# Introduction to the Minimal Supersymmetric Standard Model

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May 22nd, 2008

# 1 Outline

- Open questions of the Standard Model
- The Particle spectrum of the Minimal Supersymmetric Standard Model
- Examples of SUSY processes
- Squark pair production at the LHC

## 2 Introduction

The Standard Model (SM) has been tested to high precision.

However, many questions are still open:

- solution to hierarchy problem
  $(M_W = \mathcal{O}(100\,\text{GeV}) \leftrightarrow M_{\text{Planck}} = \mathcal{O}(10^{19}\,\text{GeV}))$
- window to gravity
- dark matter candidate
- CP-phases for baryon asymmetry, baryogenesis
- 19 free parameters in the SM

# Introduction (cont'd)

One solution to some of these questions is Supersymmetry (SUSY).

- symmetry between bosons and fermions
- minimal SUSY extension of SM $\rightarrow$ MSSM

# 3 The Particle content of the MSSM

**Matter fields:**

| Fermionic SM-field $s = \frac{1}{2}$ | SUSY partner fields $s = 0$ |
|---|---|
| Electron $e_L$, Neutrino $\nu$ | selectron $\tilde{e}_L$, sneutrino $\tilde{\nu}$ |
| Electron $e_R$ | selectron $\tilde{e}_R$ |
| up-quark $u_{L,a}$, down-quark $d_{L,a}$ | sup $\tilde{u}_{L,a}$, sdown $\tilde{d}_{L,a}$ |
| up-quark $u_{R,a}$ | sup $\tilde{u}_{R,a}$ |
| down-quark $d_{R,a}$ | sdown $\tilde{d}_{R,a}$ |

$a$ : $SU(3)$ color index

# The Particle content of the MSSM (cont'd)

## Gauge fields:

| Bosonic SM-fields $s = 1$ | SUSY partner fields $s = \frac{1}{2}$ |
|---|---|
| $B$ field | Bino $\widetilde{B}$ |
| weak bosons $W^a$ | Winos $\widetilde{W}^a$, $a = 1 \ldots 3$ |
| Gluons $g^a$ | Gluinos $\tilde{g}^a$, $a = 1 \ldots 8$ |

## The Particle content of the MSSM (cont'd)

**Higgs fields (complex doublet fields):**

| Higgs-fields $s = 0$ | SUSY partner fields $s = \frac{1}{2}$ |
|---|---|
| $H_d$ | $\widetilde{H}_1 = (\widetilde{H}_d^0, \widetilde{H}_d^-)$ |
| $H_u$ | $\widetilde{H}_2 = (\widetilde{H}_u^+, \widetilde{H}_u^0)$ |

- Fields with equal quantum numbers mix
- Physical states obtained by diagonalisation of the mixing matrices

## Remarks:

- # of fermionic degrees of freedom = # of bosonic d. o. f.
- particles and their super partners have equal masses
- if lightest supersymmetric particle (lsp) is stable $\rightarrow$ $R$-parity
  $\rightarrow$ dark matter candidate, if uncharged
- in our world:
  no SUSY particles observed so far $\Rightarrow$ SUSY must be broken
- explicit breaking: Introduce mass terms for the the bino, wino, gluino, and sfermions with mass parameters $M_1$, $M_2$, $M_3$ and $M_{\tilde{f}}$, respectively
- in SUSY GUTs: $M_1 = M_2 = M_3 = M_{1/2}$ @ $M_{\text{GUT}}$
  $M_{\tilde{f}} = M_0$ for all sfermions @ $M_{\text{GUT}}$

## 4 Charginos $\tilde{\chi}^{\pm}_{1/2}$

Charginos are the superpartners of the charged gauge $\tilde{W}^{\pm}$ and Higgs bosons $\tilde{H}^0_{u,d}$. Their mixing is described by the matrix

$$X = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

MSSM parameters:

$M_2$, $\mu$: Wino, higgsino mass parameter,can be complex ($CP$ - phases)

$\tan\beta$: ratio of the Higgs vevs

eigenvalues($X^+X$) = chargino masses$^2$ $m^2_{\tilde{\chi}^{\pm}_{1/2}}$

Charginos have electromagnetic interactions (good detectibility)!

LEP search: $m_{\tilde{\chi}^+_1} > 104\,\text{GeV} \Rightarrow |\mu|, M_2 \gtrsim 100\,\text{GeV}$

# 5 Neutralinos

Neutralinos are the SUSY partners of the neutral gauge ($\tilde{B}$, $\tilde{W}^3$) and $CP$-even Higgs bosons ($\tilde{H}_u^0$, $\tilde{H}_d^0$). These states mix, and the mass eigenstates are the eigenvectors of the diagonalisation matrix.

$$M = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta) & -\mu & 0 \end{pmatrix}$$

MSSM parameters: $M_1$, $M_2$, $\mu$, $\tan\beta$

|eigenvalues| of $M$ = neutralino masses $m_{\tilde{\chi}_i^0}$, $i = 1, \ldots, 4$

# Neutralinos (cont'd)

- We have some information about the neutralino mixing matrix from the chargino sector ($M_2$, $|\mu| \geq 100\,\text{GeV}$)
- but one new parameter: $M_1$ (Bino mass parameter)
- in SUSY GUTs: $M_1 = f(M_2)$,
  f. e. mSugra: $M_1 = \frac{5}{3}\tan^2(\theta_w)M_2 \approx 0.5M_2$ @ $M_Z$
  $\Rightarrow m_{\tilde{\chi}_1^0} \gtrsim 50\,\text{GeV}$
- no lower bound, if one assumes no relation between $M_1$ and $M_2$, even a massless neutralino is possible [my PhD thesis]
- masses in the range $1\,\text{eV} \ldots 6\,\text{GeV}$ disfavoured by cosmology
- $\tilde{\chi}_1^0$ is dark matter candidate: lsp, uncharged, uncoloured

# 6 Squarks and Sleptons

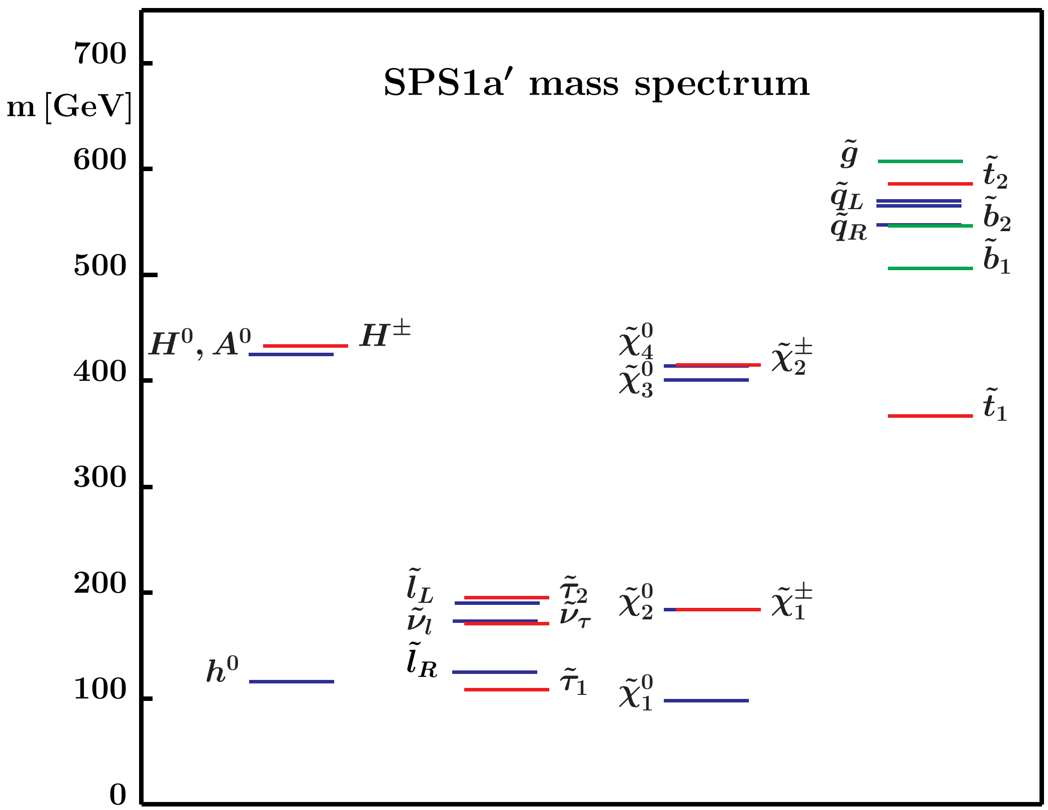
$$M_{\tilde{u}}^2 = \begin{pmatrix} M_{\tilde{q}_L}^2 + m_Z^2 \cos(2\beta)(T_3 - e_u \sin^2\theta_w) + m_u^2 & m_u(A_u - \mu \cot\beta) \\ m_u(A_u - \mu \cot\beta) & M_{\tilde{u}_R}^2 - e_u m_Z^2 \cos(2\beta)\sin^2\theta_w + m_u^2 \end{pmatrix}$$

$$M_{\tilde{d}}^2 = \begin{pmatrix} M_{\tilde{q}_L}^2 + m_Z^2 \cos(2\beta)(T_3 - e_d \sin^2\theta_w) + m_d^2 & m_d(A_d - \mu \tan\beta) \\ m_u(A_d - \mu \tan\beta) & M_{\tilde{d}_R}^2 - e_d m_Z^2 \cos(2\beta)\sin^2\theta_w + m_d^2 \end{pmatrix}$$

(the matrices for the sleptons look similar)

- $M^2_{\tilde{u},\tilde{d}}$ is diagonal, if $m_{u,d} = 0 \Rightarrow \tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ are also mass eigenstates
- in mSugra: Left and right handed Squarks of the 1st and 2nd generation have equal masses $\Rightarrow$ difficult to distinguish at colliders
- Bounds for 1st and 2nd generation: $m_{\tilde{q}} > 379\,\text{GeV}$ @ 95% CL (and $m_{\tilde{g}} > 308\,\text{GeV}$) V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **660** (2008) 449 [arXiv:0712.3805 [hep-ex]].

# 7 A Typical Particle spectrum




mSugra:

$M_{1/2} = 250$ GeV

$M_0 = 70$ GeV

$A_0 = -300$ GeV

$\tan\beta = 10$

$\mathrm{sgn}(\mu) = +1$

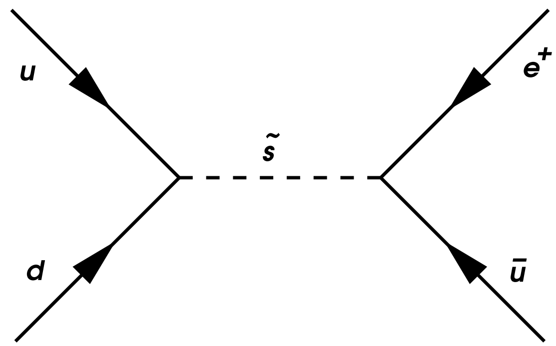
(Figure taken from J. A. Aguilar-Saavedra *et al.*,Eur. Phys. J. C **46** (2006) 43 [arXiv:hep-ph/0511344].)

This scenario fulfills all bounds from HEP and cosmology

# 8 $R$-parity

## 8.1 Motivation and Definition

In a general MSSM, proton decay is possible:




Protect the proton by a new symmetry: R-parity $R_p = (-1)^{3B+L+2S}$

Examples: $R_p(u) = (-1)^{3 \cdot 1/3 + 0 + 2 \cdot 1/2} = 1$ (as for all SM particles),

$R_p(\tilde{e}) = (-1)^{3 \cdot 0 + 1 + 2 \cdot 0} = -1$ (as for all SUSY partners).

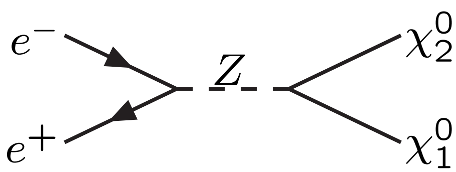
## 8.2 Consequences of $R$-parity

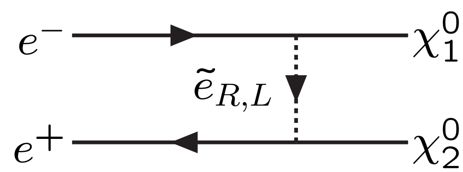
- proton is stable
- SUSY particles are produced in pairs
- the lightest SUSY particle (lsp) is stable
  $\Rightarrow$ the lsp is a dark matter candidate,
  the $\tilde{\chi}_1^0$ is a good candidate (uncharged, uncoloured)
- If one allows $R$-parity violating couplings: lepton number and baryon number violating processes are possible, bounds on $R$-parity violating couplings from proton decay, ...

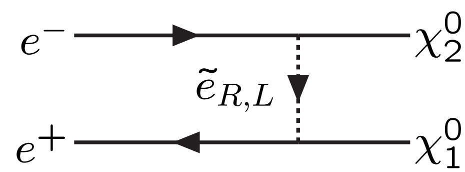
# 9 Examples for SUSY processes . . .

## At $e^+e^-$ colliders:

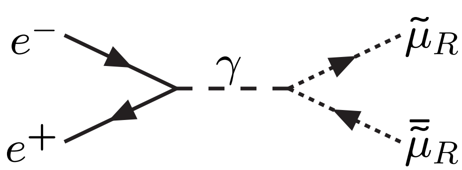
Neutralino pair production:

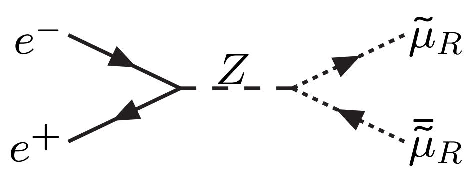



Slepton pair production:

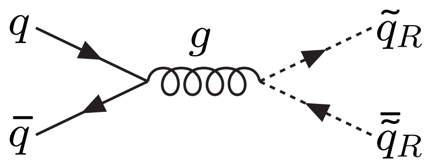


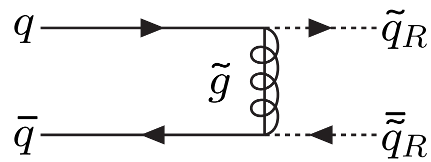



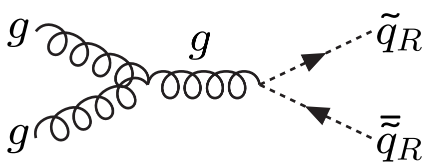
# Examples for SUSY processes . . . (cont'd)

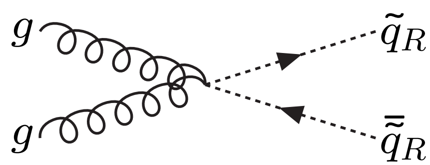
**At $pp/p\bar{p}$ colliders:**

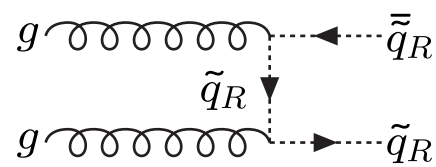
Squark pair production:



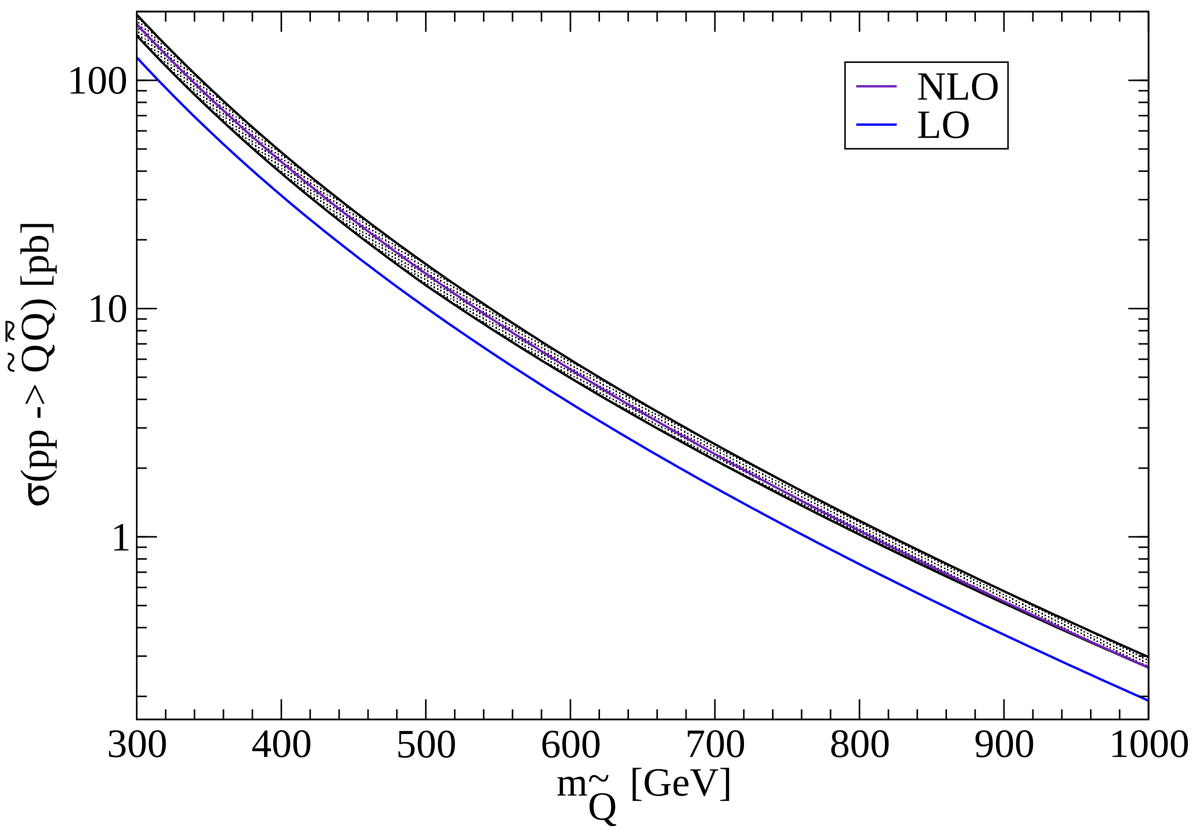



## 10 Cross sections for squark pair production at the LHC

$$\sigma(S, \mu^2, \quad pp \to \tilde{Q}\bar{\tilde{Q}}) = \sum_{i,j=g,q,\bar{q}} \int_A \mathrm{d}x_1 \, \mathrm{d}x_2 \, p_{i,1}(x_1, \mu^2) p_{j,2}(x_2, \mu^2) \hat{\sigma}_{ij}(x_1 x_2 S, \mu^2)$$

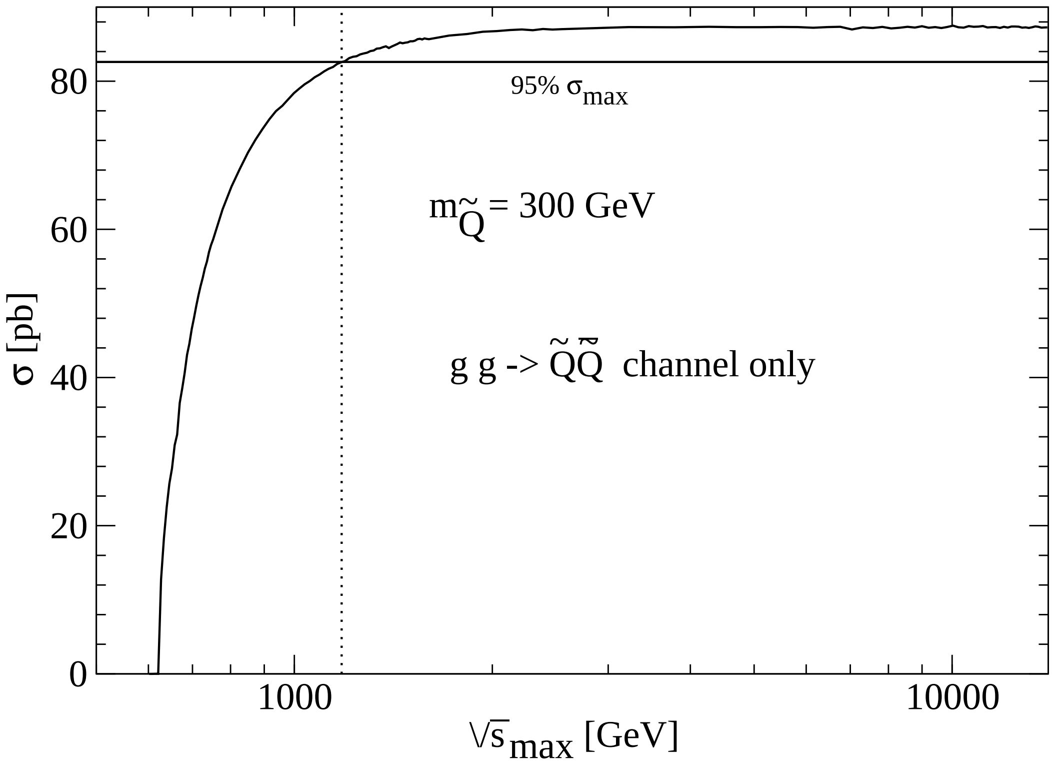
- $x_i$, $i = 1$ or 2: momentum fraction of parton $i$
- $A$: Area defined by $4m^2/s \leq x_1 x_2 \leq 1$
- $\hat{\sigma}_{ij}$: partonic cross section for $ij \to \tilde{Q}\bar{\tilde{Q}}$
- $p_{i,1/2}$: parton density $i$, carrying momentum fraction $x_{1/2}$ of the hadron 1/2

# Cross sections for squark pair production at the LHC




Plot produced with `PROSPINO` [W. Beenakker, R. Höpker and M. Spira, arXiv:hep-ph/9611232.]

# Cross sections for squark pair production at the LHC




for $\sqrt{s} \approx 1200\,\mathrm{GeV}$ cross section saturated to 95%

$\Rightarrow$ Squark pairs are produced near the production threshold

# Cross sections for squark pair production at the LHC (cont'd)

- Squark pairs are produced at the LHC at the production threshold with cross sections of about 1 pb . . . 100 pb
- NLO cross sections calculated by [W. Beenakker, R. Höpker, M. Spira and P. M. Zerwas, Nucl. Phys. B **492** (1997) 51 [arXiv:hep-ph/9610490].]
- resumed NLL cross sections approximate NLO cross sections very well

  want to improve cross section for squark pair production to NNLO accuracy by calculating NNLL resumed cross section $\rightarrow$reduce scale uncertainty and improve predictive power of the cross section

## 11 Summary

- In the MSSM, every SM particle has its SUSY partner(s).
  It is possible to include gravity, there is a dark matter candidate, and there are $CP$ phases.

- One of the expected processes at the LHC is squark pair production

- Calculate NNLL approximated cross section