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Minimal Supersymmetric Standard Model (MSSM)

1. What is and Why Supersymmetry (SUSY)?
2. What are the SUSY interactions ?
3. What is MSSM ?
4. How can I discover SUSY today?
   - Direct SUSY Trileptons searches
   - Indirect rare decay $B_s \to \mu^+\mu^-$
5. Conclusions

The present is a basic introduction to Beate's talk that follows

What is and Why Supersymmetry ?

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

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

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

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

Question : Is there any symmetry relating the two ?

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

$$\updownarrow \qquad \text{Supersymmetry}$$

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

Supersymmetric masses and interactions :

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

$\mathcal{W}(\Phi)$ 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 entering a supermultiplet $\{\Phi, \Psi\}$ have the same mass...

$$\downarrow$$

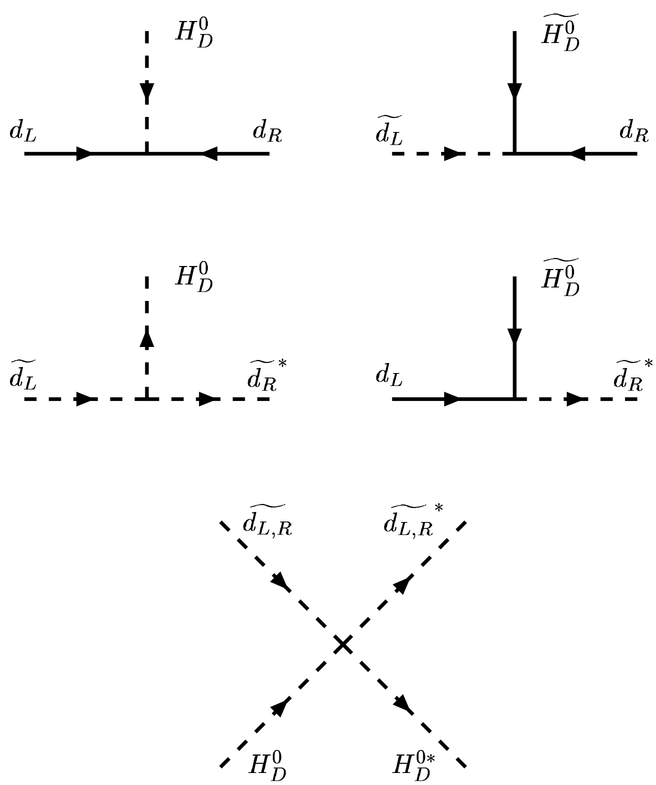
Supersymmetry must be broken at our energies

$$\downarrow$$

$$\Delta\mathcal{L}^{\mathrm{Breaking}} \;=\; M_0^2\;\Phi^2$$

Interactions :

$$\mathcal{W}^{\mathrm{Real\ \ World}}[\Phi] \;=\; \mathbf{Y_D}\;Q_L\;H_D\;D_R \;+\; \mathbf{Y_U}\;Q_L\;H_U\;U_R$$



More SM and SUSY interactions

We started with

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

$$+\ \partial_\mu\,\Phi^*\,\partial^\mu\,\Phi$$

More SM and SUSY interactions

Local gauge invariance and global supersymmetry result in

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

More SM and SUSY interactions

Local gauge invariance and global supersymmetry result in

$$
\begin{aligned}
\mathcal{L} &= i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi \\
&+ (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu)\,\Phi \\
&- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu}
\end{aligned}
$$

More SM and SUSY interactions

Local gauge invariance and global supersymmetry result in

$$\begin{aligned}\mathcal{L} &= i\,\bar{\Psi}\,\bar{\sigma}_\mu(\partial^\mu - ig\mathbf{A}^\mu)\,\Psi \\ &+ (\partial_\mu - ig\mathbf{A}_\mu)^*\,\Phi^*\,(\partial^\mu - ig\mathbf{A}^\mu)\,\Phi \\ &- \frac{1}{4}\,\mathbf{F}_{\mu\nu}\,\mathbf{F}^{\mu\nu} \\ &+ i\bar{\lambda}\,\bar{\sigma}_\mu\partial^\mu\,\lambda\end{aligned}$$

More SM and SUSY interactions

Local gauge invariance and global supersymmetry result in

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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
\end{aligned}$$

More SM and SUSY interactions

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&+ (\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 - ig\mathbf{A}^\mu)\,\lambda \\
&- \frac{1}{2}\,\frac{\partial^2\mathcal{W}}{\partial\Phi\,\partial\Phi}\Psi\,\Psi \quad + \quad \mathrm{H.c}
\end{aligned}$$

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

More SM and SUSY interactions

Local gauge invariance and global supersymmetry result in

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

N=1 SUSY Lagrangian

Local gauge invariance and global supersymmetry result in

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

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

N=1 broken SUSY Lagrangian

Local gauge invariance, global supersymmetry and supersymmetry breaking result in

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

N=1 broken SUSY Lagrangian

Local gauge invariance and global supersymmetry result in

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

What is MSSM ?

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	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$, $\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$

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

What is $\tan\beta$??

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

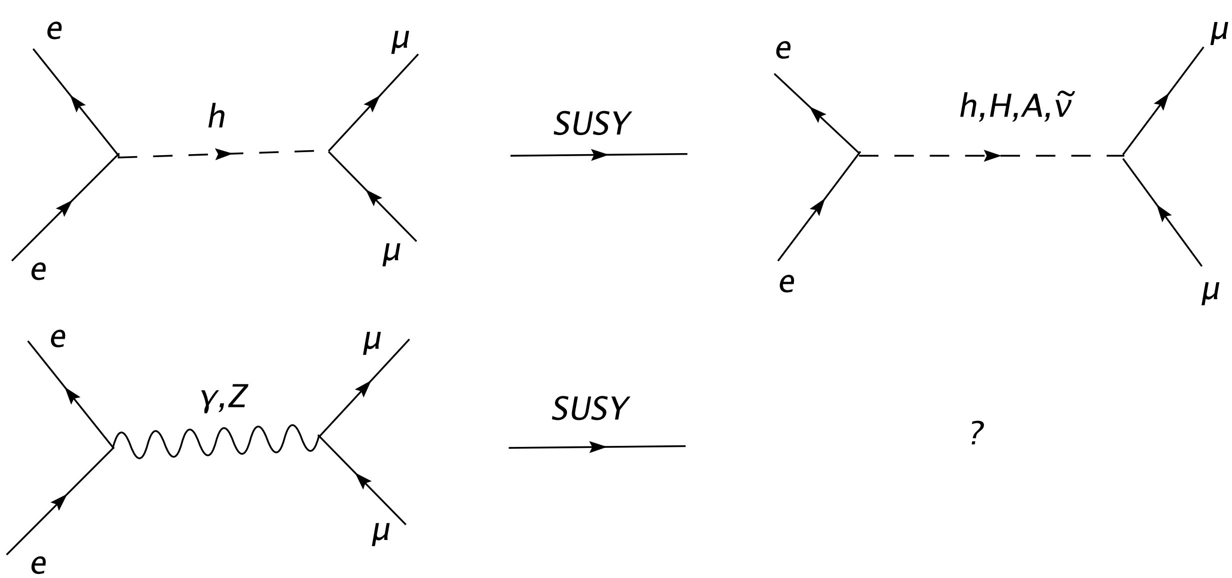
or

$$\tan\beta = \frac{v_u}{v_d}$$

How to Discover SUSY today ?

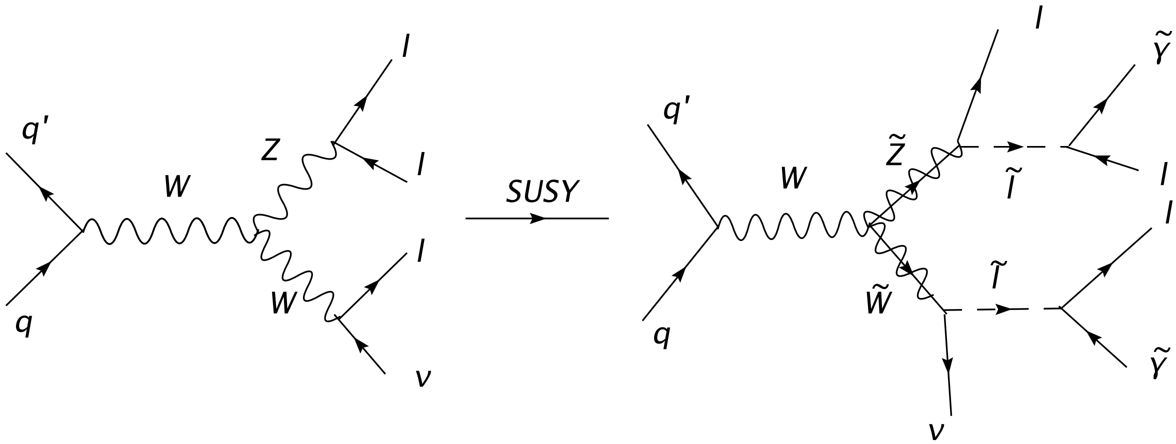
1. Start with your favorite Standard Model process
2. Supersymmetrize the intermediate legs of this process
3. Decide whether you want the SUSY particles to be produced in pairs or not i.e., R-parity symmetry on or off
4. Estimate the rate before you start typing...

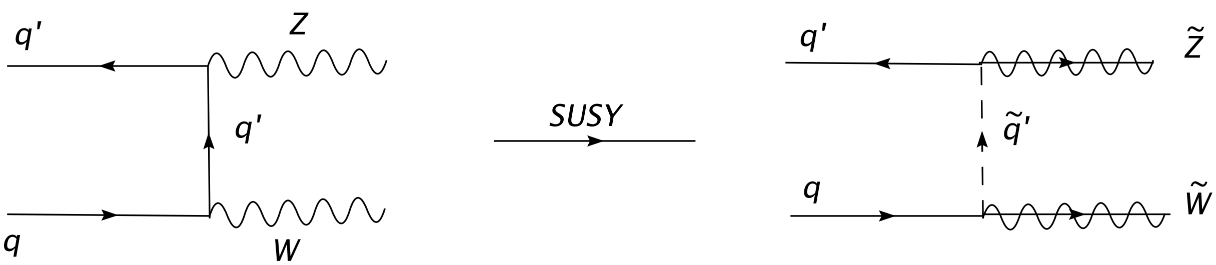
Example : Electron-Muon Scattering

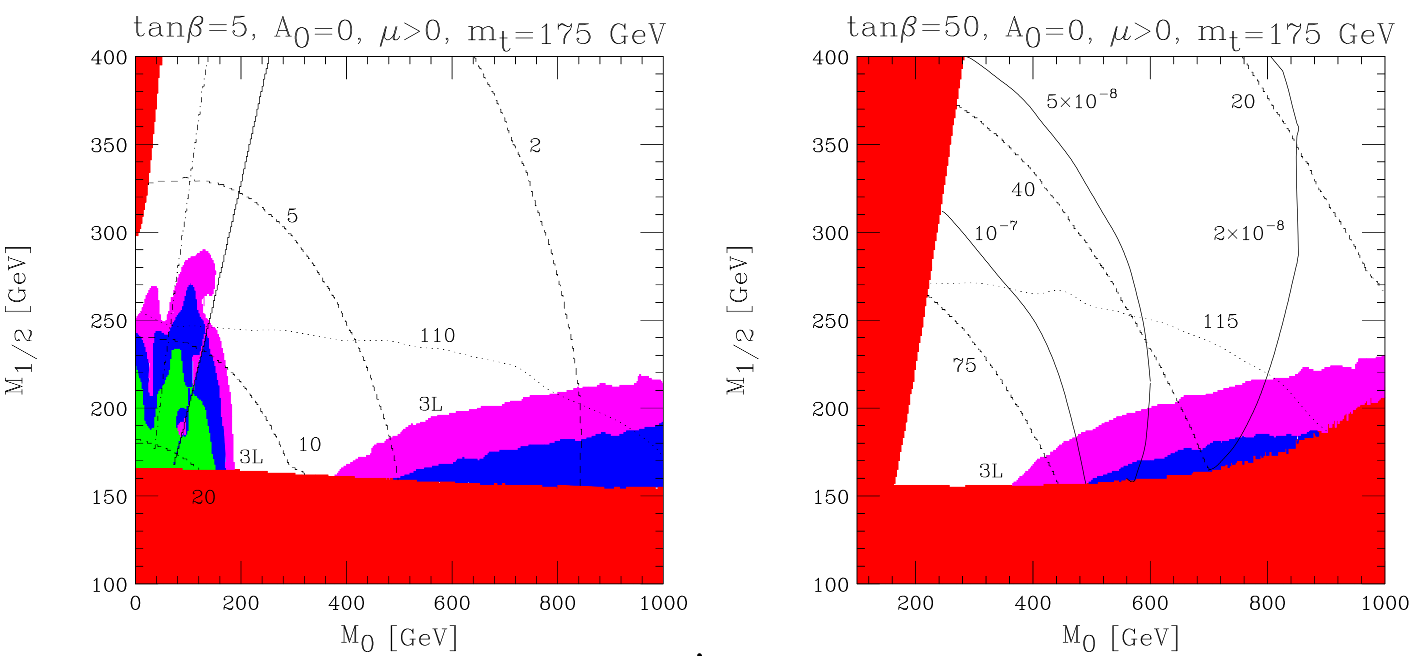


Trileptons

"Gold plated" mode at Tevatron







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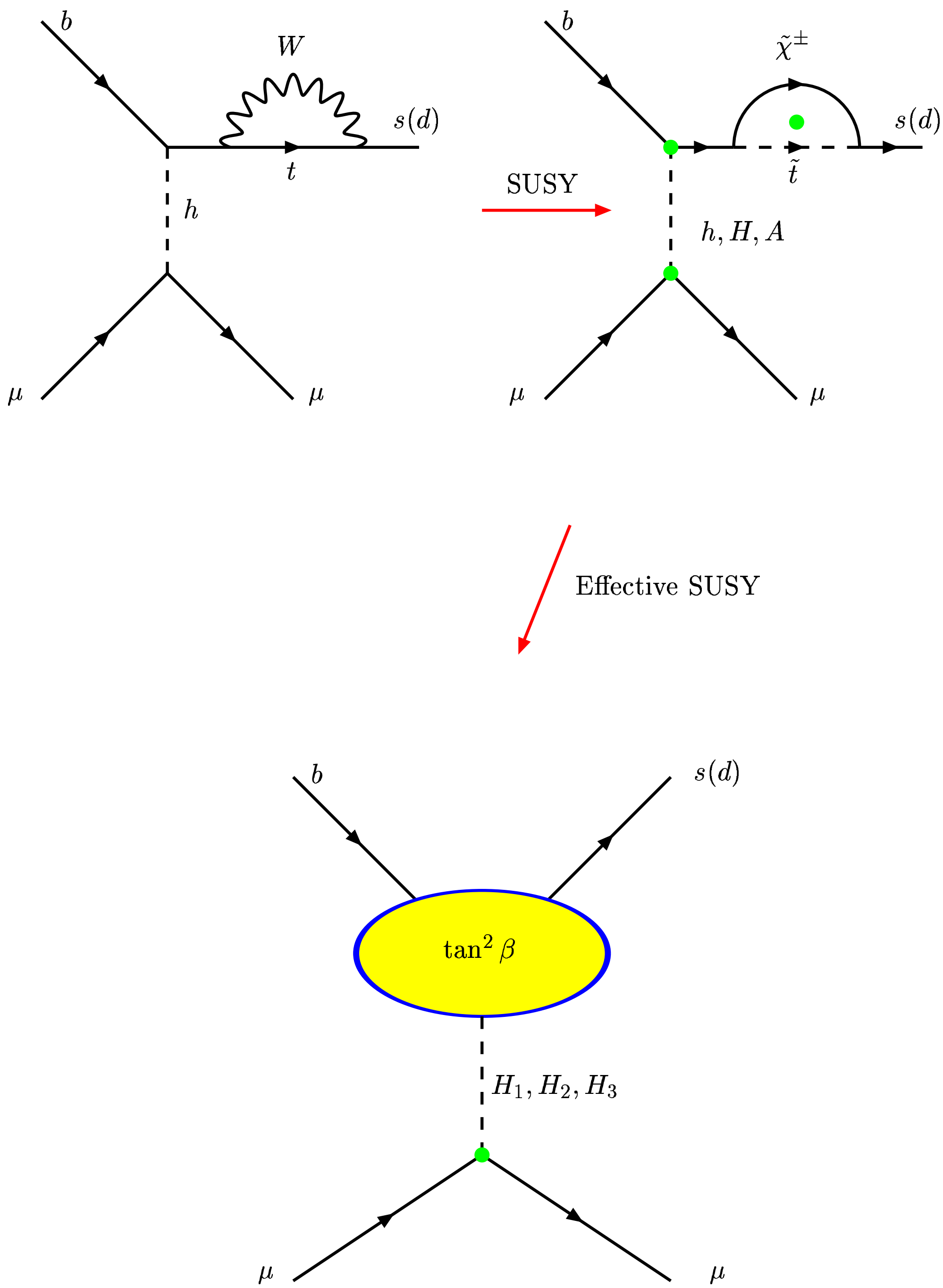
A. D, H. Dreiner, U. Nierste, P. Richardson, arXiv:hep-ph/0207026.

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



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

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

For a review see A. D., Mod. Phys. Lett. A **18** (2003) 2627

- 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 :

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

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

- Tevatron CDF/D0 Run II experimental bound :

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

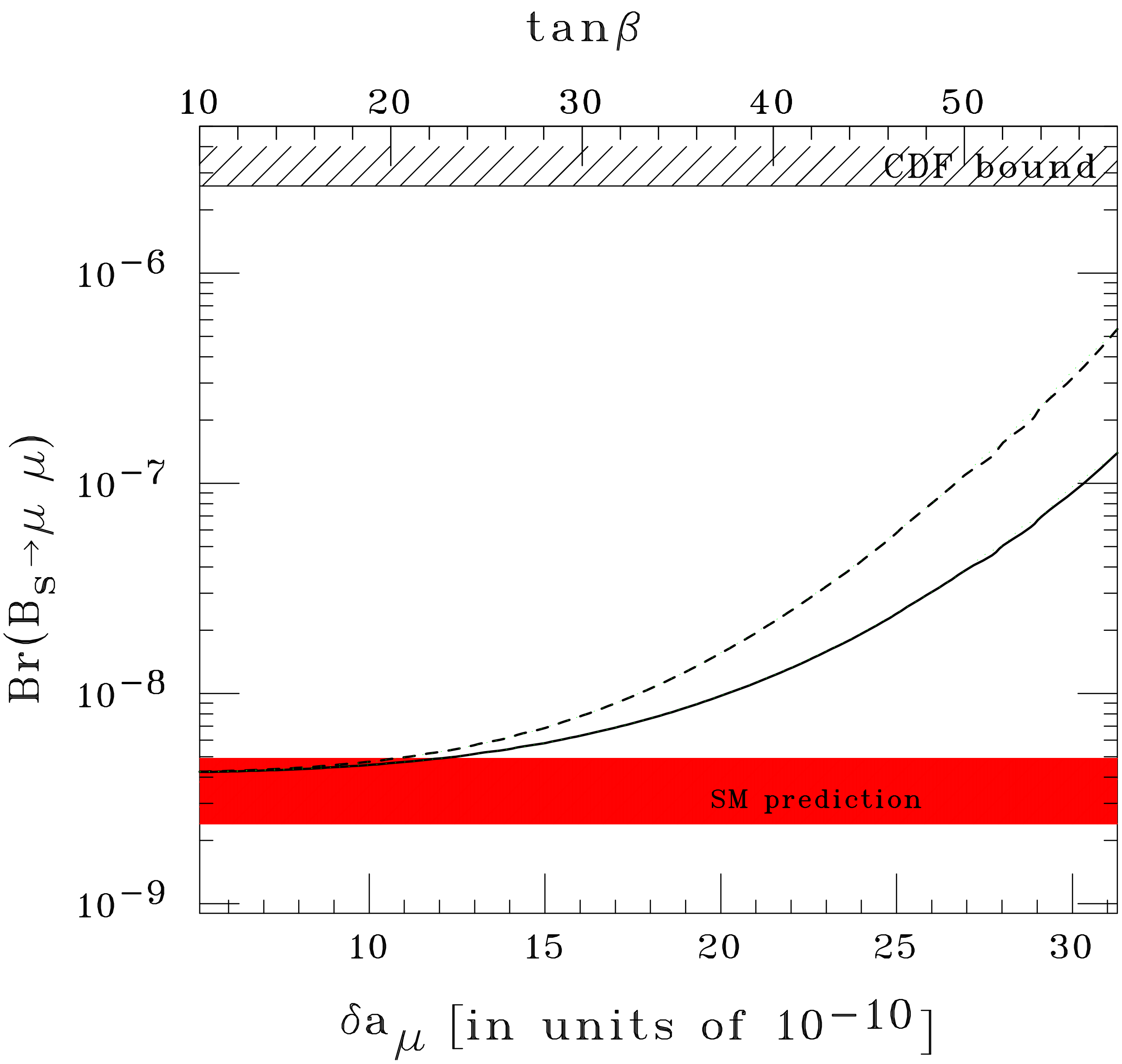
- BaBar/Belle experimental bound :

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

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

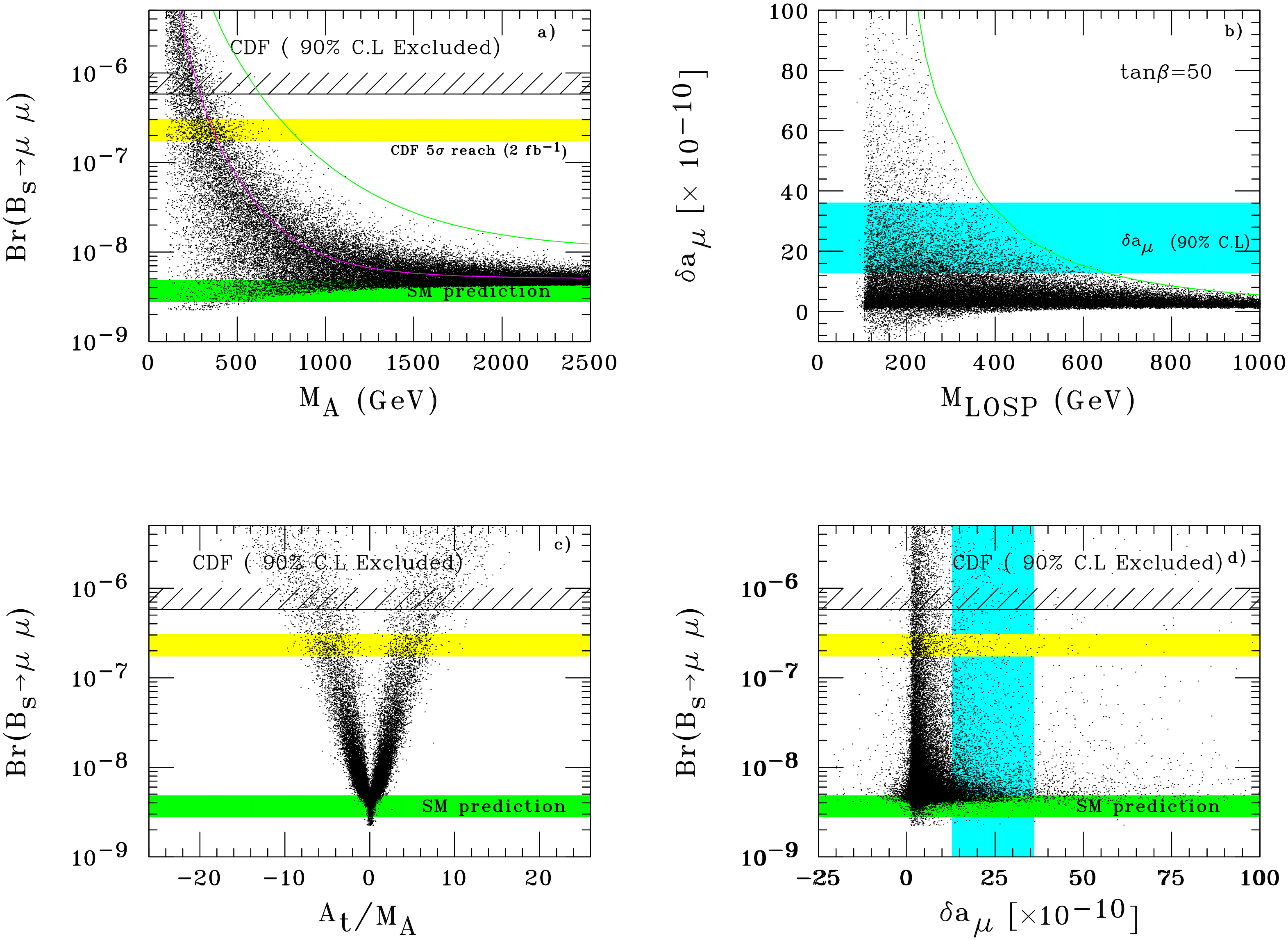
Correlation with the muon $g-2$

$M_0 = 350$ GeV, $M_{1/2} = 450$ GeV, $A_0 = 0$ GeV, $\mu > 0$



A.D, H. K. Dreiner and U. Nierste, Phys. Rev. Lett. **87**, 251804 (2001)

Bounding M_0, $M_{1/2}$ and A_0 from above!



$$M_A \lesssim 660 \text{ GeV with } x = 0.5 \text{ fb}^{-1}$$

$$M_A \lesssim 790 \text{ GeV with } x = 2 \text{ fb}^{-1}$$

$$M_A \lesssim 970 \text{ GeV with } x = 10 \text{ fb}^{-1},$$

A.D., and B. T. Huffman, Phys. Lett. B **600** (2004) 261 [arXiv:hep-ph/0407285].

Conclusions

1. Supersymmetry is a symmetry which relates particles of different spins.

2. It has a virtue of allowing non trivial interactions between fermions and bosons.

3. Our ignorance about the breaking of supersymmetry brings the unknown parameters : $M_0, M_{1/2}, A_0$

4. A Realization of broken SUSY exists and called MSSM

5. Tevatron can see MSSM signatures today directly or indirectly. Examples are : SUSY trileptons and $B_s \to \mu^+\mu^-$.

6. Supersymmetry will receive great support if a light Higgs boson is found. After all, there must be a reason why Nature decided to entertain us with particles of different spin.