MSSM phenomenology in current colliders

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Overview

- The MSSM structure
- Phenomenology at Tevatron and B-factories
  - Indirect searches : $B_{s,d} \to \mu^+\mu^-$
  - Direct searches : Trileptons
  - Higgs searches
- Conclusions

Supersymmetry

Consider the Lagrangian of a free complex scalar field and a free Weyl spinor field :

$$\mathcal{L} = i\,\bar{\Psi}\,\bar{\sigma}_\mu\,\partial^\mu\,\Psi + \partial_\mu\,\Phi^*\,\partial^\mu\,\Phi$$

1 deriv	2 deriv
$\Psi \to e^{i\beta}\,\Psi$	$\Phi \to e^{i\gamma}\,\Phi$
Seen	Unseen

$$\overset{?}{\longleftrightarrow}$$

Question : Is there any symmetry relating the two ?

Supersymmetry

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$$\boxed{\delta\Phi = a\,\xi\,\Psi}$$

Supersymmetry

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1 deriv	2 deriv
$\Psi \to e^{i\beta}\,\Psi$	$\Phi \to e^{i\gamma}\,\Phi$
Seen	Unseen

$$\boxed{\delta\Psi = i\,a^*\,\bar{\xi}\,\bar{\sigma}_\mu\,(\partial^\mu\Phi)} \qquad \boxed{\delta\Phi = a\,\xi\,\Psi}$$

Supersymmetry

SUSY Interactions and breaking

$$\Delta\mathcal{L} = \left| \frac{\partial \mathcal{W}(\Phi)}{\partial \Phi} \right|^2 - \left[\frac{1}{2} \frac{\partial^2 \mathcal{W}(\Phi)}{\partial \Phi \, \partial \Phi} \Psi \, \Psi + \mathrm{H.c} \right]$$

- $\mathcal{W}(\Phi)$ is an analytic function (superpotential)
- Masses : $\mathcal{W}[\Phi] = \frac{1}{2} \mu \, \Phi^2$

$$\Delta\mathcal{L} = |\mu|^2 \, \Phi^2 - (\frac{\mu}{2} \, \Psi\Psi + \ \mathrm{H.c})$$

- ... all fields in $\{\Phi, \Psi\}$ have the same mass...
- Supersymmetry must be broken at our energies
- $\Delta\mathcal{L}^{\mathrm{Breaking}} = M_0^2 \, \Phi^2$

The Lagrangian

$$\mathcal{L} = i\,\bar{\Psi}\,\bar{\sigma}_\mu\,\partial^\mu\,\Psi + \partial_\mu\,\Phi^*\,\partial^\mu\,\Phi$$

The Lagrangian

$$\mathcal{L} = i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi + (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu)\,\Phi$$

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$$- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu}$$

The Lagrangian

$$\mathcal{L} = i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi + (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu)\,\Phi$$

$$- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} + i\bar{\lambda}\,\bar{\sigma}_\mu\partial^\mu\,\lambda$$

The Lagrangian

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$$- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} + i\bar{\lambda}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\lambda$$

The Lagrangian

$$
\begin{aligned}
\mathcal{L} \quad = & \quad i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - i g \mathbf{A}^\mu)\,\Psi + (\partial_\mu - i g \mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - i g \mathbf{A}^\mu) \\
- & \quad \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} + i\bar{\lambda}\,\bar{\sigma}_\mu(\partial^\mu - i g \mathbf{A}^\mu)\,\lambda \\
- & \quad \frac{1}{2}\,\frac{\partial^2 \mathcal{W}}{\partial\Phi\,\partial\Phi}\Psi\,\Psi \quad + \quad \mathrm{H.c}
\end{aligned}
$$

where $\mathcal{W} = \frac{1}{2}\,\mu\,\Phi^2 + \frac{1}{3}\,\mathrm{Y}\,\Phi^3$

The Lagrangian

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-\;& \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} + i\bar{\lambda}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\lambda \\
-\;& \frac{1}{2}\,\frac{\partial^2\mathcal{W}}{\partial\Phi\,\partial\Phi}\Psi\,\Psi \quad + \quad i\sqrt{2}\,g\,\Phi^*\,\Psi\,\lambda \quad + \quad \mathrm{H.c}
\end{aligned}
$$

The Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\;& i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi + (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu)\\
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-\;& \frac{1}{2}\,\frac{\partial^2\mathcal{W}}{\partial\Phi\,\partial\Phi}\Psi\,\Psi \;+\; i\,\sqrt{2}\,g\,\Phi^*\,\Psi\,\lambda \;+\; \mathrm{H.c}\\
-\;& \left|\frac{\partial\mathcal{W}}{\partial\Phi}\right|^2 - \frac{g^2}{2}\left(\Phi^*\,\Phi\right)^2
\end{aligned}
$$

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-\;& \left|\frac{\partial\mathcal{W}}{\partial\Phi}\right|^2 - \frac{g^2}{2}\left(\Phi^*\,\Phi\right)^2 \\
-\;& M_0^2\,\Phi^*\,\Phi \quad - \quad B_0\,\Phi\,\Phi \quad - \quad A_0\,\Phi\,\Phi\,\Phi \quad + \quad \mathrm{H.c}
\end{aligned}
$$

The Lagrangian - MSSM structure

$$
\begin{aligned}
\mathcal{L} \;=\;& i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi + (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu) \\
&- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} + i\bar{\lambda}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\lambda \\
&- \frac{1}{2}\,\frac{\partial^2 \mathcal{W}}{\partial\Phi\,\partial\Phi}\Psi\,\Psi \;+\; i\,\sqrt{2}\,g\,\Phi^*\,\Psi\,\lambda \;+\; \mathrm{H.c} \\
&- \left|\frac{\partial \mathcal{W}}{\partial \Phi}\right|^2 - \frac{g^2}{2}\left(\Phi^*\,\Phi\right)^2 \\
&- M_0^2\,\Phi^*\,\Phi \;-\; B_0\,\Phi\,\Phi \;-\; A_0\,\Phi\,\Phi\,\Phi \;+\; \mathrm{H.c} \\
&- \frac{M_{1/2}}{2}\,\lambda\,\lambda \;+\; \mathrm{H.c}
\end{aligned}
$$

MSSM structure

Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Φ , Ψ
$Q_r^{i,\alpha}$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L \, , \, \begin{pmatrix} u \\ d \end{pmatrix}_L$
$D_{r,\alpha}$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	$\tilde{d}_R \, , \, d_R$
$U_{r,\alpha}$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$	$\tilde{u}_R \, , \, u_R$
L_r^i	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L \, , \, \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$
E_r	$(\mathbf{1}, \mathbf{1}, 1)$	$\tilde{e}_R \, , \, e_R$
H_d^i	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix} \, , \, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$
H_u^i	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix} \, , \, \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$

MSSM structure

Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$\lambda \quad \mathbf{A}_\mu$
$V_3^{(R)}$	$(\mathbf{8}, \mathbf{1}, 0)$	$\tilde{G}^{(R)} \; , \; G_\mu^{(R)}$
$V_2^{(\Gamma)}$	$(\mathbf{1}, \mathbf{3}, 0)$	$\tilde{W}^{(\Gamma)} \; , \; W_\mu^{(\Gamma)}$
V_1	$(\mathbf{1}, \mathbf{1}, 0)$	$\tilde{B} \; , \; B_\mu$

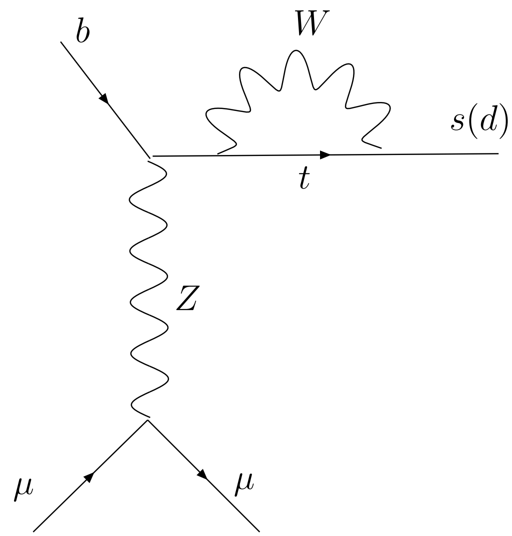
and

$$\tan\beta \;=\; \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

Phenomenology in current colliders

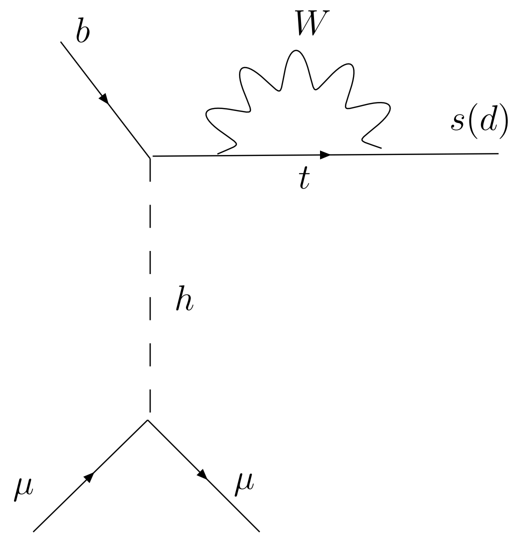
- Indirect Searches (Tevatron and B-factories)
  - Rare B-meson decays like $B_{s,d} \longrightarrow l^+ l^-$
    - Recently it has been discovered that such decays are affected by orders of magnitude in the MSSM
  - $b \longrightarrow s\gamma$, $B \longrightarrow K l^+ l^-$, $B \longrightarrow \phi K_S, ..$
- Direct Searches (Tevatron)
  - Neutralinos+Charginos, trileptons in final state
  - Squarks and Gluinos
  - Higgs boson(s)
  - R-parity violation, multilepton events

$B_{d,s} \to \mu^+\mu^-$



SM : Buchalla and Buras, 93

$B_{d,s} \to \mu^+\mu^-$



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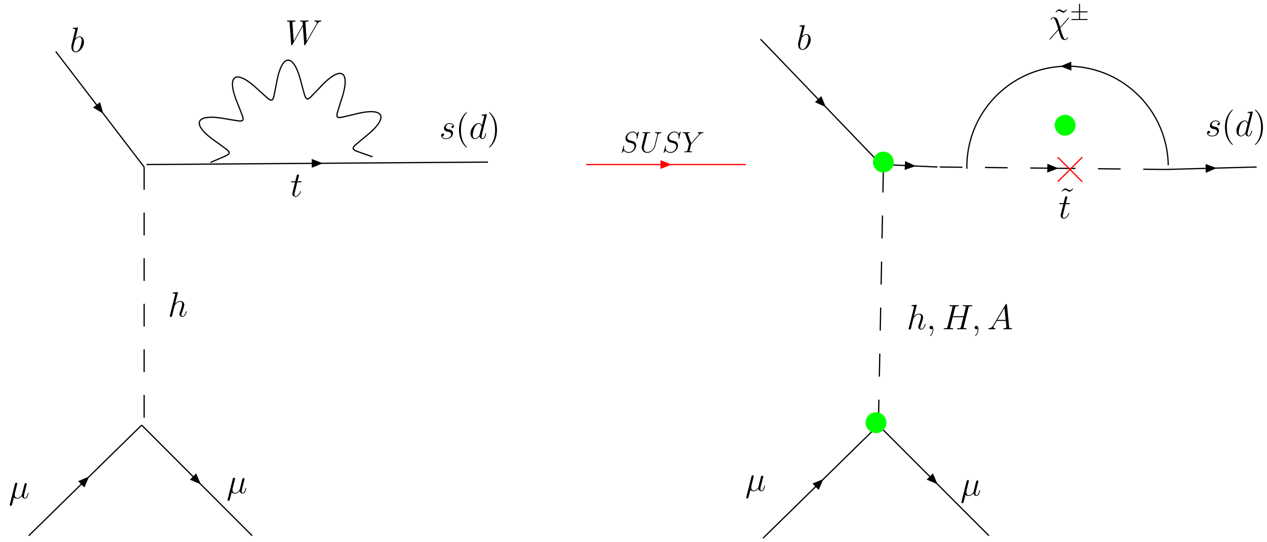
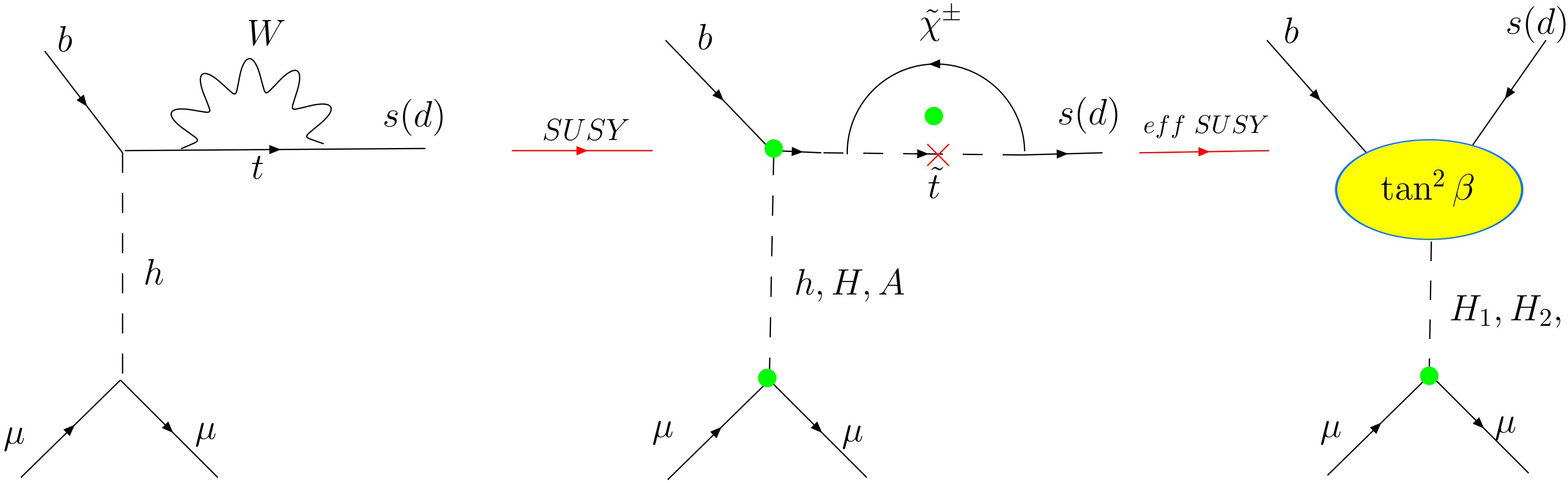


$B_{d,s} \to \mu^+\mu^-$



$$C_{S,P} \propto \; m_\mu \frac{\tan^3\beta}{M^2_{H_3}} \; f(M_{SUSY}) \Rightarrow \mathcal{B}(B_s \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{M^4_{H_3}} \;\; !!$$

A. D., and A. Pilaftsis, Phys. Rev. D **67**, 015012 (2003) [arXiv:hep-ph/0209306].

Literature on $B_s \to \mu^+\mu^-$

MSSM : K. S. Babu and C. Kolda, '99,
C. Bobeth, T. Ewerth, F. Krüger and J. Urban, '01, '02
G. Isidori, A. Retico, '01,'02
A. Dedes and A. Pilaftsis, '02
A. J. Buras, P. H. Chankowski, J. Rosiek and L. Slawianowska, "02

mSUGRA : A. Dedes, H. K. Dreiner and U. Nierste, '01
R. Arnowitt, B. Dutta, T. Kamon and M. Tanaka, '02
J. K. Mizukoshi, X. Tata and Y. Wang,'02
A. Dedes, H. K. Dreiner and U. Nierste, P. Richardson, '02
T. Ibrahim and P. Nath, '02

SO(10) : R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz De Austri, '03

GMSB, AMSB : S. w. Baek, P. Ko and W. Y. Song, '02

Exp Review : T. Kamon [CDF Collaboration], '02

Theory Review : A. Dedes , '03.

Predictions and Experimental Bounds

- Standard Model Prediction

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.7 \pm 1.2) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.0 \pm 0.3 \pm 0.3) \times 10^{-10}$$

- General MSSM prediction

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \text{up to } 10^{-5}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = \text{up to } 10^{-6}$$

Predictions and Experimental Bounds

- Tevatron CDF/D0 Run II experimental bound

$$\mathcal{B}(B_s \to \mu^+\mu^-) \;<\; 5.8/4.1 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

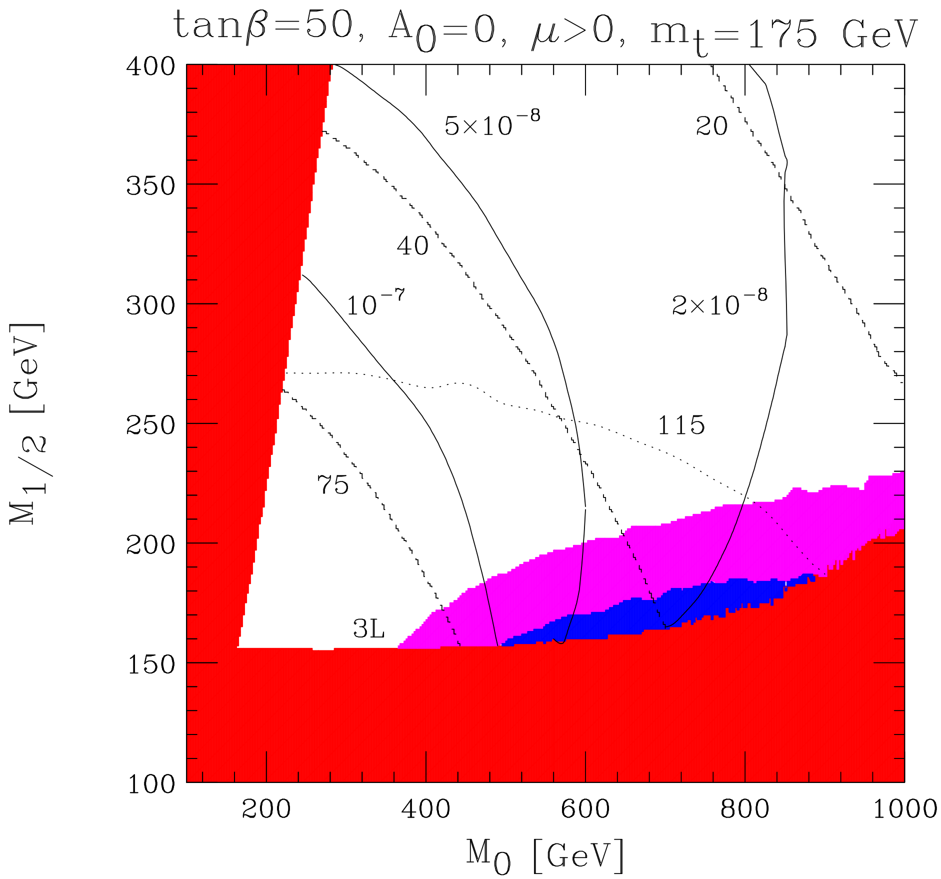
- BaBar/Belle experimental bound

$$\mathcal{B}(B_d \to \mu^+\mu^-) \;<\; 8.3/16 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

...any evidence at Tevatron or at BaBar/Belle may be a SUSY footprint...

See talk by V. Papadimitriou

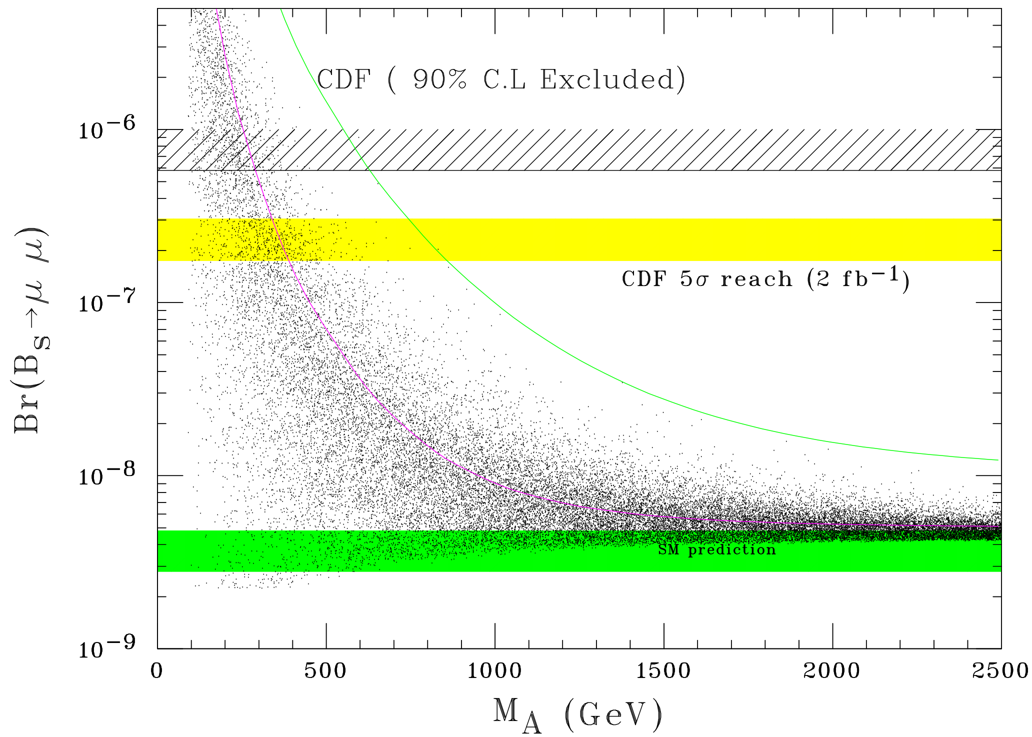
mSUGRA predictions



- Solid : $\mathcal{B}(B_s \to \mu^+\mu^-)$
- Dashed : $(g-2)_\mu$
- Dotted : Light Higgs mass

A. D, H. Dreiner, U. Nierste, P. Richardson, arXiv:hep-ph/0207026.

Bounding the Higgs sector! A.D, T. Huffman, '04



$$\mathcal{B}(B_s \to \mu^+\mu^-) \simeq 5 \times 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{650 \text{ GeV}}{M_A}\right)^4$$

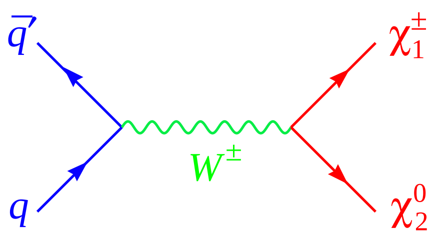
Trileptons

- “Gold plated” mode at Tevatron : $q\bar{q}' \to \chi_1^{\pm}\chi_2^0 \to 3l + \not{E}_T$

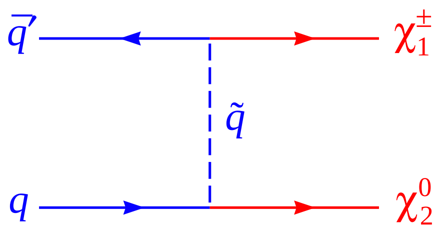
Trileptons

- "Gold plated" mode at Tevatron : $q\bar{q}' \longrightarrow \chi_1^{\pm}\chi_2^0 \longrightarrow 3l + \not{E}_T$

$q\bar{q}' \to \chi_1^{\pm}\chi_2^0$



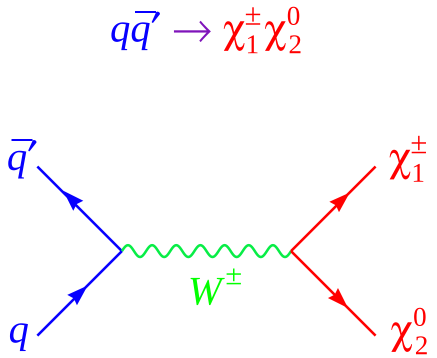
(a)



(b)

Trileptons

- “Gold plated” mode at Tevatron : $q\bar{q}' \to \chi_1^\pm \chi_2^0 \to 3l + \not{E}_T$



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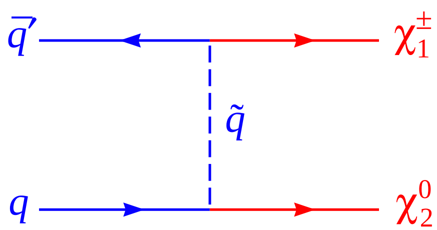
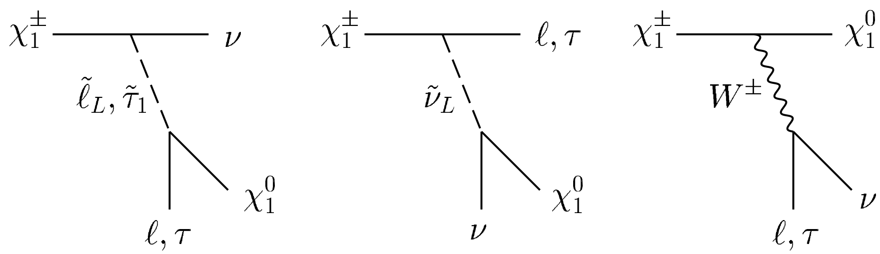
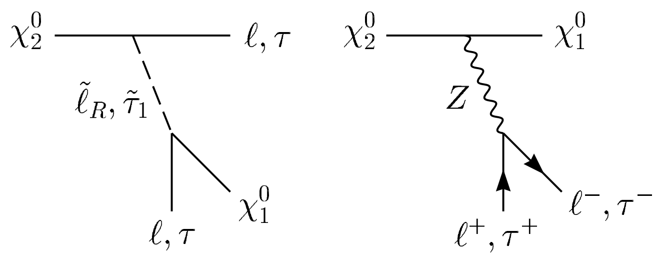


(b)



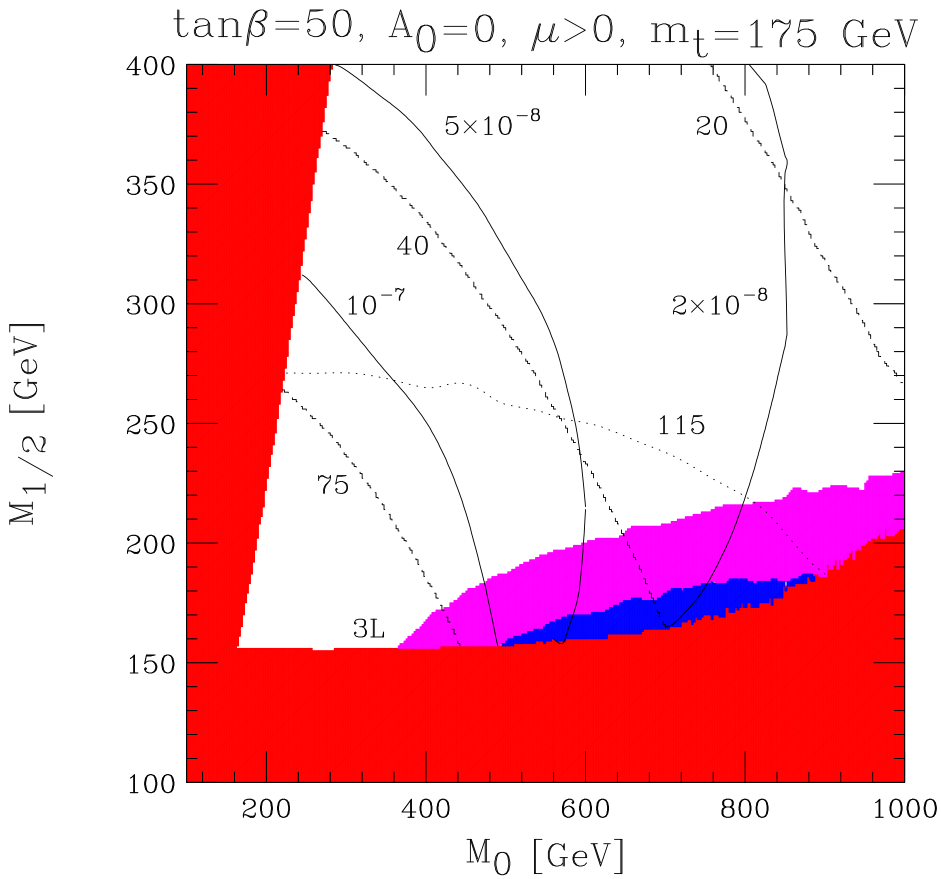
(a)



(b)

Arnowitt and Nath ’87; Baer, Tata, Paige, Drees ’97; Lykken and Matchev ’99

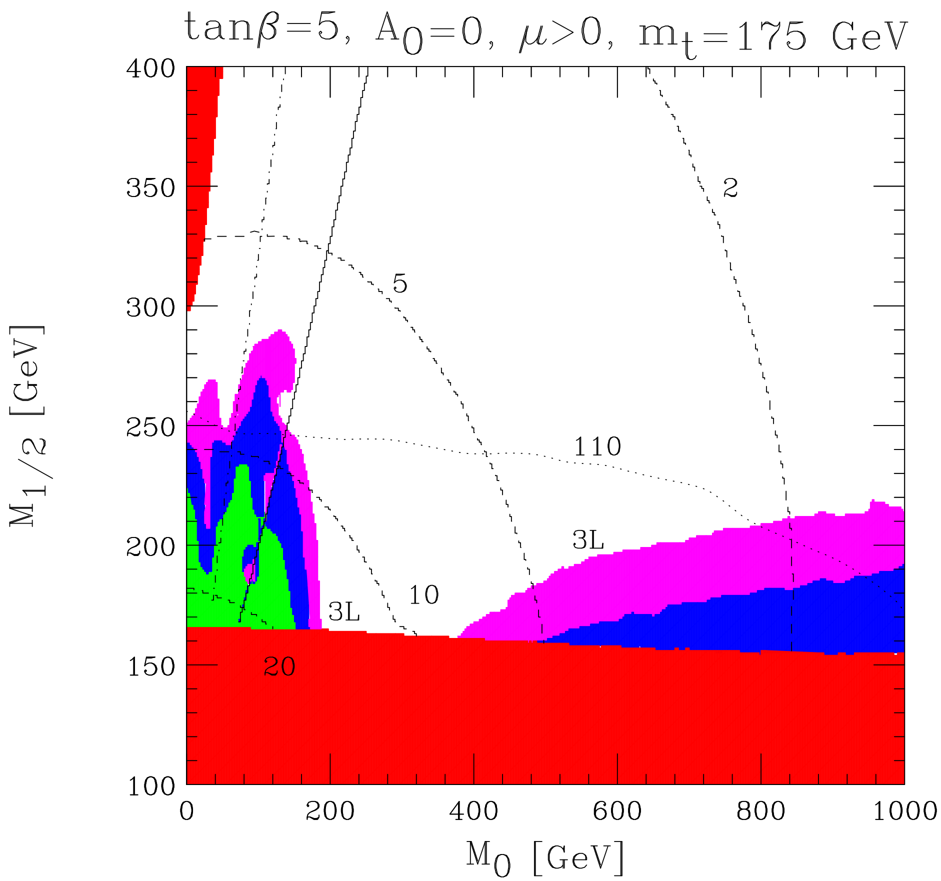
Trileptons at Tevatron



- Solid : $\mathcal{B}(B_s \to \mu^+\mu^-)$
- Dashed : $(g-2)_\mu$
- Dotted : Light Higgs mass
- $\mathcal{L} = 10\ \text{fb}^{-1}$
- $\mathcal{L} = 30\ \text{fb}^{-1}$

A. D, H. Dreiner, U. Nierste, P. Richardson, arXiv:hep-ph/0207026.

Trileptons at Tevatron



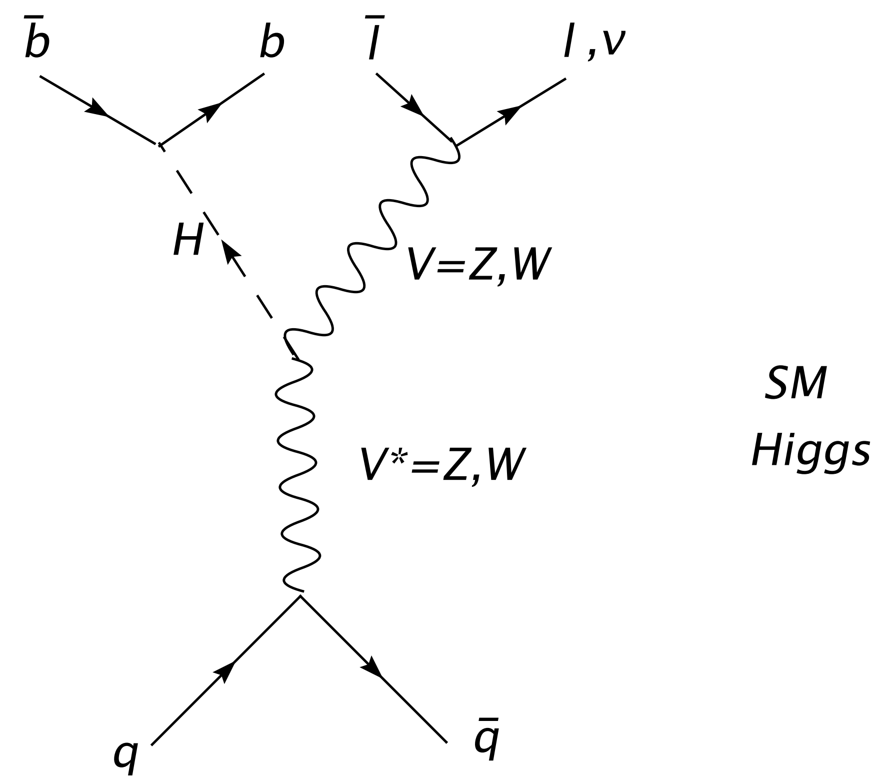
- Solid : $\mathcal{B}(B_s \to \mu^+\mu^-)$
- Dashed : $(g-2)_\mu$
- Dotted : Light Higgs mass
- $\mathcal{L} = 2\ \mathrm{fb}^{-1}$
- $\mathcal{L} = 10\ \mathrm{fb}^{-1}$
- $\mathcal{L} = 30\ \mathrm{fb}^{-1}$

A. D, H. Dreiner, U. Nierste, P. Richardson, arXiv:hep-ph/0207026.

Higgs Boson at Tevatron (SM)

- Higgs boson(s) in association with vector bosons

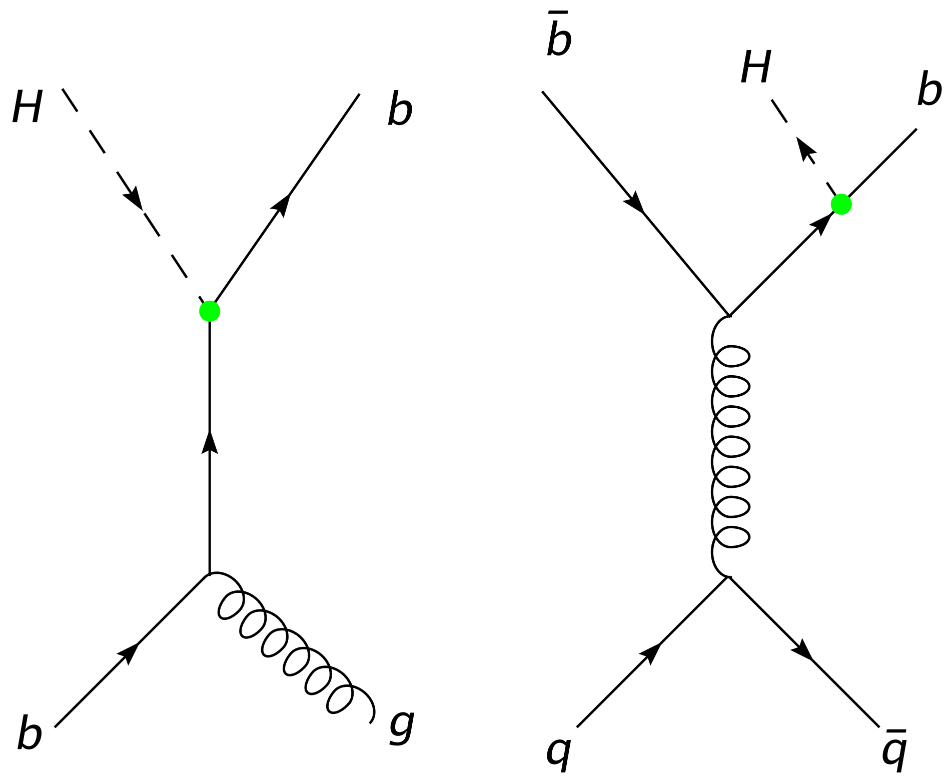
$q\bar{q} \to V^* \to VH$.



Higgs Boson at Tevatron (MSSM)

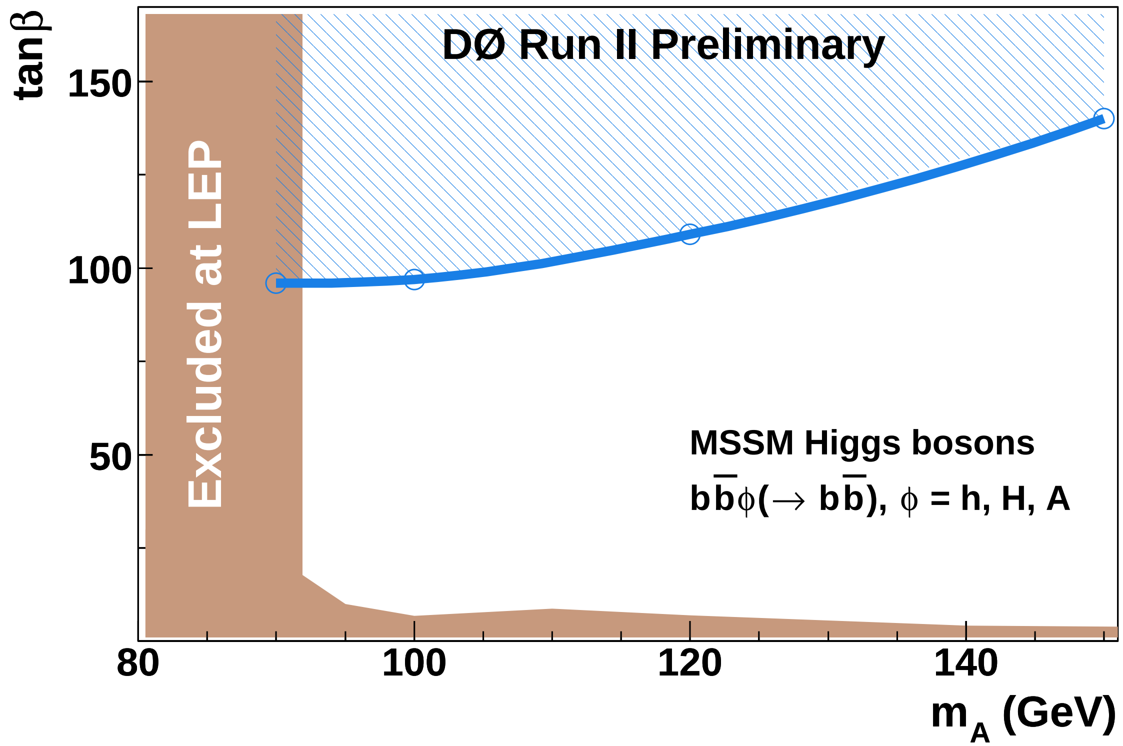
- MSSM predicts three neutral and two charged Higgs bosons. One of the neutral Higgs bosons should weight no more than ~ 150 GeV.
- Large couplings $H\bar{b}b$ and $H\bar{\tau}\tau$ at large $\tan\beta$
- Higgs may now be sizeably produced in association with one or more quarks
- gluon fusion, $gg \to H \to \tau\tau$, is also more effective now

Higgs Bosons at Tevatron (MSSM)



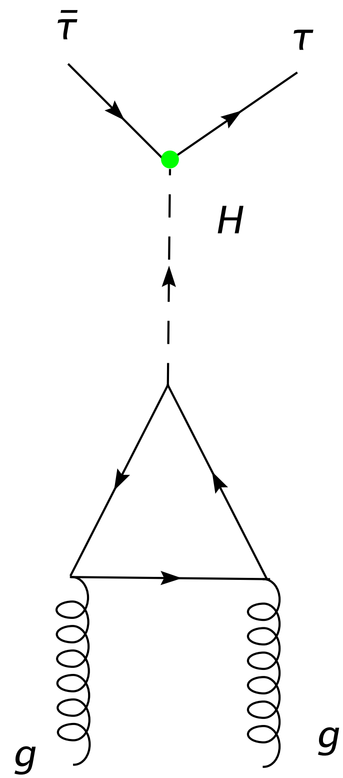
Higgs Bosons at Tevatron (MSSM)

...multi b-jets in final state...



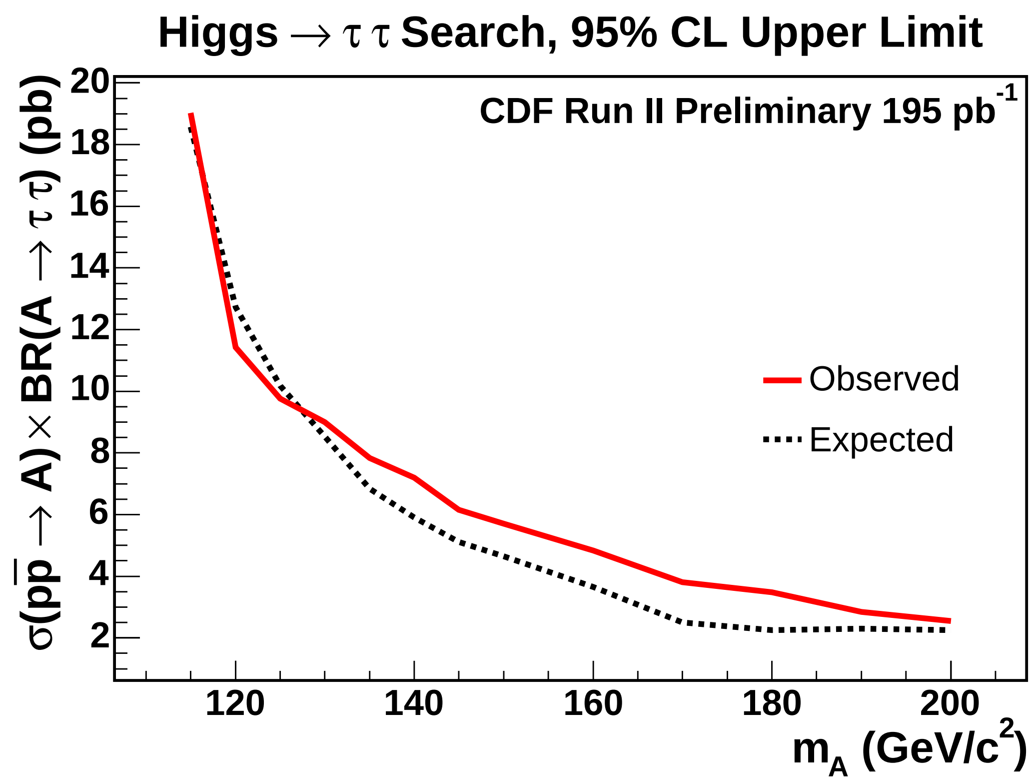
V. Büscher, hep-ex/0411063

Higgs Bosons at Tevatron (MSSM)



Higgs Bosons at Tevatron (MSSM)

Upper limits on the cross section $\sigma \cdot Br(H \to \tau\tau)$ in comparison with the expected limit.



V. Büscher, hep-ex/0411063

Conclusions

- MSSM phenomenology is under serious investigation in current colliders
- Indirect Searches (Tevatron B-factories)
  - The rare decay $B_{s,d} \to \mu^+\mu^-$ is enhanced by orders of magnitude in the MSSM if $\tan\beta$ is large and the Higgs sector relatively light
- Direct Searches (Tevatron)
  - There is a chance for final state SUSY trilepton events to appear at Tevatron if
  - $\tan\beta$ is small and charginos $\lesssim 150$ GeV

Conclusions

- MSSM Higgs searches
  - large $\tan\beta \gtrsim 40$ region through single or multi b-jets in the final state
  - gluon fusion with taus in the final state

Conclusions

Searches for Supersymmetry are currently highly active at Tevatron and B-factories. Physics can be transfered to LHC and to ... exciting times ahead.