Constraints on Supersymmetry using 5 fb^{-1} LHC data

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Where is SUSY?
Where is SUSY?

Accelerators
Where is SUSY?

Accelerators

Telescopes
Where is SUSY?

Accelerators

Telescopes

Underground facilities
Exp Data & Th Frame
Exp data
Exp Data & Th Frame

Exp data

✓ LEP II & Tevatron limits on SUSY particle masses
Exp Data & Th Frame

Exp data

✓ LEP II & Tevatron limits on SUSY particle masses
✓ Direct SUSY search at LHC @ 5/fb
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✓ Relic abundance of Dark Matter in the Universe
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✓ g-2 of the muon
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Theory Framework
Exp Data & Th Frame

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Theory Framework
MSSM with SUGRA SUSY breaking
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Theory Framework

MSSM with SUGRA SUSY breaking

Min parameter set: $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$
SUSY Production at the LHC
SUSY Production at the LHC
SUSY Production at the LHC
SUSY x-sections at the LHC @ 7 TeV

\[ \tilde{g} \tilde{g} \]

\[ \tilde{g} \tilde{q} \]

\[ \tilde{q} \tilde{q} \]

\[ \tilde{\chi} \tilde{\chi} \]
LHC Reach at 7 and 14 TeV
LHC Reach at 7 and 14 TeV
LHC Reach at 7 and 14 TeV

7 TeV excluded at 95% CL

14 TeV excluded at 95% CL
LHC Reach at 7 and 14 TeV
LHC Reach at 7 and 14 TeV
LHC Reach at 7 and 14 TeV

Energy is more important than luminosity
Rare Decays: $Br[B_s \rightarrow \mu^+ \mu^-]$
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Rare Decays: $\text{Br} [B_S \rightarrow \mu^+ \mu^-]$

$$\text{Br} [B_S \rightarrow \mu \mu] = \frac{2\tau_B m_B^5}{64\pi f_{B_S}^2} \sqrt{1 - \frac{4m_l^2}{m_B^2}} \left[ \left(1 - \frac{4m_l^2}{m_B^2}\right) \left|\frac{C_S - C'_S}{m_b + m_s}\right|^2 + \left|\frac{C_P - C'_P}{m_b + m_s}\right|^2 + 2\frac{m_{\mu}}{m_{B_S}^2} (C_A - C'_A) \right]^2$$

**SM**

**MSSM**

SM: Br=3.5 $\cdot 10^{-9}$
Ex: <4.5 $\cdot 10^{-9}$
**Rare Decays:** \( Br[B_s \rightarrow \mu^+\mu^-] \)

\[
Br[B_s \rightarrow \mu\mu] = \frac{2\tau_B m_B^5}{64\pi f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}}} \left[ \left(1 - \frac{4m_l^2}{m_B^2}\right) \left| \frac{C_S - C'_S}{m_b + m_s} \right|^2 + \left| \frac{C^P - C'_P}{m_b + m_s} \right| + \frac{2m_\mu m_\tau}{m_{B_s}^2} \left( C_A - C'_A \right) \left| \frac{m_{t_1}^2}{\mu^2} - \frac{m_{t_2}^2}{\mu^2} \right| \right]
\]

\[
C_S \approx \frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{ts}^* \left( \frac{\tan^3 \beta}{4 \sin^2 \theta_W} \right) \left( \frac{m_b m_\mu m_t m_\mu}{M_W^2 M_A^2} \right) \sin 2\theta_t \left( \frac{m_{t_1}^2}{\mu^2} \log \left[ \frac{m_{t_1}^2}{\mu^2} \right] - \frac{m_{t_2}^2}{\mu^2} \log \left[ \frac{m_{t_2}^2}{\mu^2} \right] \right)
\]

**SM**

**MSSM**

**SM: Br=3.5 \cdot 10^{-9}**

**Ex: <4.5 \cdot 10^{-9}**
Rare Decays: \( Br[B_s \rightarrow \mu^+ \mu^-] \)

**SM**

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Br[B_s \rightarrow \mu \mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1 - \frac{4m_l^2}{m_B^2}} \left[ \left( 1 - \frac{4m_l^2}{m_B^2} \right) \left| \frac{C_S - C'_S}{m_b + m_s} \right|^2 + \left| \frac{C_P - C'_P}{m_b + m_s} \right|^2 + 2 \frac{m_\mu}{m_{B_s}^2} (C_A - C'_A) \right]^2
\]

\[
C_S \sim \frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{ts}^* \left( \frac{\tan^3 \beta}{4 \sin^2 \theta_W} \right) \left( \frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2} \right) \sin 2\theta_t \left( \frac{m_{t_1}^2}{\mu^2} \log \left[ \frac{m_{t_1}^2}{\mu^2} \right] - \frac{m_{t_2}^2}{\mu^2 - m_{t_2}^2} \right)
\]

**MSSM**

**Enhancement**
Rare Decays: \( Br[B_s \rightarrow \mu^+ \mu^-] \)

\[
Br[B_s \rightarrow \mu\mu] = \frac{2\tau_B m_B^5}{64\pi f_{B_s}^2} \sqrt{1 - \frac{4m_l^2}{m_B^2}}
\]

\[
\left[ \left(1 - \frac{4m_l^2}{m_B^2}\right) \left|\frac{C_S - C'_S}{m_b + m_s}\right|^2 + \left|\frac{C_P - C'_P}{m_b + m_s}\right|^2 + 2\frac{m_\mu}{m_{B_s}^2} \left|C_A - C'_A\right|^2 \right]
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\]

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Ex: <4.5 \cdot 10^{-9}

Enhancement

Suppression
Rare Decays: $Br[B_s \rightarrow \mu^+\mu^-]$ Constraint
Rare Decays: $Br[B_s \rightarrow \mu^+\mu^-]$ Constraint

SM: $Br=3.5 \cdot 10^{-9}$
Ex: $<4.5 \cdot 10^{-9}$
Rare Decays: $\mathcal{B}[B_s \rightarrow \mu^+ \mu^-]$ Constraint

95% C.L. Excluded regions for

$\mathcal{B}[B_s \rightarrow \mu^+ \mu^-] < 4.5 \cdot 10^{-9}$
$\mathcal{B}[B_s \rightarrow X_s \gamma] = (3.55 \pm 0.24) \cdot 10^{-4}$
$\mathcal{B}[B_u \rightarrow \tau\nu] = (1.68 \pm 0.31) \cdot 10^{-4}$

SM: $\mathcal{B}=3.5 \cdot 10^{-9}$
Ex: $<4.5 \cdot 10^{-9}$
Rare Decays: $Br[B_s \rightarrow \mu^+\mu^-]$ Constraint

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Negative interference is possible
Anomalous magnetic moment
Anomalous magnetic moment

\[ a_{\mu}^{\text{exp}} = 11\,659\,2089(63) \cdot 10^{-11} \]

\[ a_{\mu}^{\text{SM}} = 11\,659\,1834(49) \cdot 10^{-11} \]
Anomalous magnetic moment

\[ a^{\text{exp}}_\mu = 11\,659\,2089(63) \cdot 10^{-11} \]
\[ a^{SM}_\mu = 11\,659\,1834(49) \cdot 10^{-11} \]
\[ a^{\text{exp}}_\mu - a^{SM}_\mu = 255 \pm 80 \cdot 10^{-11} \]
Anomalous magnetic moment

\[ a_{\mu}^{exp} = 11\,659\,2089(63) \cdot 10^{-11} \]
\[ a_{\mu}^{SM} = 11\,659\,1834(49) \cdot 10^{-11} \]
\[ a_{\mu}^{QED} = 11\,658\,4705.6(2.9) \cdot 10^{-11} \]
\[ a_{\mu}^{weak} = 151(4) \cdot 10^{-11} \]
\[ a_{\mu}^{hadr} = 6877.2(46.3) \cdot 10^{-11} \]
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vacuum pol
Anomalous magnetic moment

\[
a^\text{exp}_\mu = 11\ 659\ 2089(63) \cdot 10^{-11} \\
a^\text{SM}_\mu = 11\ 659\ 1834(49) \cdot 10^{-11} \\
\]
\[
a^\text{exp}_\mu - a^\text{SM}_\mu = 255 \pm 80 \cdot 10^{-11} \\
\]

\[
a^\text{QED}_\mu = 11\ 658\ 4705.6(2.9) \cdot 10^{-11} \\
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\]

vacuum pol  light-light scat
Anomalous magnetic moment

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\begin{align*}
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EW vacuum pol
light-light scat

SUSY
Anomalous magnetic moment

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EW

vacuum pol  light-light scat

\[
| a_\mu^{\text{SUSY}} | \approx \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \tan\beta \left( 1 - \frac{4\alpha}{\pi} \log \frac{M_{\text{SUSY}}}{m_\mu} \right) \approx 140 \cdot 10^{-11} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan\beta
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SUSY
Anomalous magnetic moment

\[ a_{\mu}^{\text{exp}} = 11 659 2089(63) \cdot 10^{-11} \]
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EW

\[ | a_{\mu}^{\text{SUSY}} | \approx \frac{\alpha(M_Z)}{8\pi \sin^2 \theta_W} \frac{m_{\mu}^2}{M_{\text{SUSY}}^2} \tan \beta (1 - \frac{4\alpha}{\pi} \log \frac{M_{\text{SUSY}}}{m_{\mu}}) \approx 140 \cdot 10^{-11} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan \beta \]

SUSY

Enhancement
Anomalous magnetic moment

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\[ |a_{\mu}^{SUSY}| \approx \frac{\alpha(M_Z)}{8\pi Sin^2\theta_W} \frac{m_\mu^2}{M_{SUSY}^2} tan\beta \left(1 - \frac{4\alpha}{\pi} \log \frac{M_{SUSY}}{m_\mu}\right) \approx 140 \cdot 10^{-11} \left(\frac{100\,\text{GeV}}{M_{SUSY}}\right)^2 tan\beta \]

\[ \text{vacuum pol} \quad \text{light-light scat} \]

\[ \text{Suppression} \quad \text{Enhancement} \]
$g$-2 Constraint on Parameter space

The only requirement that limits the SUSY masses from above

Fixes the sign of $\mu$

\[ \tan \beta \]
The only requirement that limits the SUSY masses from above

Almost excluded by rare decay

\[ Br[ B_s \rightarrow \mu^+ \mu^-] \]
$\sigma_{Higgs} = \frac{1}{32} \int_{0}^{1} dx_1 dx_2 \ g[x_1] \ g[x_2] \ |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m_{Higgs}^2} \delta(E^2 x_1 x_2 - m_{Higgs}^2)$

$\mathcal{M}_h = \frac{\alpha_s}{4\pi} \frac{m_h^2}{2\sqrt{2}v} \left( \frac{\cos \alpha}{\sin \beta} F_{1/2}^h \left[ \frac{4m_t^2}{m_h^2} \right] - \frac{\sin \alpha}{\cos \beta} F_{1/2}^h \left[ \frac{4m_b^2}{m_h^2} \right] \right)$,

$\mathcal{M}_H = \frac{\alpha_s}{4\pi} \frac{m_H^2}{2\sqrt{2}v} \left( \frac{\sin \alpha}{\sin \beta} F_{1/2}^H \left[ \frac{4m_t^2}{m_H^2} \right] + \frac{\cos \alpha}{\cos \beta} F_{1/2}^H \left[ \frac{4m_b^2}{m_H^2} \right] \right)$,

$\mathcal{M}_A = \frac{\alpha_s}{4\pi} \frac{m_A^2}{2\sqrt{2}v} \left( \frac{\cos \beta}{\sin \beta} F_{1/2}^A \left[ \frac{4m_t^2}{m_A^2} \right] + \frac{\sin \beta}{\cos \beta} F_{1/2}^A \left[ \frac{4m_b^2}{m_A^2} \right] \right)$
$\sigma_{Higgs} = \frac{1}{32} \int_0^1 dx_1 dx_2 \ g[x_1] \ g[x_2] \ |M_{Higgs}|^2 \frac{2\pi}{m_{Higgs}^2} \delta(E^2 x_1 x_2 - m_{Higgs}^2)$

$M_h = \frac{\alpha s}{4\pi} \frac{m_h^2}{2\sqrt{2}v} \left( \frac{\cos\alpha}{\sin\beta} F_{1/2}^h \left[ \frac{4m_t^2}{m_h^2} \right] - \frac{\sin\alpha}{\cos\beta} F_{1/2}^h \left[ \frac{4m_b^2}{m_h^2} \right] \right)$,

$M_H = \frac{\alpha s}{4\pi} \frac{m_H^2}{2\sqrt{2}v} \left( \frac{\sin\alpha}{\sin\beta} F_{1/2}^H \left[ \frac{4m_t^2}{m_H^2} \right] + \frac{\cos\alpha}{\cos\beta} F_{1/2}^H \left[ \frac{4m_b^2}{m_H^2} \right] \right)$,

$M_A = \frac{\alpha s}{4\pi} \frac{m_A^2}{2\sqrt{2}v} \left( \frac{\cos\beta}{\sin\beta} F_{1/2}^A \left[ \frac{4m_t^2}{m_A^2} \right] + \frac{\sin\beta}{\cos\beta} F_{1/2}^A \left[ \frac{4m_b^2}{m_A^2} \right] \right)$,
Heavy Higgs Production at the LHC

\[ \sigma_{\text{Higgs}} = \frac{1}{32} \int_0^1 dx_1 dx_2 \ g[x_1] \ g[x_2] \ |\mathcal{M}_{\text{Higgs}}|^2 \frac{2\pi}{m_{\text{Higgs}}^2} \delta(E^2x_1x_2 - m_{\text{Higgs}}^2) \]

\[ \mathcal{M}_h = \frac{\alpha_s}{4\pi} \frac{m_h^2}{2\sqrt{2}v} \left( \frac{\cos\alpha}{\sin\beta} F_{1/2}^h \left[ \frac{4m_t^2}{m_h^2} \right] \right) - \frac{\sin\alpha}{\cos\beta} \left( \frac{m_h^2}{4\sqrt{2}v} \right) \]

\[ \mathcal{M}_H = \frac{\alpha_s}{4\pi} \frac{m_H^2}{2\sqrt{2}v} \left( \frac{\sin\alpha}{\sin\beta} F_{1/2}^H \left[ \frac{4m_t^2}{m_H^2} \right] \right) + \frac{\cos\alpha}{\cos\beta} \left( \frac{m_H^2}{4\sqrt{2}v} \right) \]

\[ \mathcal{M}_A = \frac{\alpha_s}{4\pi} \frac{m_A^2}{2\sqrt{2}v} \left( \frac{\cos\beta}{\sin\beta} F_{1/2}^A \left[ \frac{4m_t^2}{m_A^2} \right] \right) + \frac{\sin\beta}{\cos\beta} \left( \frac{m_A^2}{4\sqrt{2}v} \right) \]
Relic Abundance of the Dark Matter

The Dark Matter Annihilation
Relic Abundance of the Dark Matter

The Dark Matter Annihilation

**WMAP:** $\Omega_{DM} h^2 = 0.1131 \pm 0.0034$

$h \approx 0.71$
Relic Abundance of the Dark Matter

The Dark Matter Annihilation

WMAP: \( \Omega_{DM} h^2 = 0.1131 \pm 0.0034 \)

\( h \approx 0.71 \)

\( \Omega h^2 = \frac{3 \cdot 10^{-27}}{< \sigma v >} \)
Relic Abundance of the Dark Matter

The Dark Matter Annihilation

**WMAP:**

\[ \Omega_{DM} h^2 = 0.1131 \pm 0.0034 \]

\[ h \approx 0.71 \]

\[ <\sigma v> = 2 \cdot 10^{-26} \text{cm}^3/\text{s} \]
The Dark Matter Annihilation

**WMAP:**

\[ \Omega_{DM} h^2 = 0.1131 \pm 0.0034 \]

\[ h \approx 0.71 \]

\[ \langle \sigma v \rangle = 2 \cdot 10^{-26} \text{cm}^3/\text{s} \]

\[ \Omega h^2 = \frac{3 \cdot 10^{-27}}{\langle \sigma v \rangle} \]

\[ \langle \sigma v \rangle \sim \frac{M_X^4 m_b^2 \tan^2 \beta}{\sin^4 2\theta_W M_Z^2} \left( N_{31} \sin \beta - N_{41} \cos \beta \right)^2 \left( N_{21} \cos \theta_W - N_{11} \sin \theta_W \right)^2 \]

\[ \left( 4M_X^2 - M_A^2 \right)^2 + M_A^2 \Gamma_A^2 \]

\[ |\tilde{\chi}_1^0\rangle = N_{11}|B_0\rangle + N_{21}|W_0^3\rangle + N_{31}|H_1\rangle + N_{41}|H_2\rangle \]
Relic Abundance of the DM Constraint

The value of $\tan \beta$

$\tan \beta \approx 50$ almost everywhere except for the coannihilation regions

The value of $m_A$

$m_A$ may be as low as 500 GeV except for the coannihilation regions
SUSY Limits without Direct DM Search

The values of $A_0$ and $\tan \beta$ are adjusted

This includes:

- the Higgs searches
- the relic abundancy
- and collider limits
Direct DM Searches

\[ \sigma = \frac{4}{\pi} \frac{m_{\text{DM}}^2 m_N^2}{(m_{\text{DM}} + m_N)^2} \left( Z f_p + (A - Z) f_n \right)^2 \]

\[ f_{p,n} = \sum_{q=u,d,s} G_q f_{Tq}^{(p,n)} \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG} \sum_{q=c,b,t} G_q \frac{m_{p,n}}{m_q} \]

\[ m_p f_{Tq}^{(p)} \equiv \langle p | m_q \bar{q} q | p \rangle \]

\[ G_q(A) = 0, \]

\[ G_u(h) = \frac{-e^2 m_u}{2 \sin^2 2\theta_W M_Z} (N_{21} \cos \theta_W - N_{11} \sin \theta_W) \]

\[ G_d(h) = \frac{e^2 m_d}{2 \sin^2 2\theta_W M_Z} (N_{21} \cos \theta_W - N_{11} \sin \theta_W) \]

\[ G_u(H) = \frac{-e^2 m_u}{2 \sin^2 2\theta_W M_Z} (N_{21} \cos \theta_W - N_{11} \sin \theta_W) \]

\[ G_d(H) = \frac{-e^2 m_d}{2 \sin^2 2\theta_W M_Z} (N_{21} \cos \theta_W - N_{11} \sin \theta_W) \]
SUSY Limits from Direct DM Search

Low Energy Form Factors

Lattice Form Factors
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**SUSY Limits from Direct DM Search**
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- LHC constraints are rather insensitive to large values of $m_0$
- They can be supplemented by direct DM searches
SUSY Limits from Combined Fit to all Data with 5/fb

The values of $\tan \beta$ and $A_0$ are adjusted.
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Constraints from the lightest Higgs of 125 GeV
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Fig. 1
Left: distribution of all constraints up to $m_1^2 = 3000$ GeV, showing that the 2 does not increase because of the relic density for large neutralino masses in contrast to Ref. [33]. The white cross represents $m_1^2_{\text{min}} = 4$. The white region in the top left corner is excluded because the stau is always the LSP. The red region in this corner is excluded by the relic density constraint requiring large $\tan\beta$, which in turn causes a large increase in the stau sector leading to the stau becoming the LSP again. Right: contributions to the 2 of all constraints. The contour for each constraint represents the 95% CL exclusion limit which can be translated to an $m_1^2$ contribution of 5.99 for each constraint separately.

Fig. 2
Left: Preferred region of the g-2 observable alone under the constraint that $\tan\beta$ and $A_0$ are fixed by all other constraints. Here we show the 1 band for different treatment of the errors of g-2 which corresponds to a $m_1^2$ value below 2.3. We compare these bands with the 68% CL exclusion limit of the direct searches at the LHC, which fulfills the same relation. The quadratic addition of the errors (light green band) as well as the linear addition (dark green band) is largely excluded by the LHC constraints. The shallow increase of the $m_1^2$ value for large SUSY masses, because g-2 prefers light SUSY particles, gives a light preference for small SUSY masses in the overall distribution. Right: Light Higgs mass distribution given for the $\tan\beta$ and $A_0$ including all data. The 114.4 GeV mass contour is directly linked to the $m_1^2$ contribution of the Higgs mass constraint. The contour of the 95% CL exclusion limit of the Higgs mass constraint shown in Fig.1b is therefore directly linked to the Higgs mass distribution, which can be seen in Fig.2 right panel.
Constraints from the lightest Higgs of 125 GeV

$M_{Higgs} = 125 \pm 3.6 \text{ GeV}$
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Let 2012 be the year of Higgs discovery and SUSY evidence!