat{G}_\alpha \hat{G}_\alpha + h.c.)$$

if vector gauge $R(\hat{G}) = 0 \quad \Rightarrow \quad R(G^\mu) = 0, \quad R(\tilde{G}^\alpha) = 1$

are automatically R-symmetric
R-symmetry

• Nelson-Seiberg theorem: R-sym connected to SUSY breaking
• R-symmetry cannot be broken spontaneously
• two options: exact or broken explicitly

  in the MSSM it is broken by soft gaugino masses \( M_{\tilde{G}} \tilde{G}^\alpha \tilde{G}_\alpha \)

• for exact we need
  \[
  \text{R(superpotential)}=2 \quad \int d^2 \theta \ W
  \]
  \[
  \text{R(soft terms)} =0
  \]

• freedom to assign the R-charges to chiral superfields
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  $R(\text{soft terms}) = 0$

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  our choice: SM particles have $R = 0$, superpartners $R \neq 0$

  matter  $R(\hat{Q}) = 1 \Rightarrow R(\tilde{q}) = 1, \ R(q) = 0$

  Higgs  $R(\hat{H}) = 0 \Rightarrow R(H) = 0, \ R(\tilde{H}) = -1$
Constraints from R-symmetry

**terms allowed:**

- superpotential: Yukawa
  
- soft terms: scalar masses

also $\Delta L=2$ Majorana neutrino mass

\[ y_d \hat{H}_d \hat{Q} \hat{D}^c \]

\[ M_\tilde{q}^2 |\tilde{q}|^2 \]

\[ \hat{H}_u \hat{L} \hat{H}_u \hat{L} \quad \text{allowed} \]
Constraints from R-symmetry

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  \[ M_q^2 |\tilde{q}|^2 \]
- Also $\Delta L=2$ Majorana neutrino mass
  \[ \hat{H}_u \hat{L} \hat{H}_u \hat{L} \] allowed

Terms forbidden:

- Superpotential
  \[ \mu \hat{H}_d \hat{H}_u \]
- L- and B-violation
  \[ \hat{L} \hat{Q} \hat{L}, \hat{H}_u \hat{L} \]
- Tri-linear couplings
  \[ A_d H_d \tilde{Q} \tilde{d}^* \]
- Majorana masses
  \[ M_\tilde{G} \tilde{G}^\alpha \tilde{G}_\alpha \]
Constraints from R-symmetry

Terms allowed:
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Terms forbidden:
- Superpotential
  - Mu-term
  - L- and B-violation

- Soft terms:
  - Tri-linear couplings
  - Majorana masses

Since mu-term and Majorana masses are forbidden, need new means to give masses to gauginos/higgsinos
The field content of MRSSM: fields of the MSSM with addition of:

- chiral superfields in the adjoint representation
  
  e.g. SU(3) octet
  \[
  \hat{O} = O + \sqrt{2} \tilde{O} \theta + \theta \theta F_O
  \]
  \[
  R(\hat{O}) = 0 \Rightarrow R(O) = 0, \quad R(\tilde{O}) = -1
  \]
  to build a Dirac gluino
  \[
  \tilde{g}_D = \tilde{O}_L + \tilde{g}_R
  \]

- similarly for the SU(2) triplet and U(1) singlet superfields

- new scalar fields in adjoint representations:
  octet of sgluons \(O\),
  triplet of \(T\)
  and a singlet \(S\)

- super-soft Dirac mass generates sgluon coupling to squarks
Minimal R-symmetric SSM

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- **two chiral iso-dublets** with R-charge 2
  \[
  \hat{R}_u, \hat{R}_d
  \]
  to build a mu-type term
  \[
  W \ni \mu_d \hat{R}_d \cdot \hat{H}_d + \mu_u \hat{R}_u \cdot \hat{H}_u
  \]

- other couplings allowed
  \[
  W \ni \Lambda_d \hat{R}_d \cdot \hat{T}\hat{H}_d + \lambda_d \hat{S}\hat{R}_d \cdot \hat{H}_d + (u \to d)
  \]
  important to get Higgs boson mass

- new scalar R-Higgs bosons

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The field content of MRSSM: fields of the MSSM with addition of:

- **chiral superfields in the adjoint representation**
  
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  \[ \tilde{g}_D = \tilde{O}_L + \tilde{g}_R \]

- similarly for the SU(2) triplet  and U(1) singlet
  \[ \hat{T} \]
  \[ \tilde{S} \]
  superfields

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  important to get Higgs boson mass

- new scalar R-Higgs bosons

---

**important consequences for collider physics, dark matter, flavour physics, ...**
R-symmetric soft masses can be generated as

- **super-soft Dirac mass**
  \[
  \int d^2 \theta \frac{\hat{W}^\alpha}{M} \text{Tr} \hat{G}^\alpha \hat{\Sigma} \to M^D \hat{G} \hat{G}'
  \]
  with D-type spurion \( \langle \hat{W}^\alpha \rangle = \theta^\alpha D' \)

- **B\(\mu\)**-term
  \[
  \int d^4 \theta \frac{x^+ x}{M^2} \hat{H}_u \hat{H}_d \to B_\mu H_u H_d
  \]

- **masses for R-Higgses**
  \[
  \int d^4 \theta \frac{x^+ x}{M^2} \hat{R}_d^\dagger \hat{R}_d \to M^2_{R_d} (|R^+_d|^2 + |R^0_d|^2)
  \]

- **masses for scalar fields**
  \[
  \int d^4 \theta \frac{x^+ x}{M^2} \text{Tr} \hat{\Sigma}^\dagger \hat{\Sigma} \to M^2_\sigma (\sigma^2 + \sigma^*^2)
  \]
  with F-type spurion \( \langle \hat{X} \rangle = \theta^2 F_X \)
### R-charges of the superfields and their component fields

<table>
<thead>
<tr>
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<td><strong>Matter</strong></td>
<td>$\hat{l}, \hat{e}$</td>
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<td></td>
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### MRSSM

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### Physical fields:

matter, gauge and Higgs as in MSSM
R-charges of the superfields and their component fields

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- gluinos and neutralinos are Dirac
- additional pair of charginos
MRSSM

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Physical fields:
- matter, gauge and Higgs as in MSSM
- gluinos and neutralinos are Dirac
- additional pair of charginos
- gauge-adjoint scalars (e.g. sgluons) and R-Higgs bosons
MRSSM Lagrangian

Superpotential

\[ W = \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u \]
\[ + \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u \]
\[ - Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \]

soft SUSY breaking terms

\[ V_{SB}^{EW} = B_\mu (H_d^- H_u^+ - H_d^0 H_u^0) + \text{h.c.} \]
\[ + m_{H_d}^2 (|H_d^0|^2 + |H_d^-|^2) + m_{H_u}^2 (|H_u^0|^2 + |H_u^+|^2) \]
\[ + m_{R_d}^2 (|R_d^0|^2 + |R_d^-|^2) + m_{R_u}^2 |R_u^0|^2 + m_{R_d}^2 |R_d^-|^2 \]
\[ + m_S^2 |S|^2 + m_T^2 |T^0|^2 + m_T^2 |T^-|^2 + m_T^2 |T^+|^2 + m^2 |O|^2 \]
\[ + \tilde{d}_{L,i}^* m_{q,i,j} \tilde{d}_{L,j} + \tilde{d}_{R,i}^* m_{d,i,j} \tilde{d}_{R,j} + \tilde{u}_{L,i}^* m_{u,i,j} \tilde{u}_{L,j} + \tilde{u}_{R,i}^* m_{u,i,j} \tilde{u}_{R,j} \]
\[ + \tilde{e}_{L,i}^* m_{e,i,j} \tilde{e}_{L,j} + \tilde{e}_{R,i}^* m_{e,i,j} \tilde{e}_{R,j} + \tilde{\nu}_{L,i}^* m_{\nu,i,j} \tilde{\nu}_{L,j} \cdot \]
Can the MRSSM accommodate the Higgs mass, EWPO and LHC constraints?

Diessner, JK, Kotlarski, Stockinger, JHEP12 (2014) 124
Can the MRSSM accommodate the Higgs mass, EWPO and LHC constraints?

Answer not obvious because:

- mixing with other states lowers the tree level mass
- no LR stop mixing – an important MSSM mechanism to rise the Higgs mass is not present
- the vev of the EW triplet contributes to the rho parameter at tree-level
- the W mass (and other PO) affected by loops (lecture by A. Pich)
- LHC and flavor constraints

Diessner, JK, Kotlarski, Stockinger, JHEP12 (2014) 124
lightest Higgs – tree level

- EW symmetry breaking triggered by vev’s of neutral fields

\[ H_d^0 = \frac{1}{\sqrt{2}}(v_d + \phi_d + i\sigma_d), \quad H_u^0 = \frac{1}{\sqrt{2}}(v_u + \phi_u + i\sigma_u), \]
\[ T^0 = \frac{1}{\sqrt{2}}(v_T + \phi_T + i\sigma_T), \quad S = \frac{1}{\sqrt{2}}(v_S + \phi_S + i\sigma_S); \]

- 4 scalar neutral fields \( \{\phi_d, \phi_u, \phi_T, \phi_S\} \) mix to give physical Higgses

\[ \mathcal{M}_{H^0} = \begin{pmatrix} \mathcal{M}_{\text{MSSM}} & \mathcal{M}_{21}^T \\ \mathcal{M}_{21} & \mathcal{M}_{22} \end{pmatrix} \]
approximate formula for the lightest Higgs at tree level

\[ m_{H_1,\text{approx}}^2 = m_Z^2 \cos^2 2\beta - v^2 \left( \frac{(g_1 M_B^D + \sqrt{2} \lambda \mu)^2}{4(M_B^D)^2 + m_S^2} + \frac{(g_2 M_W^D + \Lambda \mu)^2}{4(M_W^D)^2 + m_T^2} \right) \cos^2 2\beta \]

under simplifying assumptions of large pseudoscalar A mass and
\[ \lambda = \lambda_u = -\lambda_d, \quad \Lambda = \Lambda_u = \Lambda_d, \quad \mu_u = \mu_d = \mu \text{ and } v_S \approx v_T \approx 0: \]

always lower than in the MSSM due to mixing with S and T
lightest Higgs – full one-loop level

- large enhancement of the tree-level value
  - $\sim 1$ TeV stops without LR mixing not enough
  - important contributions from $\Lambda, \lambda \sim -1$
  - stops $\sim 0.5$ TeV would also work fine

calculations done in DRbar, using SARAH, FeynArts, FormCalc and SPheno
Beyond tree-level

\[
\frac{G_\mu}{\sqrt{2}} = \frac{\pi \hat{\alpha}}{2 \hat{s}_W^2 m_W^2} \frac{1}{1 - \Delta \hat{r}_W}
\]

using \( \hat{s}_W^2 = 1 - \frac{m_W^2}{m_Z^2 \hat{\rho}} \)

we get the master formula of Degrassi, Franchiotti, Stirlin (1990)

\[
m_W^2 = \frac{1}{2} m_Z^2 \hat{\rho} \left[ 1 + \sqrt{1 - \frac{4\pi \hat{\alpha}}{\sqrt{2} G_\mu m_Z^2 \hat{\rho} (1 - \Delta \hat{r}_W)}} \right]
\]

need to calculate \( \hat{\alpha}, \hat{\rho}, \) and \( \Delta \hat{r}_W \).

instructive to expand

\[
m_W \approx m_W^{\text{ref}} + \frac{m_Z \hat{c}_W}{2(\hat{c}_W^2 - \hat{s}_W^2)} \left[ \hat{c}_W^2 \delta(\hat{\rho}) - \hat{s}_W^2 (\delta(\Delta \hat{r}_W) + \delta(\hat{\alpha})) \right]
\]
W mass – full one-loop level

\[ M_W \text{ (GeV)} \]

\[ \Lambda_u \]

\[ \Lambda_u \]

- Complete MRSSM prediction
- SM + \( \nu_T \) contribution + approximation for \( T \) from all sectors
- SM + approximation for \( T \) from all sectors
- SM + approximation for \( T \) from neut/char sector
- SM + \( \nu_T \) contribution

\[ \tan\beta = 3 \]

\[ \tan\beta = 40 \]
to understand qualitatively expand in terms of S, T, U parameters

\[
m_W = m_W^{\text{ref}} + \frac{\hat{\alpha} m_Z \hat{c}_W}{2(c_W^2 - \hat{s}_W^2)} \left( -\frac{S}{2} + \hat{c}_W T + \frac{\hat{c}_W^2 - \hat{s}_W^2}{4\hat{s}_W^2} U \right)
\]

dominant contribution to the W mass from T \sim 0.09

which receives large corrections from chargino/neutralino sector \sim \Lambda_u^4
three benchmarks with $\tan \beta = 3, 10, 40$

<table>
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<tr>
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</tr>
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<td>$S$</td>
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<td>$U$</td>
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Higgs at two loops

Antonio Pich ➔ before calculating full one-loop, check dominant two-loop from top/stop because of large top Yukawa
Higgs at two loops

Antonio Pich ➔ before calculating full one-loop, check dominant two-loop from top/stop because of large top Yukawa

In the MSSM the answer is well known

The MRSSM is distinctively different

- new large couplings $\Lambda, \lambda \sim -1$, is perturbativity still at work?
- new sectors enter the game: Dirac gluinos and scalar gluons

Recent release of SARAH provides tools to calculate in eff. potential

Goodsell, Nickel, Staub, arXiv:1411.0675
2-loop EW corrections small,\ninspite large 1-loop
QCD corrections

without sgluon, MRSSM $\sim$ MSSM when no LR mixing
with sgluon, MRSSM $\sim$ MSSM with LR mixing
but for different reason

2-loop EW corrections small, inspite large 1-loop
Higgs at two loops

Diesner, JK, Kotlarski, Stockinger, arXiv:1504.05386

2-loop EW corrections small, inspite large 1-loop

QCD corrections

without sgluon, MRSSM \sim MSSM when no LR mixing
with sgluon, \quad MRSSM \sim MSSM with LR mixing
but for different reason

QCD corrections + few GeV \quad \Lambda_u \text{ can be smaller}
Colored sector

Dirac gluinos
e.g. squark pair production

\[ q'_L \rightarrow \tilde{g}_k \rightarrow \tilde{q}_L \]
\[ q'_R \rightarrow \tilde{g}_k \rightarrow \tilde{q}_R \]
\[ q_R \rightarrow \tilde{g}_k \rightarrow \tilde{q}_R \]
\[ q_L \rightarrow \tilde{g}_k \rightarrow \tilde{q}_L \]
Colored sector

Dirac gluinos
e.g. squark pair production

- lower sensitivity to squarks
- higher sensitivity to gluinos
Colored sector

Dirac gluinos
e.g. squark pair ptoduction

- lower sensitivity to squarks
- higher sensitivity to gluinos

Sgluons have tree-level couplings
- to gluons and gluinos
- to squarks through the D-term

can be produced
- singly only via loop-induced coupling in ggF
- or in pairs
Summary

- Well motivated R-symmetric SUSY model discussed
- Gauginos become Dirac particles, new scalar partners
- Viable benchmarks with
  - \( \sim 125 \text{ GeV} \) lightest Higgs boson mass
  - agreement with EWPO and flavor physics
  - stable vacuum
  - consistent with LHC constraints
- Conserved R-charge restricts production channels and decay modes
  - distinct phenomenology at colliders
  - sgluons can be light and seen at the LHC
Well motivated R-symmetric SUSY model discussed

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Many things to do: work out the full LHC phenomenology, dark matter etc.

work in progress
Backup
benchmarks:

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in one loop

\Lambda_u reduces to

-1.11  -0.5  -1.03

HiggsSignals's p-value

- 0.61  0.61  0.65
- 0.72  0.66  0.72

HiggsBounds's obsratio

- 0.61  0.61  0.63
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m_{H_1}

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m_W

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benchmarks

BMP1

BMP2

BMP3
Tree-level couplings

- $\sigma \sigma^* g$ and $\sigma \sigma^* g g$ couplings as required by gauge invariance
- to gluinos
- Dirac gluino mass $\rightarrow$ trilinear scalar couplings to squarks

$$-\sqrt{2} i g_s f^{abc}_{\alpha \beta \gamma} \tilde{g}^a_L \tilde{g}^b_R \sigma^c + h.c.$$ 

Although $R=0$, single sgluon cannot be produced at treel level

Loop-induced couplings

- to a gluon or quark pair through diagrams with squarks or gluinos

(gluino loops vanish)

Choi, Drees, JK, Kim, Popenda, Zerwas '09
Plehn, Tait, '09

Colored scalars: sgluons
At the LHC sgluons can be produced **singly** via

exciting possibility of resonant s-channel sgluon production

exclusion up to $\sim 2.5$ TeV for a state $s8$
with full strength coupling

Han, Lewis, Liu, 1010.4309
At the LHC sgluons can be produced \textit{singly} via exciting possibility of resonant s-channel sgluon production

exclusion up to $\sim 2.5$ TeV for a state $s8$ with full strength coupling

Han, Lewis, Liu, 1010.4309
At the LHC sgluons can be also produced in pairs.


at 8 TeV in tttt channel, excluded up to ~ 850 GeV