Phenomenology of Scalar fermions in the MSSM

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CYCU–18/12/2007

In collaboration with W. Hollik JHEP'06, R. Benbrick PRD'05 and work in progress

Outline

- MSSM: Short review
- Scalar fermions at LHC
- Scalar fermions al ILC
- Radiative corrections to $\tilde{f}_i \to \tilde{f}_j Z$, $\tilde{f}_i \to \tilde{f'}_j W^{\pm}$ and CP violation
- Conclusions

MSSM: Short review

• SUSY is one of the best motivated extension of Standard Model. Naturalness problem and Dark matter.

• SUSY transformations:

$$\begin{aligned} \{l, q\}_{L,R} &\leftrightarrow \{\widetilde{l}, \widetilde{q}\}_{L,R} \\ \{\gamma, Z, W^{\pm}, g\} &\leftrightarrow \{\widetilde{\gamma}, \widetilde{Z}, \widetilde{W}^{\pm}, \widetilde{g}\} \\ \{H_1, H_2\} &\leftrightarrow \{\widetilde{H}_1, \widetilde{H}_2\} \end{aligned}$$

• Since $m_e \neq m_{\widetilde{e}}$ $\Rightarrow$ SUSY is broken

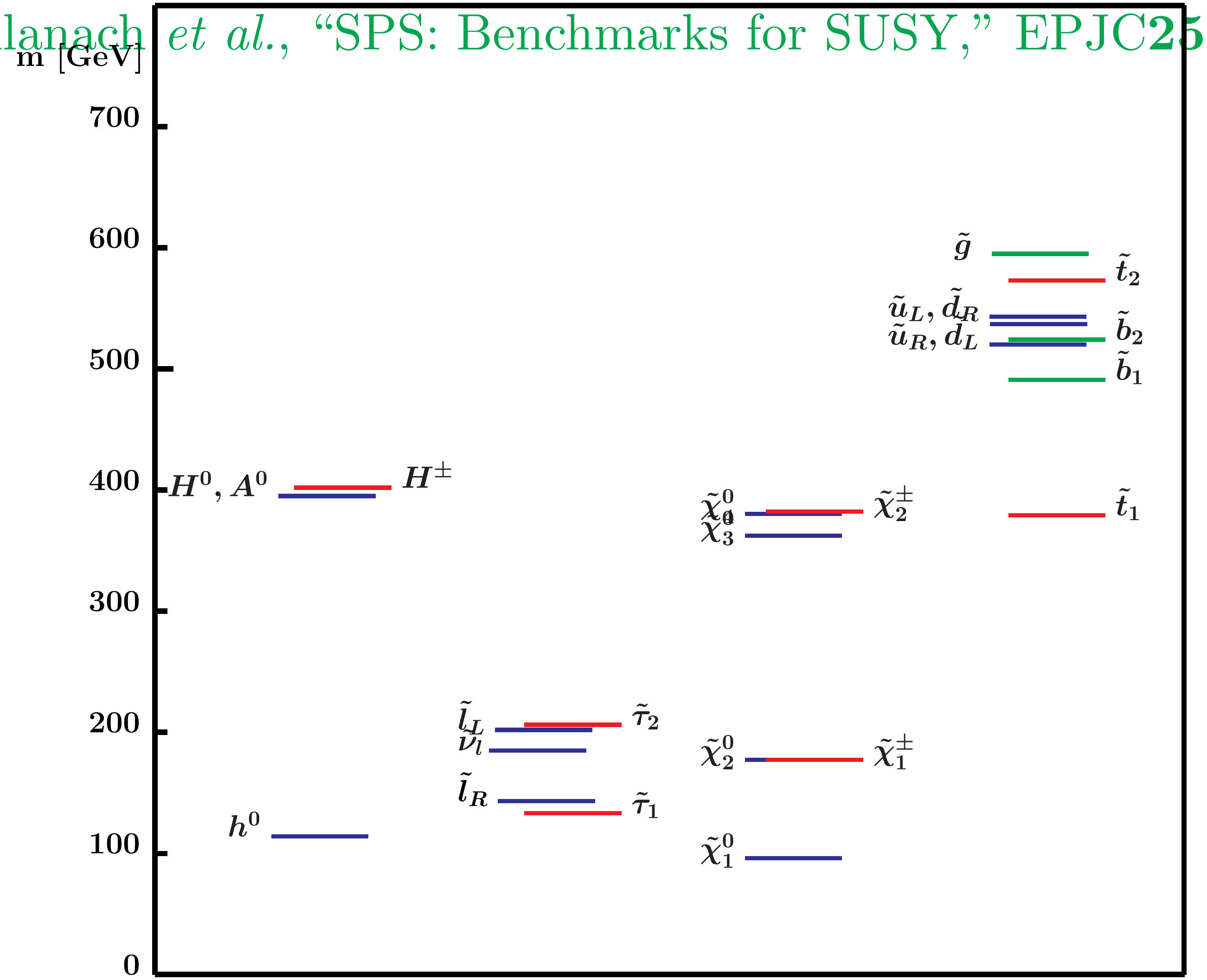
→ SUSY particles are expected arround TeV scale

→ leads to large amount of new free parameters: (Soft SUSY breaking): (MSSM: 105 parameters!)

→ Assumptions about SUSY breaking: Minimal mSUGRA 5 parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$ and sign μ

SPS1 mSUGRA: $m_0 = 0.4\, m_{1/2} = -A_0 = 100$ GeV $\tan\beta = 10$,

B. C. Allanach *et al.*, "SPS: Benchmarks for SUSY," EPJC **25** (2002)



- If R parity is conserved, squarks and gluino are produced in pairs:

$$p\bar{p}/pp \longrightarrow \tilde{q}\tilde{q}, \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} + X$$

- squark decay $\tilde{q} \rightarrow q\tilde{g}$ if possible, if not $\tilde{q} \rightarrow q\tilde{\chi}^0_{1,2..}$ or $\tilde{q} \rightarrow q'\tilde{\chi}^+_{1,2}$.

$$\tilde{q} \rightarrow q\tilde{\chi}^0_i \rightarrow \begin{cases} qZ^*\tilde{\chi}^0_1 \\ ql^+\tilde{l}^- \end{cases} \rightarrow \begin{cases} ql^+l^-\tilde{\chi}^0_1 \\ ql^+l^-\tilde{\chi}^0_1 \end{cases}$$

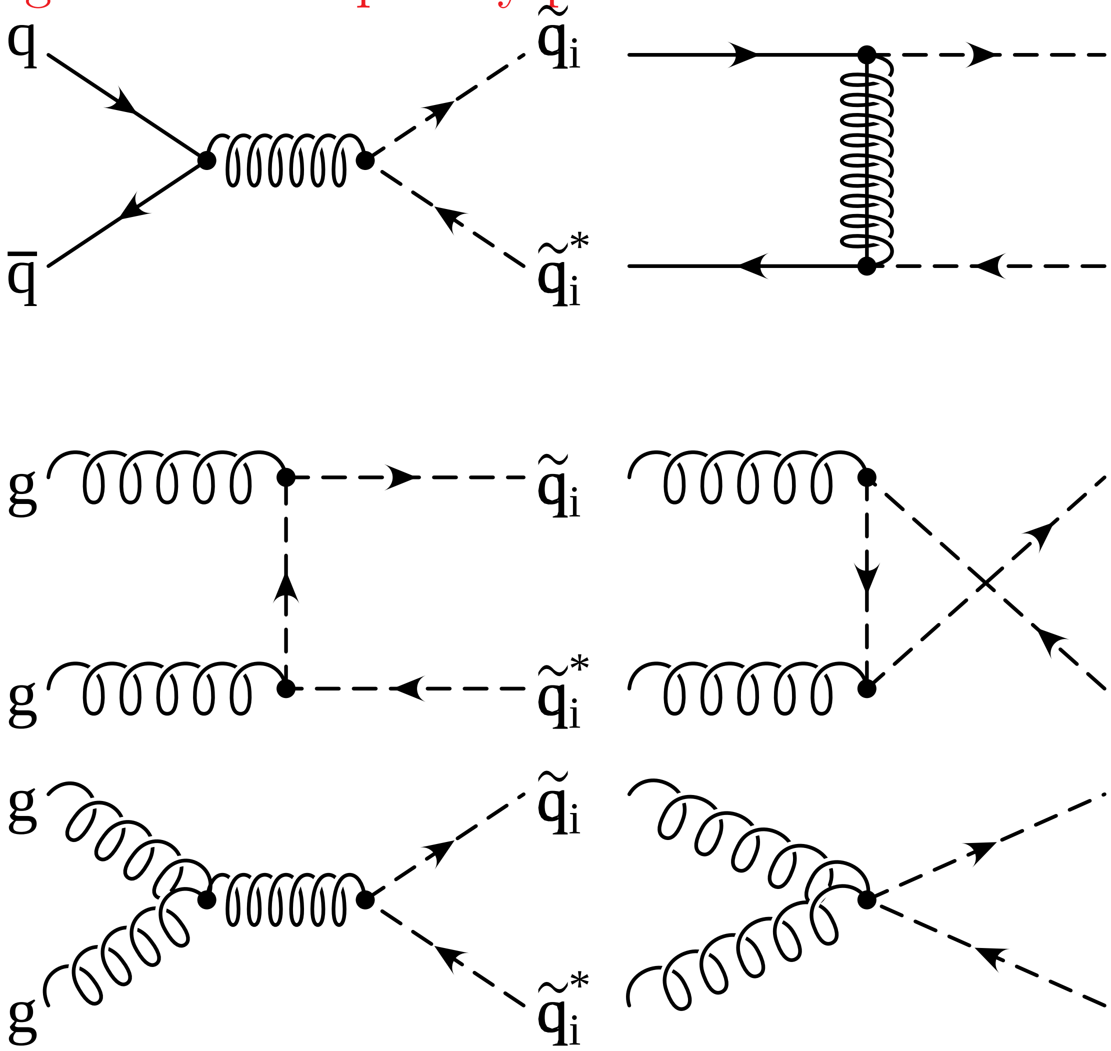
The signal in general: multi-jet + multi-leptons + $\not{E}$

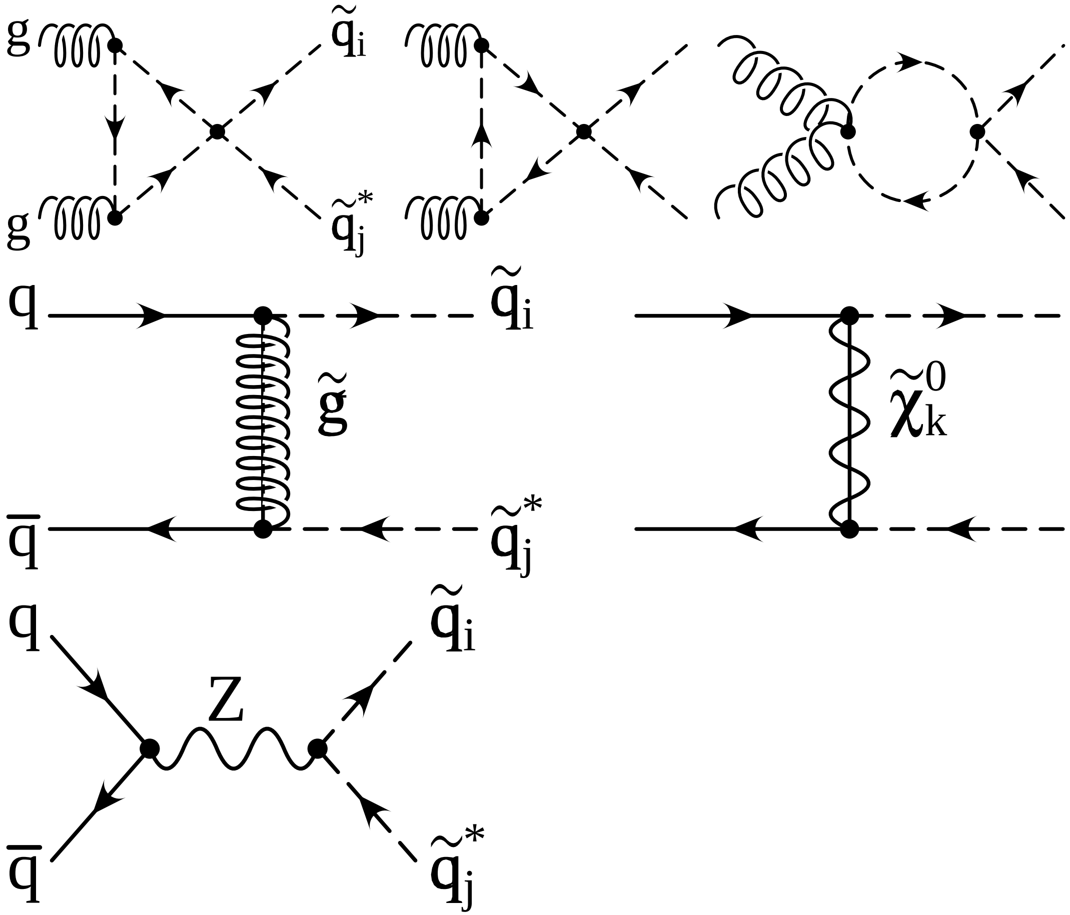
- gluino can decay $\tilde{g} \rightarrow q\tilde{q}^* \rightarrow qq'\widetilde{\chi}^+_i \rightarrow qq'W^*\widetilde{\chi}^0_1 \rightarrow qq'l\nu\widetilde{\chi}^0_1$

The signal for gluino pair production is 2 leptons with the same charge + jet + $\not{E}$ (Almost background-free signal)

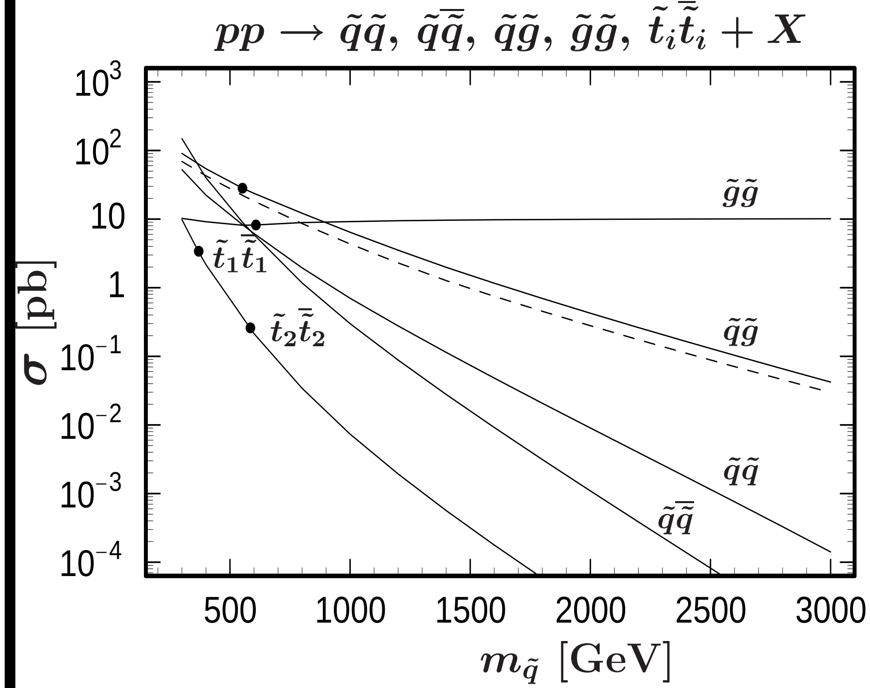
- Background is large: $t\bar{t}$, WW, ZZ, $W + jets$..., but large amount of $\not{E}$, high p_T jets, large numbers of jets and leptons are <u>good handles on signal</u>.

Squarks and gluinos are copiously produced at hadron machines

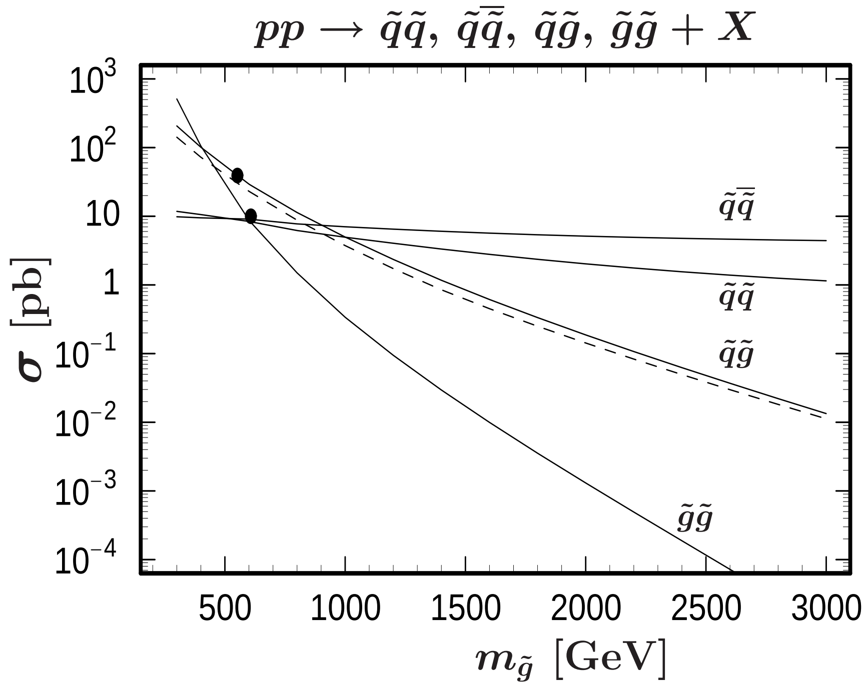




g
g
$\tilde{q}_i$
$\tilde{q}_j^*$
q
$\bar{q}$
$\tilde{q}_i$
$\tilde{g}$
$\tilde{q}_j^*$
$\tilde{\chi}_k^0$
q
$\bar{q}$
Z
$\tilde{q}_i$
$\tilde{q}_j^*$

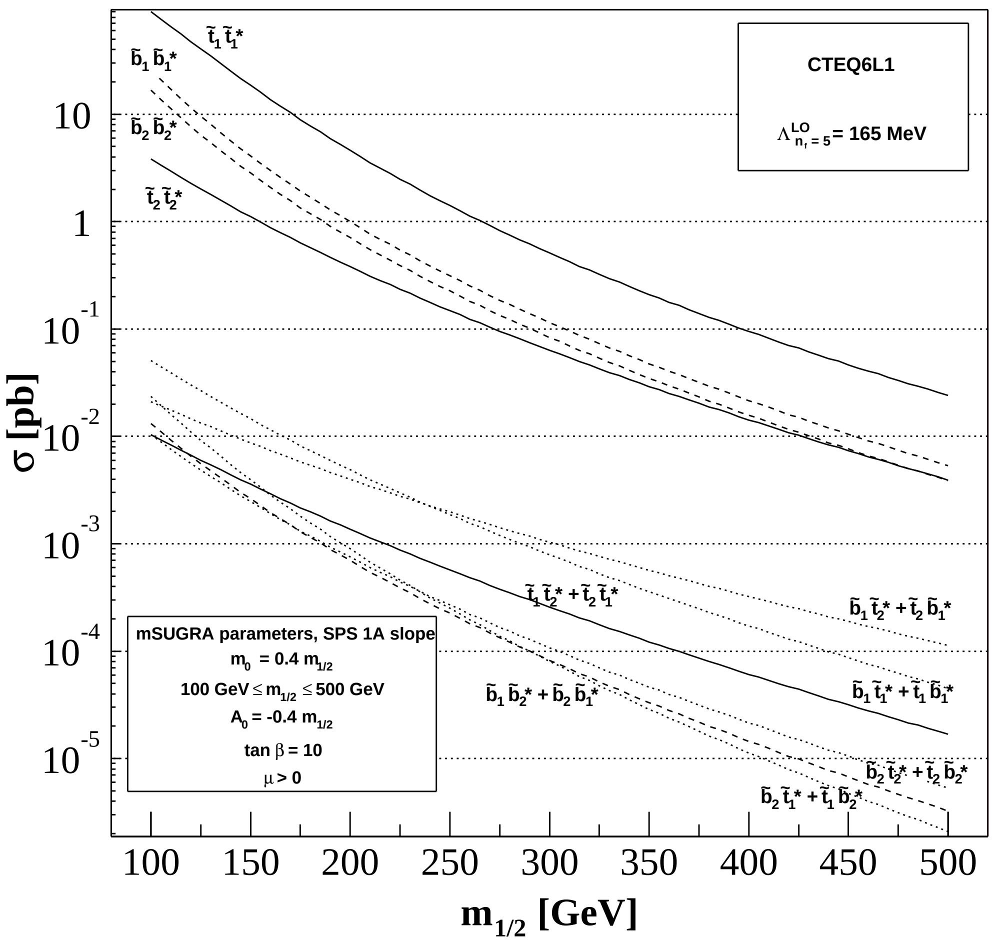


$pp \to \tilde{q}\tilde{q},\ \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g},\ \tilde{t}_i\bar{\tilde{t}}_i + X$
σ [pb]
$m_{\tilde{q}}$ [GeV]
$\tilde{g}\tilde{g}$
$\tilde{q}\tilde{g}$
$\tilde{q}\tilde{q}$
$\tilde{q}\bar{\tilde{q}}$
$\tilde{t}_1\bar{\tilde{t}}_1$
$\tilde{t}_2\bar{\tilde{t}}_2$



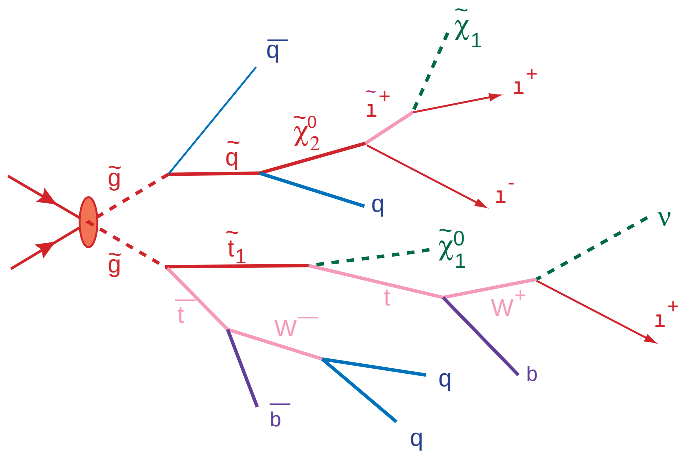
$pp \to \tilde{q}\tilde{q},\ \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g} + X$
σ [pb]
$m_{\tilde{g}}$ [GeV]
$\tilde{q}\bar{\tilde{q}}$
$\tilde{q}\tilde{q}$
$\tilde{q}\tilde{g}$
$\tilde{g}\tilde{g}$

$p\,p \to \tilde{q}_i\,\tilde{q}'^{*}_j$, *LHC*, $\sqrt{S} = 14$ *TeV*



Cascade decays

Gluino/squark production event topology allowing sparticle mass reconstruction



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

Such cascade decays allow to reconstruct sleptons, neutralinos, squarks, gluinos... in favorable cases with %level mass resolutions

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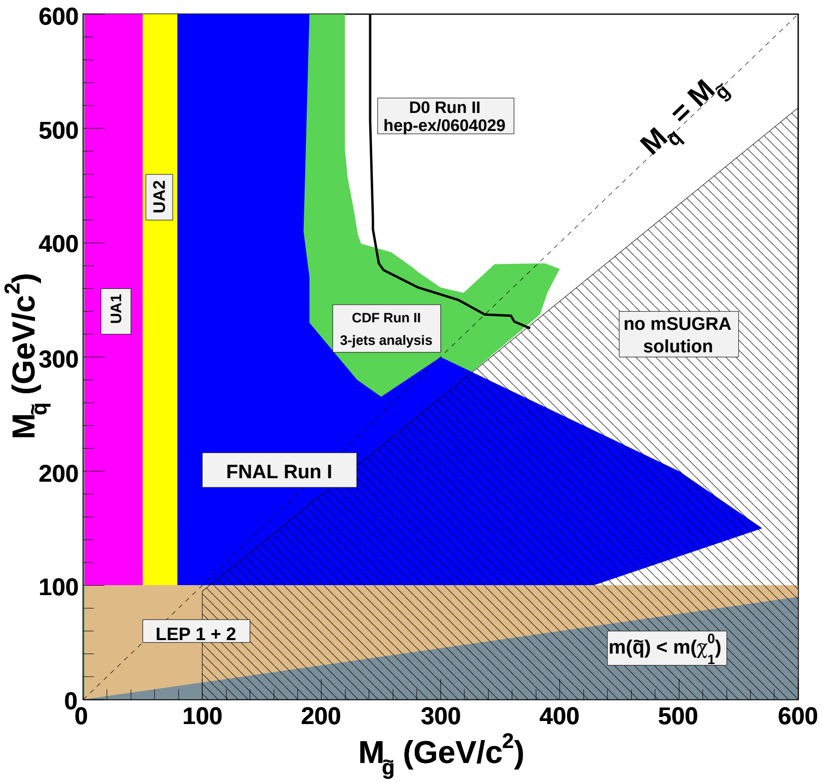
Experimental search for Sfermions at Tevatron

• CDF/D0 using $\not{E}$+jets, excludes $\tilde{q}$ of the 1st and 2nd generations with masses $m_{\tilde{q},\tilde{g}} \lesssim \mathcal{O}(340, 260\ \text{GeV})$ [hep-ex/0106011,0604029,0707.1455]



• Search for $\widetilde{g}$ and $\widetilde{q}$ using like-sign dilepton at $p\bar{p}$:

hep-ex/0106061,0702051

$\widetilde{q} \to q'\tilde{\chi}_1^+ \quad , \quad q\tilde{\chi}_2^0 \quad , \quad q\widetilde{g} \quad ; \quad \widetilde{g} \to q\widetilde{q} \to qq'\tilde{\chi}_1^+ \quad , \quad \widetilde{g} \to q\widetilde{q} \to qq\tilde{\chi}_2^0$

$\tilde{\chi}_1^+ \to l^+\nu\tilde{\chi}_1^0 \quad , \quad \tilde{\chi}_2^0 \to l^+l^-\tilde{\chi}_1^0$

At the end $\widetilde{g}\widetilde{g}$, $\widetilde{g}\widetilde{q}$ and $\widetilde{q}\widetilde{q}^* \to e^\pm e^\pm, \mu^\pm\mu^\pm$ and $e^\pm\mu^\pm$, the limits are:

$m_{\widetilde{g}} > 221$ GeV for $m_{\widetilde{g}} = m_{\widetilde{q}}$ and $m_{\widetilde{g}} > 168$ GeV for $m_{\widetilde{g}} >> m_{\widetilde{q}}$

$m_{\widetilde{g}} > 300$ GeV for $m_{\widetilde{q}} = m_{\widetilde{g}}$

• While for $\widetilde{t}$ and $\widetilde{b}$ the bounds are lower [CDF: PRD'01, hep-ex/07072567]. Assuming $\widetilde{t} \to \widetilde{\chi}_1^0 c$ and $\widetilde{b} \to \widetilde{\chi}_1^0 b$, we have $m_{\widetilde{t}} > 132$ GeV for $m_{\chi_1^0} = 48$ GeV and $m_{\widetilde{b}} > 193$ GeV for $m_{\chi_1^0} = 40$ GeV

Experimental search for Sfermions at LEP

LEP experiments searches: [OPAL, PLB545:272,2002]

- from $e^+e^- \to \widetilde{t}_1\widetilde{t}_1$, $m_{\widetilde{t}_1} - m_{LSP} \geq 10$ GeV:

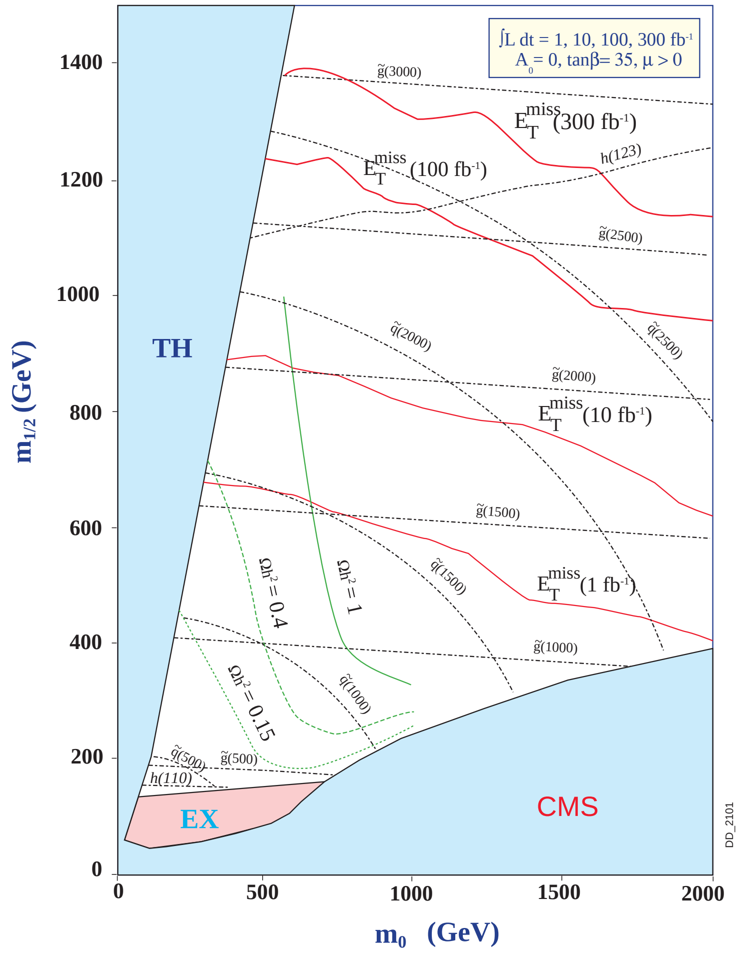
  i) if $\widetilde{t}_1 \to c\widetilde{\chi}_1^0$, $m_{\widetilde{t}_1} > 97.6(95.7)$ GeV for $\widetilde{\theta}_t = 0$ ($\widetilde{\theta}_t = 0.98 \;\; Z\tilde{t}_1\tilde{t}_1 = 0$).

  ii) if $\widetilde{t}_1 \to bl\widetilde{\nu}$, $l = e, \mu, \tau$, $m_{\widetilde{t}_1} > 96(92.6)$ GeV for $\widetilde{\theta}_t = 0$ ($\widetilde{\theta}_t = 0.98$).

  iii) if $\widetilde{t}_1 \to b\tau\widetilde{\nu}_\tau$ with 100% Br, $m_{\widetilde{t}_1} > 95.5(91.5)$ GeV for $\widetilde{\theta}_t = 0$ ($\widetilde{\theta}_t = 0.98$).

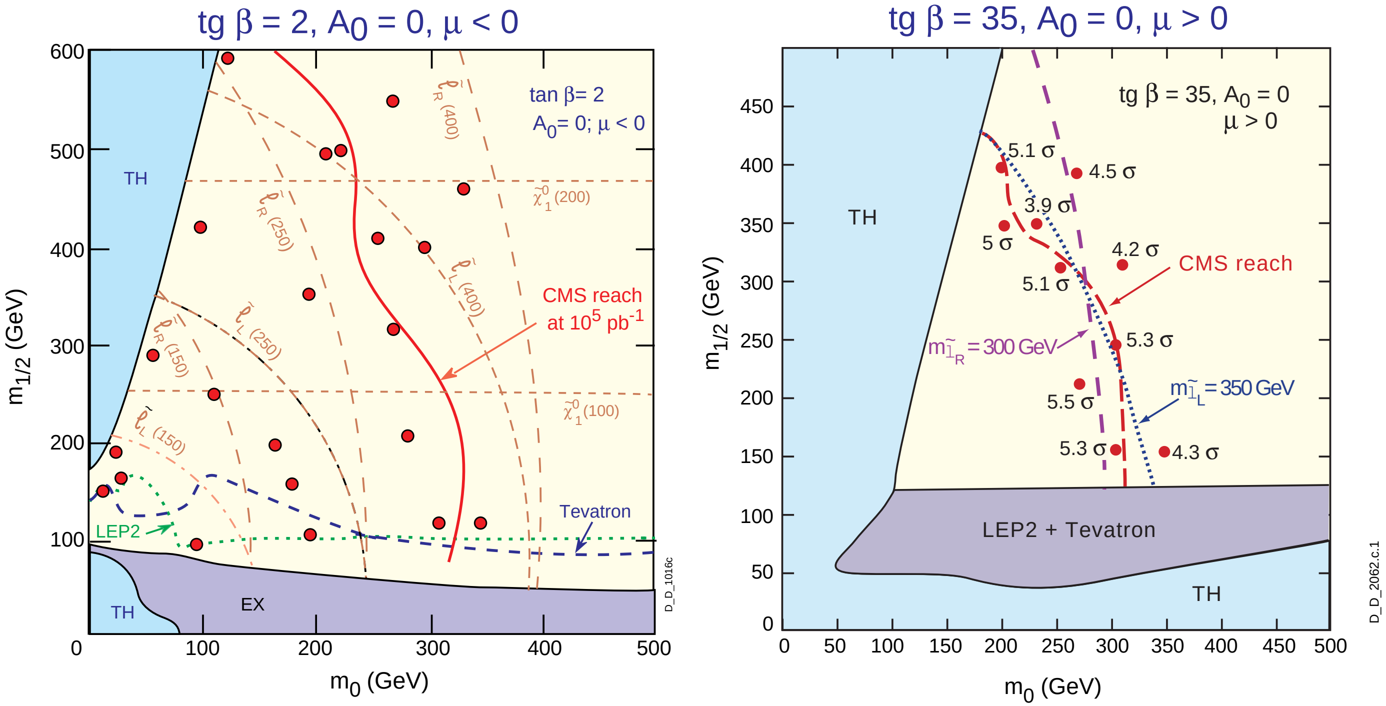
- from $e^+e^- \to \widetilde{b}_1\widetilde{b}_1$, $\widetilde{b}_1 \to b\widetilde{\chi}_1^0$ with $m_{\widetilde{b}_1} - m_{LSP} \geq 10$ GeV,: $m_{\widetilde{b}_1} \gtrsim 96.9(85.1)$ GeV for $\widetilde{\theta}_b = 0$ ($\widetilde{\theta}_b = 1.17$).

The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss}+ jets inclusive channel for various integrated luminosities



Slepton mapping of parameter space

mSUGRA-MSSM
Significance of expected excess of events in 2 lepton final state over SM + SUSY bkgd with 10^5 pb^{-1}
5σ contour, $\sigma = S / \sqrt{S+B}$



6 December 2008

Evidence for squark and gluino production in pp collisions at $\sqrt{s}$ = 14 TeV

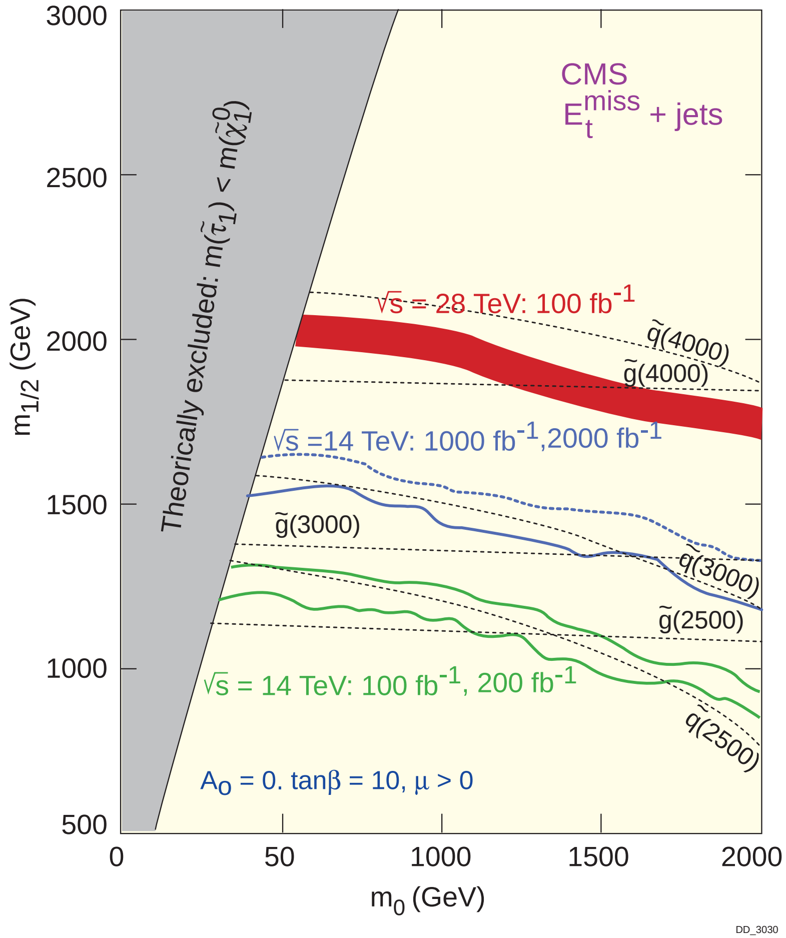
CMS collaboration

Abstract

Experimental evidence for squark and gluino production in pp collisions $\sqrt{s}$ = 14 TeV with an integrated luminosity of 97 pb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high E_T jets and large missing E_T, and the measured effective mass, i.e. the scalar sum of the four highest P_T jets and the event $\not{E}_T$, is consistent with squark and gluino masses of order of 650 GeV/c^2. The probability that the measured yield is consistent with the background is 0.26%.

Submitted to *European Journal of Physics*

Squark / gluino reach at $\sqrt{s}$ = 28 TeV



Scalar fermions al ILC

$$\mathcal{M}^2_{\tilde{f}} = \left(\begin{array}{cc} m_f^2 + \widetilde{M}_L^2 + m_Z^2 c_{2\beta}\,(I_3^f - Q_f s_W^2) & m_f(A_f - \mu\ (\tan\beta)^{-2I_3^f}) \\ m_f(A_f - \mu\ (\tan\beta)^{-2I_3^f}) & m_f^2 + \widetilde{M}_R^2 + m_Z^2 c_{2\beta}\, Q_f s_W^2 \end{array} \right)$$

$$\left(\begin{array}{c} \tilde{f}_1 \\ \tilde{f}_2 \end{array} \right) = R^{\tilde{f}} \left(\begin{array}{c} \tilde{f}_L \\ \tilde{f}_R \end{array} \right) = \left(\begin{array}{cc} \cos\widetilde{\theta}_f & \sin\widetilde{\theta}_f \\ -\sin\widetilde{\theta}_f & \cos\widetilde{\theta}_f \end{array} \right) \left(\begin{array}{c} \tilde{f}_L \\ \tilde{f}_R \end{array} \right) ,$$

yielding the physical mass eigenvalues ($m_{\tilde{f}_1} < m_{\tilde{f}_2}$),

$$m^2_{\tilde{f}_{1,2}} = \frac{1}{2}(2m_f^2 + m_{LL}^2 + m_{RR}^2 \mp \sqrt{(m_{LL}^2 - m_{RR}^2)^2 + 4m_{LR}^2 m_f^2}) .$$

The mixing angle $\widetilde{\theta}_f$ obeys the relation

$$\tan 2\widetilde{\theta}_f = \frac{2m_{LR}m_f}{m_{LL}^2 - m_{RR}^2} \to 0 \quad \text{for 1st and 2nd generation} .$$

The interaction of the neutral gauge bosons γ and Z with the sfermion-mass eigenstates is described by the Lagrangian

$$\mathcal{L} = \quad -ieA^\mu \sum_{i=1,2} Q_f \tilde{f}_i^* \overleftrightarrow{\partial}_\mu \tilde{f}_i + ig_s T^a g_a^\mu \sum_{i=1,2} \tilde{q}_i^* \overleftrightarrow{\partial}_\mu \tilde{q}_i$$

$$+i\frac{g_s}{\sqrt{2}} \sum_{i=1,2} \tilde{q}_i \tilde{g} (R^{\widetilde{q}}_{j1} \mathbb{L} + R^{\widetilde{q}}_{j2} \mathbb{R}) q + iZ^\mu \sum_{i,j=1,2} g_{Z\widetilde{f}_i\widetilde{f}_j} \tilde{f}_i^* \overleftrightarrow{\partial}_\mu \tilde{f}_j$$

with the couplings

$$g_{Z\widetilde{f}_i\widetilde{f}_j} = -\frac{e}{s_W c_W}\{(I_3^f - Q_f s_W^2) R^{\widetilde{f}}_{j1} R^{\widetilde{f}}_{i1} - Q_f s_W^2 R^{\widetilde{f}}_{j2} R^{\widetilde{f}}_{i2}\}$$

$$g_{Z\widetilde{f}_1\widetilde{f}_2} = -\frac{e}{s_W c_W} \sin 2\widetilde{\theta}_f$$

Motivations for $e^+e^- \to \widetilde{f}_i \widetilde{f}_j^*$

- LHC will produce scalar fermions (if they exist) with mass reach: $m_{\tilde{q}} \lesssim$ 2-3 TeV and $m_{\tilde{l}} \lesssim 250 - 300$ GeV.

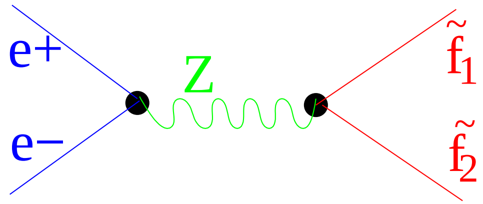
- $m_{\tilde{q}}$ has to be calculated from the reconstruction of cascade decay which end with LSP. $\delta m_{\tilde{\chi}_1^0} \approx 4.8$GeV, $\to \delta m_{\tilde{q}} \approx$ 7-12 GeV
[G. Weiglein *et al.*, "Physics interplay of the LHC/ILC," hep-ph 0410364]

- At ILC, the mass of SUSY particles can be reconstructed with high precision if Kinematically accessible, ($\delta m_{\tilde{\chi}_1^0} \approx 0.05$ GeV).
Complementarity of ILC/LHC

Particle	Mass	"LHC"	"ILC"	"LHC+ILC"
h^0	116.0	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_R$	125.3	4.8	0.05	0.05
$\tilde{e}_L$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	$5-8$	0.24	0.24
$\tilde{q}_R$	547.2	$7-12$	–	$5-11$
$\tilde{q}_L$	564.7	8.7	–	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.1	8.0	–	6.5

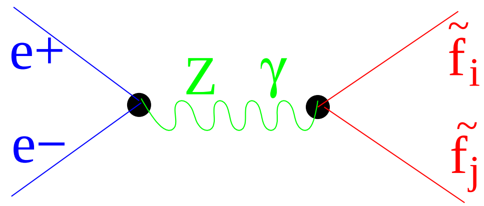
Table 1: *Accuracies for representative mass measurements of SUSY particles in individual LHC, ILC and coherent "LHC+ILC" analyses for the reference point SPS1a′ [mass units in* GeV*]. $\tilde{q}_R$ and $\tilde{q}_L$ represent the flavors $q = u, d, c, s$. [Errors presently extrapolated from SPS1a simulations.]*

- $e^+e^- \to \tilde{f}_i \tilde{f}_j^*$ ideal machine for determination of sfermion masses and provide direct measurement of the mixing angles $e^+e^- \to Z^* \to \tilde{f}_1 \tilde{f}_2^*$ [E. L. Berger, J. Lee, T. M.Tait "Squark mixing in electron positron reactions" PRD**69** (2004)]



- $\to$ Requires accurate theoretical predictions including radiative corrections in order to match experimental accuracy.

$e^+e^- \to \tilde{f}_i \tilde{f}_j^*$ at tree level



- The tree level angular distribution for $\tilde{f}_i$, $\tilde{f}_j^*$ is given by

$$\frac{d\sigma_0}{d\Omega} = N_C \frac{s\lambda_{ij}^3}{1024\pi^2}(|\mathcal{M}_L^0|^2 + |\mathcal{M}_R^0|^2)\sin^2\theta$$

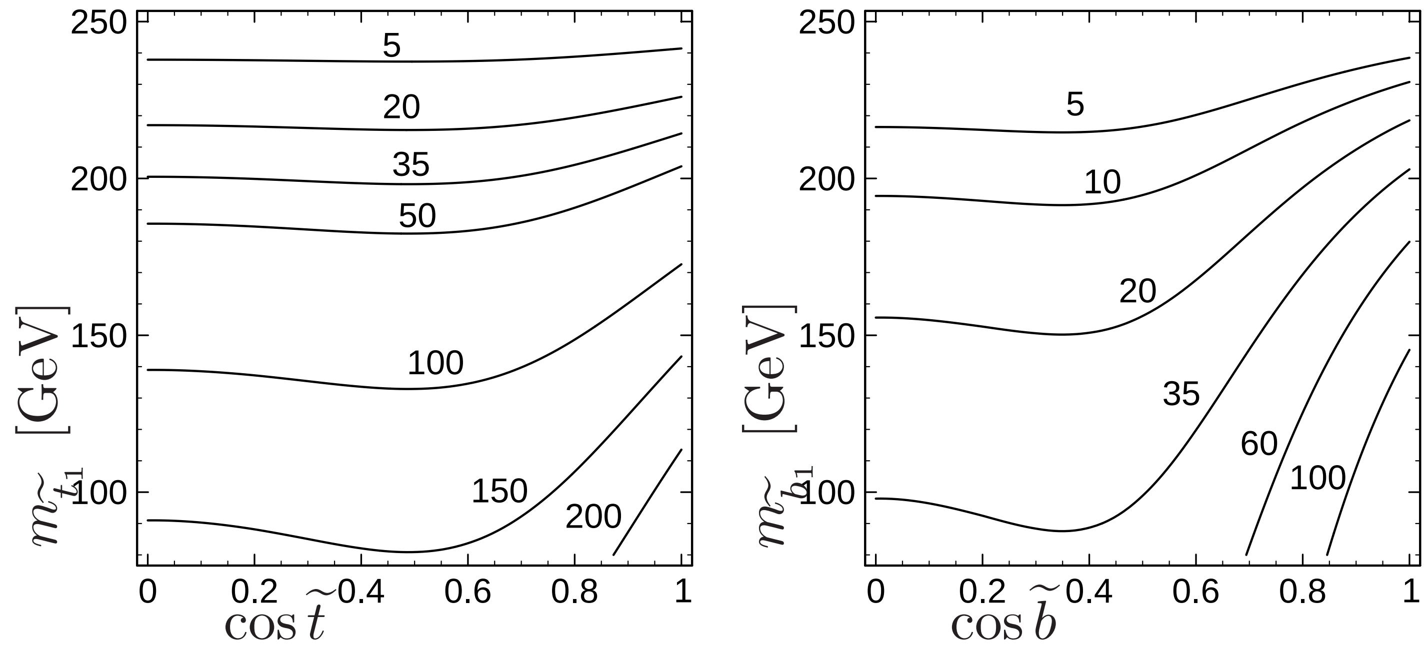
$$\mathcal{M}^0_{L,R} = 2e^2(-\delta_{ij}\frac{Q_f}{s} + \frac{g_{L,R}\, g_{Z\tilde{f}_i\tilde{f}_j}}{(s - M_Z^2)})\,,\ g_L = \frac{1-2s_W^2}{2s_W c_W}$$

$$\sigma_{tot}^{ii} \propto \sqrt{1 - 4m_{\tilde{q}_i}^2/s}^{\,3}$$

$$A_{FB} = \frac{\int_{\theta\le\pi/2} d\Omega \frac{d\sigma}{d\Omega} - \int_{\theta\ge\pi/2} d\Omega \frac{d\sigma}{d\Omega}}{\int_{\theta\le\pi/2} d\Omega \frac{d\sigma}{d\Omega} + \int_{\theta\ge\pi/2} d\Omega \frac{d\sigma}{d\Omega}} = \frac{\sigma_F - \sigma_B}{\sigma}$$

At tree level $A_{FB} = 0$ but at one loop level $A_{FB} \neq 0$

(a) $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1$ [fb] (b) $\sigma(e^+e^- \to \tilde{b}_1\tilde{b}_1$ [fb]



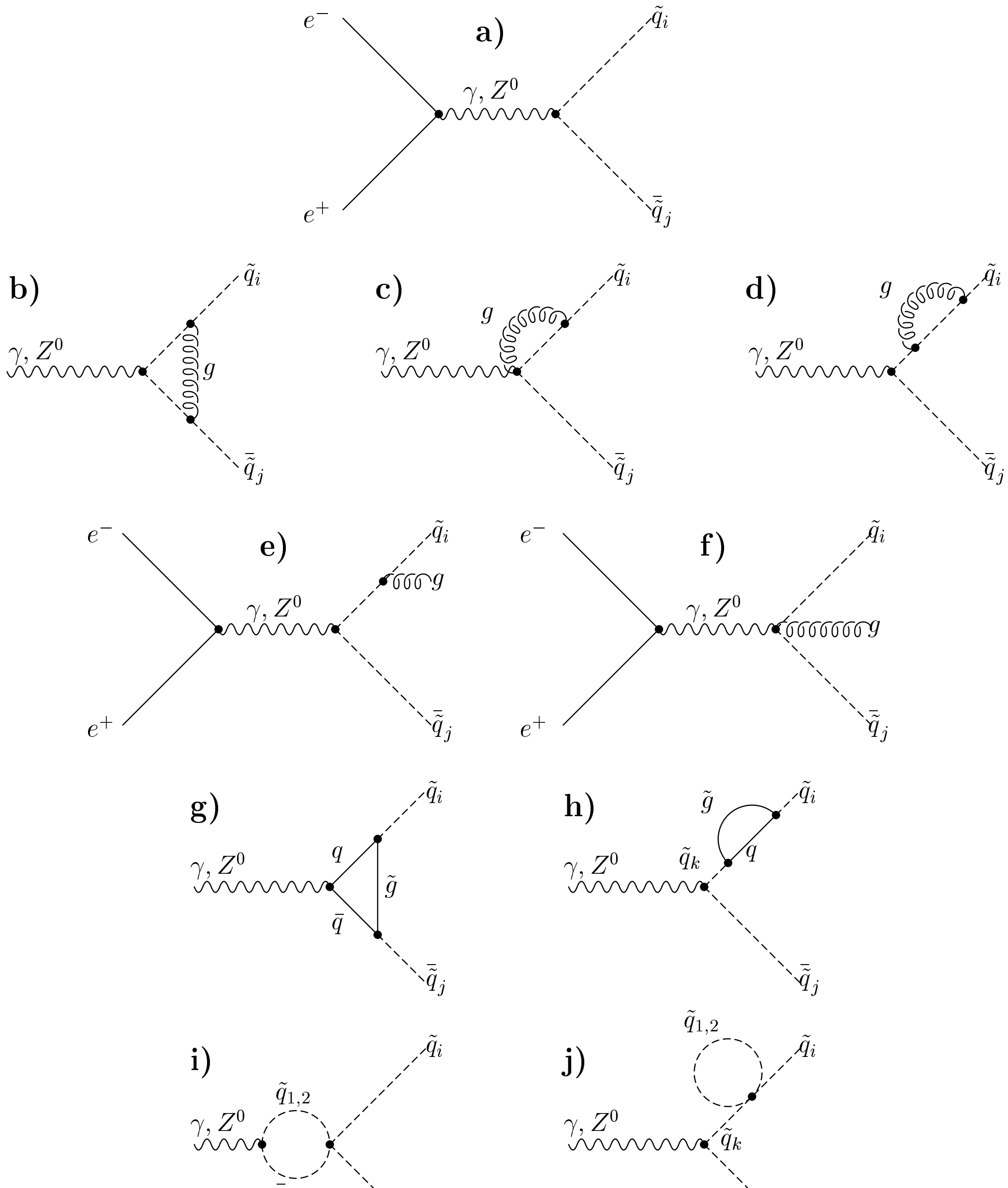
Radiative corrections to $e^+e^- \to \tilde{f}_i \tilde{f}_j^*$

- SUSY-QCD corrections: gluon and gluino.

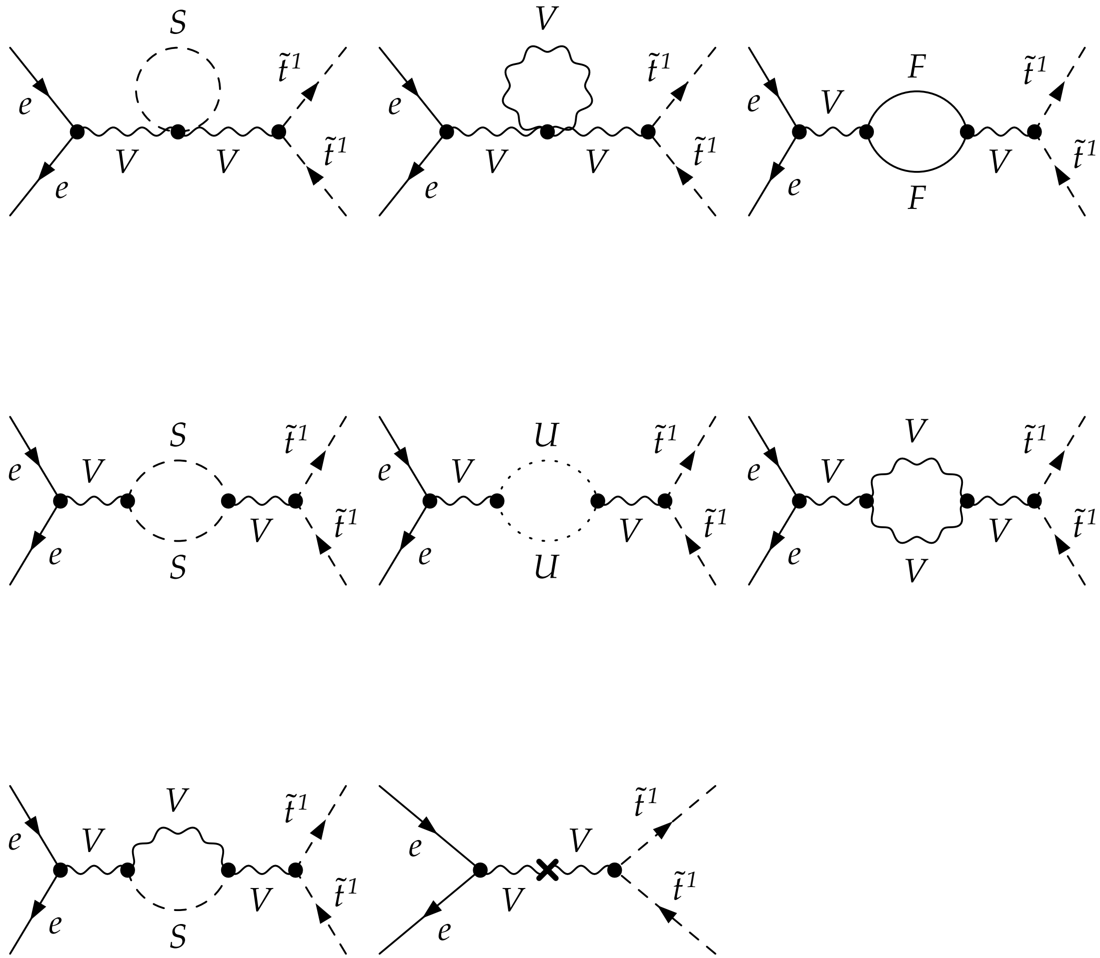
With gluino exchange: squarks masses eigenstates mix (like γ and Z in SM)

$$\begin{pmatrix} \Sigma_{\tilde{q}_1 \tilde{q}_1}(k^2) & \Sigma_{\tilde{q}_1 \tilde{q}_2}(k^2) \\ \Sigma_{\tilde{q}_2 \tilde{q}_1}(k^2) & \Sigma_{\tilde{q}_2 \tilde{q}_2}(k^2) \end{pmatrix}$$

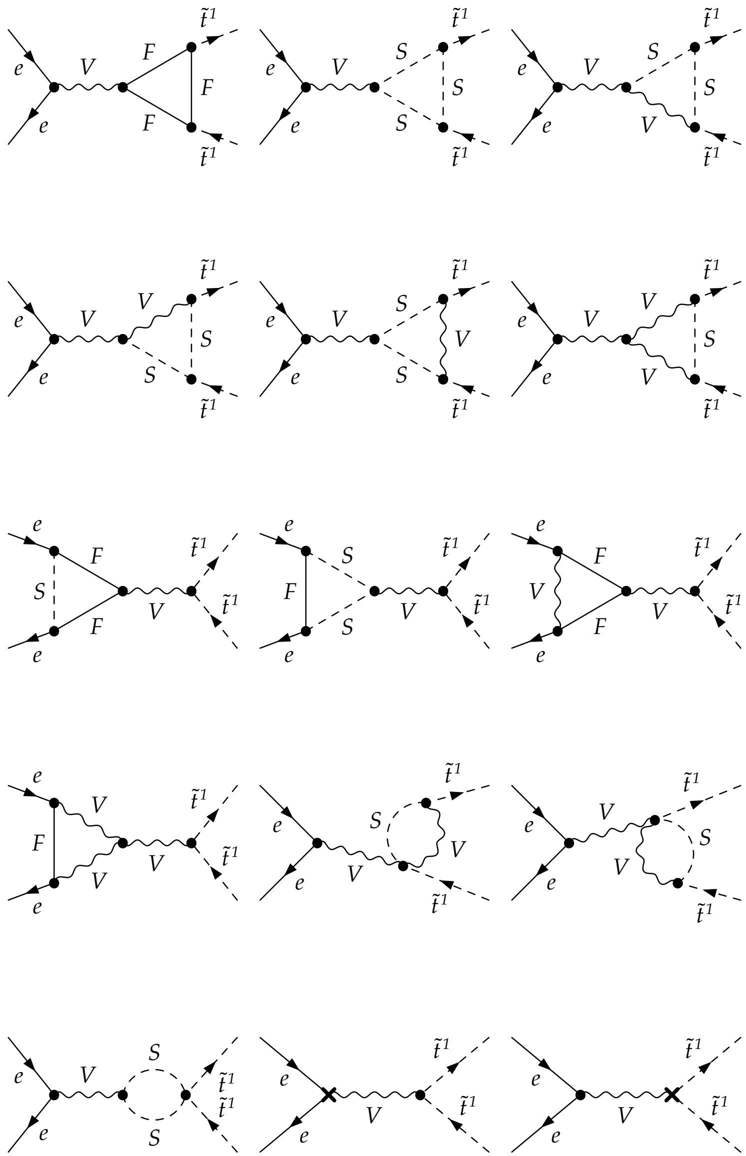
24-1



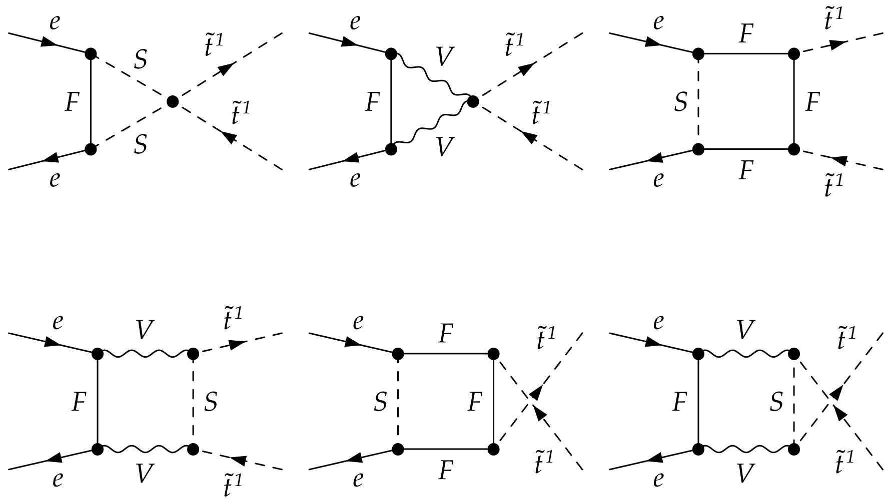
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
e^-
e^+
γ, Z^0
$\tilde{q}_i$
$\bar{\tilde{q}}_j$
g
q
$\bar{q}$
$\tilde{g}$
$\tilde{q}_k$
$\tilde{q}_{1,2}$



S
V
V
$\tilde{t}^1$
$\tilde{t}^1$
e
e
V
F
F
U
U


e
V
F
S
$\tilde{t}^1$

24-4



www.FeynArts.de
www.FormCalc.de by Thomas Hahn (MPI Munich)

Operating for

- SM(with on shell renormalization),
- MSSM(no renormalization yet)...
- 2HDM(no renormalization yet)...
- you can enter your own model!
- needed: Mathematica, Fortran and Form

On shell renormalization

• 1-loop amplitudes are UV and Infra-Red divergent: Regularization

• $e^+e^- \to \tilde{f}_i \tilde{f}_j$ is SUSY process: Dimensional reduction for UV

• I-R divergences: give a fictitious small mass for γ and g

• UV divergences are canceled by redefinition (renormalization) of the fields and couplings constants.

• I-R divergences are canceled by real photon or gluon emission in the final states: $e^+e^- \to \tilde{f}_i \tilde{f}_j \gamma$: Bremsstrahlung

Parameters and fields to renormalize:

$$e \to (1+\delta Z_e)e \qquad , \qquad M^2_{W,Z} \to M^2_{W,Z} + \delta M^2_{W,Z}\,,$$

In the on-shell scheme $s_W^2 = 1 - M_W^2/M_Z^2$, counterterm for s_W is then

$$\frac{\delta s_W^2}{s_W^2} = \frac{c_W^2}{s_W^2}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right) \quad , \quad \frac{\delta c_W^2}{c_W^2} = \frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\,.$$

Since γ and Z mix at 1-loop level:

$$Z \to Z_{ZZ}^{1/2} Z + Z_{Z\gamma}^{1/2} A\,, \quad A \to Z_{AA}^{1/2} A + Z_{\gamma Z}^{1/2} Z\,, \quad .$$

For SUSY part, we have to renormalize the sfermion fields and $\widetilde{\theta}_f$ as:

$$\widetilde{f}_1 \to Z_{11}^{1/2}\widetilde{f}_1 + Z_{12}^{1/2}\widetilde{f}_2 \ \ , \ \widetilde{f}_2 \to Z_{22}^{1/2}\widetilde{f}_2 + Z_{21}^{1/2}\widetilde{f}_1 \ \ , \ \ \widetilde{\theta}_f \to \widetilde{\theta}_f + \delta\widetilde{\theta}_f$$

$$Z_{ab}^{1/2} = \delta_{ab} + \frac{1}{2}\delta Z_{ab}$$

• The on-shell conditions for M_W, M_Z, m_f, e, and for the gauge-field renormalization constants as in the SM.

• On-shell conditions for $\widetilde{f}_i$, specified by:

i) on shell mass renormalization $\hat{\Sigma}_{\widetilde{f}_i\widetilde{f}_i}(p^2 = m_i^2) = 0$,

ii) zero mixing on each mass shell $\hat{\Sigma}_{\widetilde{f}_1\widetilde{f}_2}(p^2 = m_1^2) = 0$, $\hat{\Sigma}_{\widetilde{f}_2\widetilde{f}_1}(m_2^2) = 0$

iii) residue =1 for the diagonal sfermion propagators,

$$\delta Z_{11} = \frac{\partial}{\partial p^2}\Sigma_{\widetilde{f}_1\widetilde{f}_1}(p^2)|_{p^2=m^2_{\widetilde{f}_1}} \quad , \quad \delta Z_{22} = \frac{\partial}{\partial p^2}\Sigma_{\widetilde{f}_2\widetilde{f}_2}(p^2)|_{p^2=m^2_{\widetilde{f}_2}} \quad ,$$

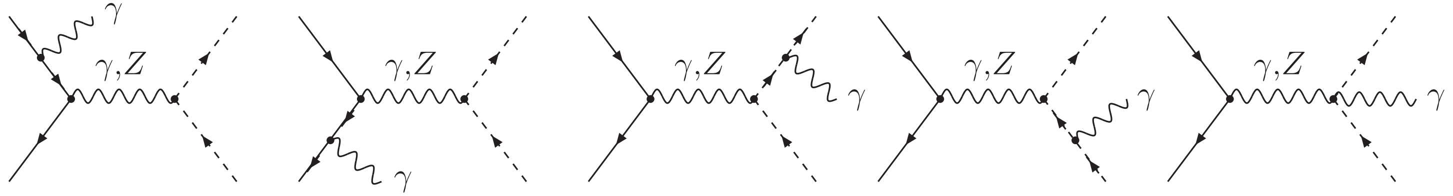
$$\delta Z_{12} = \frac{\Sigma_{\widetilde{f}_1\widetilde{f}_2}(m^2_{\widetilde{f}_2})}{m^2_{\widetilde{f}_2} - m^2_{\widetilde{f}_1}} \quad , \quad \delta Z_{21} = \frac{\Sigma_{\widetilde{f}_2\widetilde{f}_1}(m^2_{\widetilde{f}_1})}{m^2_{\widetilde{f}_1} - m^2_{\widetilde{f}_2}}$$

$$\delta\widetilde{\theta}_f = \frac{1}{2}\frac{\Sigma_{\widetilde{f}_1\widetilde{f}_2}(m^2_{\widetilde{f}_2}) + \Sigma_{\widetilde{f}_1\widetilde{f}_2}(m^2_{\widetilde{f}_1})}{m^2_{\widetilde{f}_2} - m^2_{\widetilde{f}_1}} \, ,$$

The one-loop amplitude is:

$$|\mathcal{M}_1|^2 = \underbrace{|\mathcal{M}_0|^2}_{\mathcal{O}(\alpha^2)} + \{\ 2\,\Re\mathrm{e}\underbrace{[\mathcal{M}_0^*(\mathcal{M}^1+\delta\mathcal{M}^1)]}_{\mathcal{O}(\alpha^2\alpha)} + \underbrace{|\mathcal{M}^1+\delta\mathcal{M}^1|^2}_{\mathcal{O}(\alpha^4)}\ \}$$

The Bremsstrahlung



$$|\mathcal{M}(e^+e^- \to \tilde{f}_i\tilde{f}_j^*\gamma)|^2 = \mathcal{O}(\alpha^2\alpha)$$

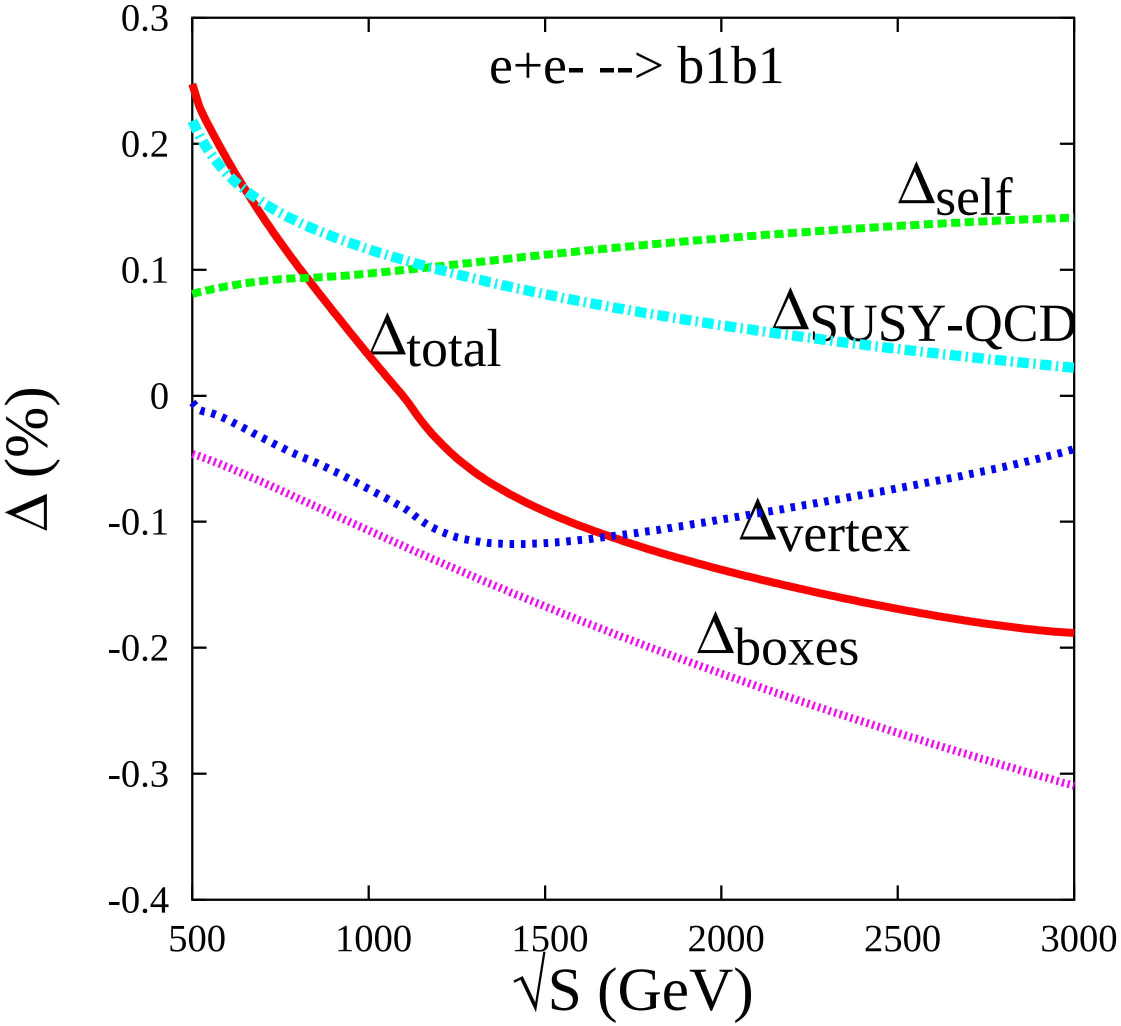
For the Soft photon: we use a cut ΔE_γ: $\sigma^{\mathrm{soft}}(\lambda,\Delta E) = \sigma_0 I_2(\lambda,\Delta E_\gamma)$

For the hard photon:[M.Böhm, S.Dittmaier NPB409'93]

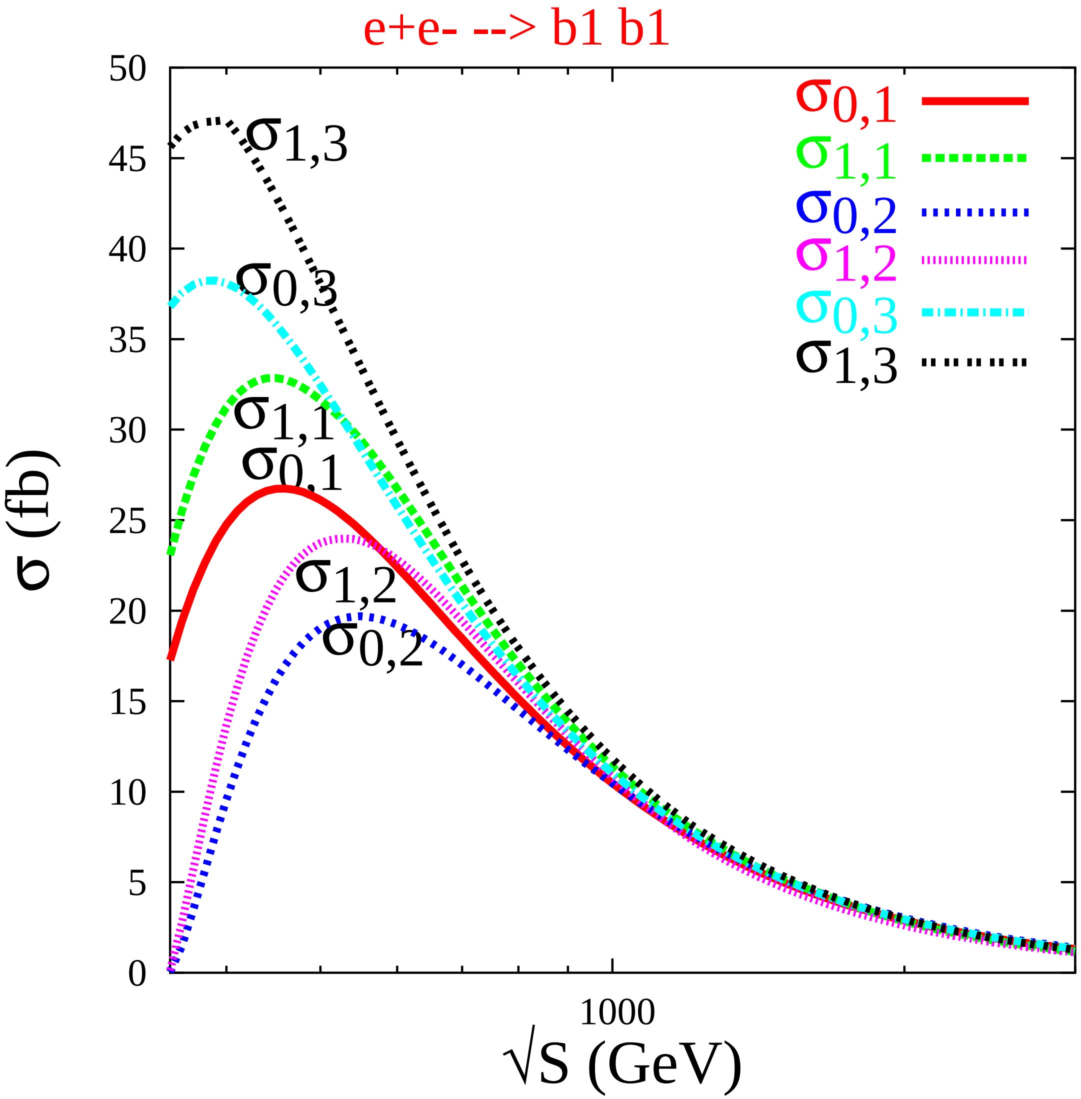
If the photon is radiated from the e legs, $m_e \approx 0$: collinear divergence:

$$\sigma(e^+e^- \to \tilde{f}_i\bar{\tilde{f}}_j\gamma) \;=\; \sigma^{\mathrm{soft}}(\lambda,\Delta E) + \underbrace{\sigma^{\mathrm{hard}}(\Delta E,\Delta\theta)}_{2\to 3\mathrm{process}} + \sigma^{\mathrm{coll}}(\Delta E,\Delta\theta)\,.$$

29-1

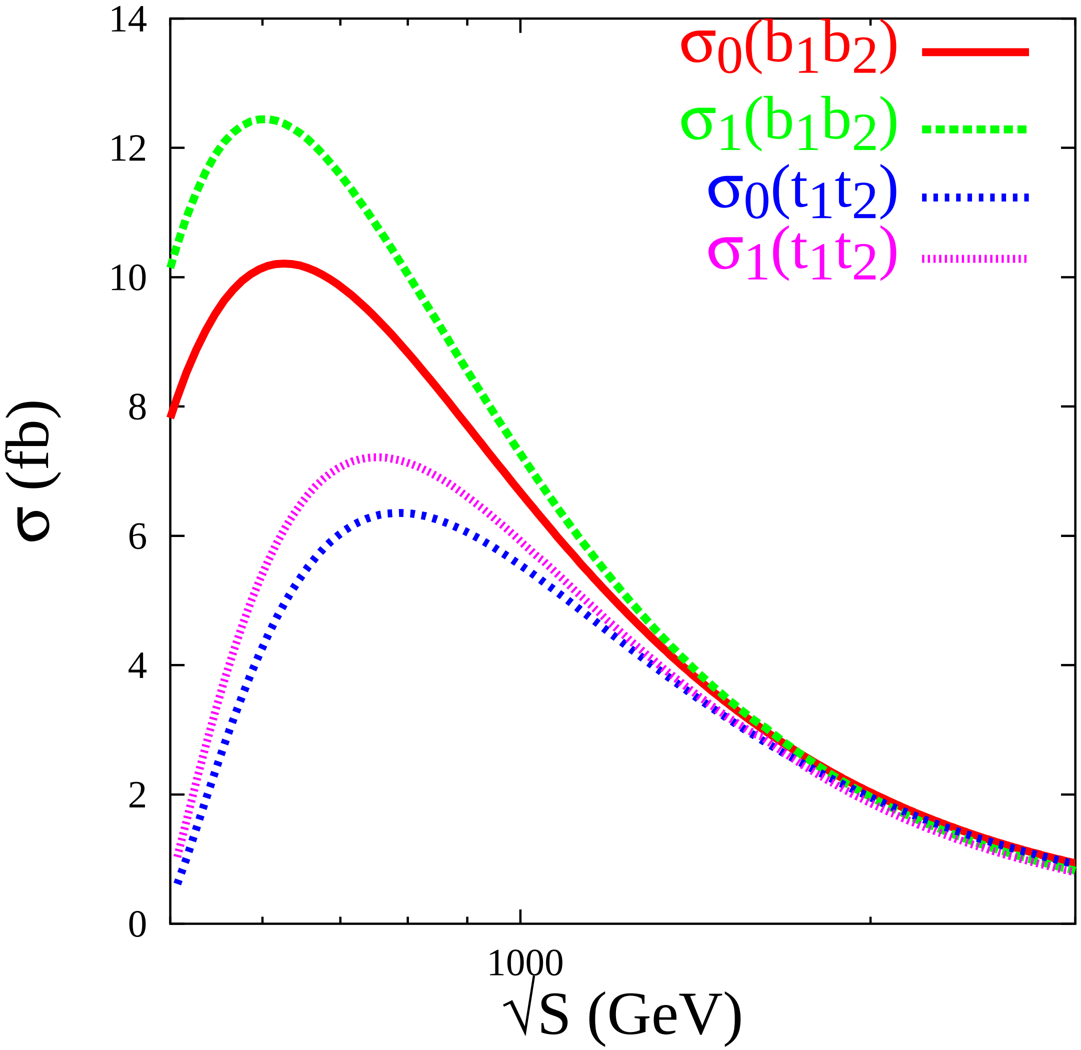

e+e- --> b1b1
Δ_{self}
$\Delta_{SUSY-QCD}$
Δ_{total}
Δ_{vertex}
Δ_{boxes}
Δ (%)
√S (GeV)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
500
1000
1500
2000
2500
3000

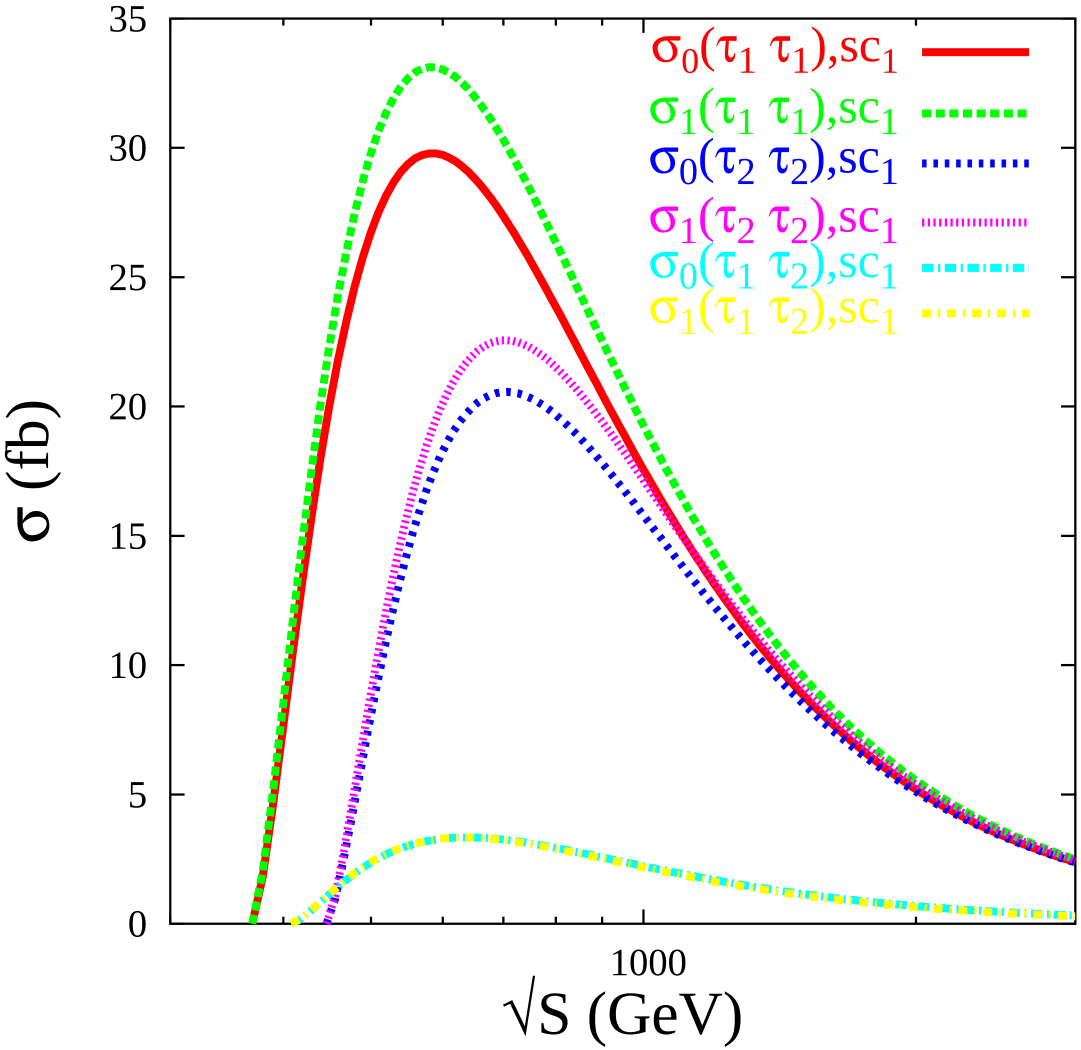
29-2



e+e- --> b1 b1
σ (fb)
√S (GeV)
1000
0
5
10
15
20
25
30
35
40
45
50
σ0,1
σ1,1
σ0,2
σ1,2
σ0,3
σ1,3

29-3





$\sigma_0(\tau_1\ \tau_1)$,sc$_1$
$\sigma_1(\tau_1\ \tau_1)$,sc$_1$
$\sigma_0(\tau_2\ \tau_2)$,sc$_1$
$\sigma_1(\tau_2\ \tau_2)$,sc$_1$
$\sigma_0(\tau_1\ \tau_2)$,sc$_1$
$\sigma_1(\tau_1\ \tau_2)$,sc$_1$
σ (fb)
35
30
25
20
15
10
5
0
1000
$\sqrt{S}$ (GeV)

$$|\mathcal{M}_1|^2 = \underbrace{|\mathcal{M}_0|^2}_{\mathcal{O}(\alpha^2)} + \{\, 2\,\Re\mathrm{e}\,\underbrace{[\mathcal{M}_0^*(\mathcal{M}^1 + \delta\mathcal{M}^1)]}_{\mathcal{O}(\alpha^2\alpha)} + \underbrace{|\mathcal{M}^1 + \delta\mathcal{M}^1|^2}_{\mathcal{O}(\alpha^4)} \,\}$$

- $\mathcal{M}^1$ contains large Sudakov Log terms: $\ln^2(s/M^2)$

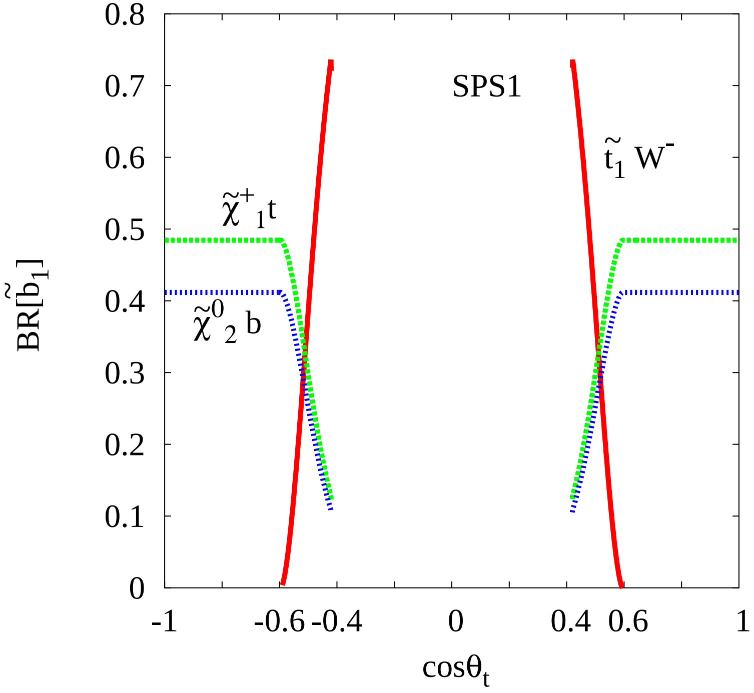
$\sqrt{s}$	500GeV		1.5 TeV		3 TeV	
sc_1	-.074	-.073	-.22	-.20	-.36	-.32
sc_2	-.049	-.048	-.17	-.16	-.31	-.28

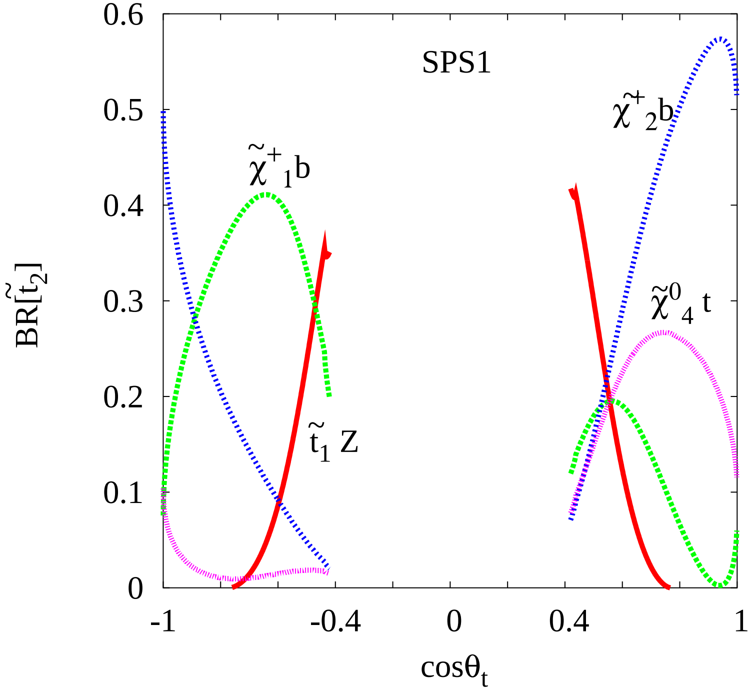
$\mathcal{O}(\alpha)$ coorrections (in %) (left column) and $\mathcal{O}(\alpha^2)$ (right column)

- Resummation has been done in: [M. Beccaria et al , "Sudakov expansions at 1-loop and beyond for charged scalar and fermion pair production in SUSY at e^+e^-", Int.J.Mod.Phys'03: hep-ph/0304110.]

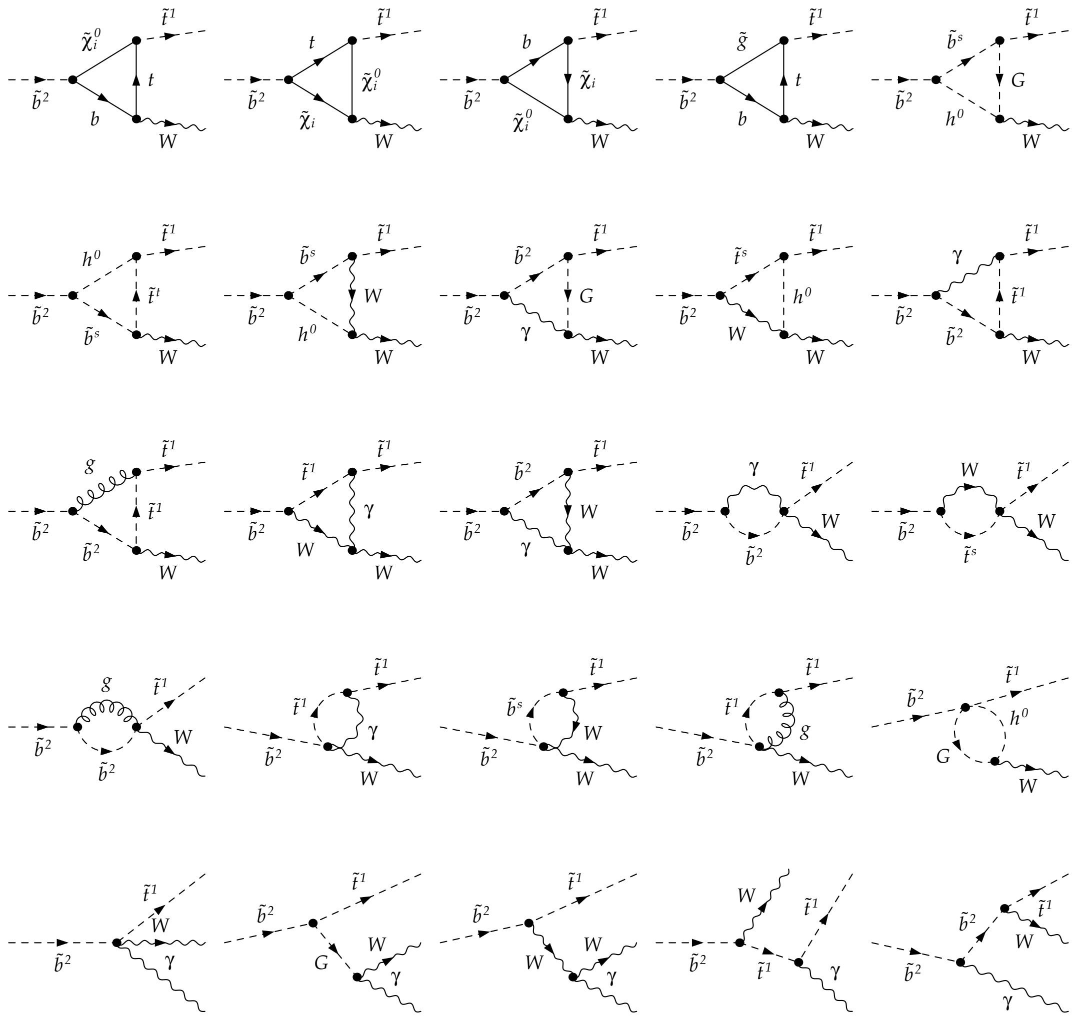
1-loop, resummation effects are close at $\sqrt{s} \approx 1$ TeV but drastically differ for $\sqrt{s} \approx$ 2-3 TeV

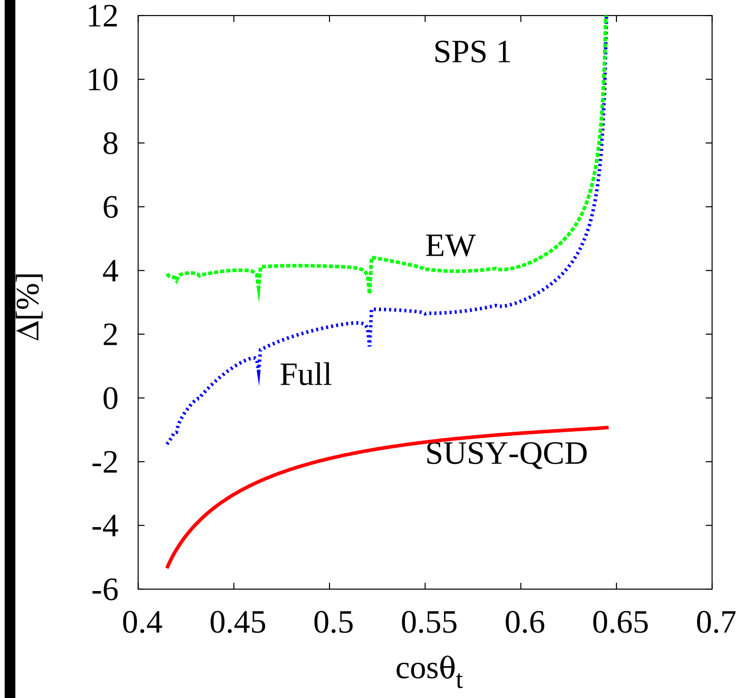
$\tilde{t}_2 \to \tilde{t}_1 Z$ and $\tilde{b}_1 \to \tilde{t}_1 W$ at tree level

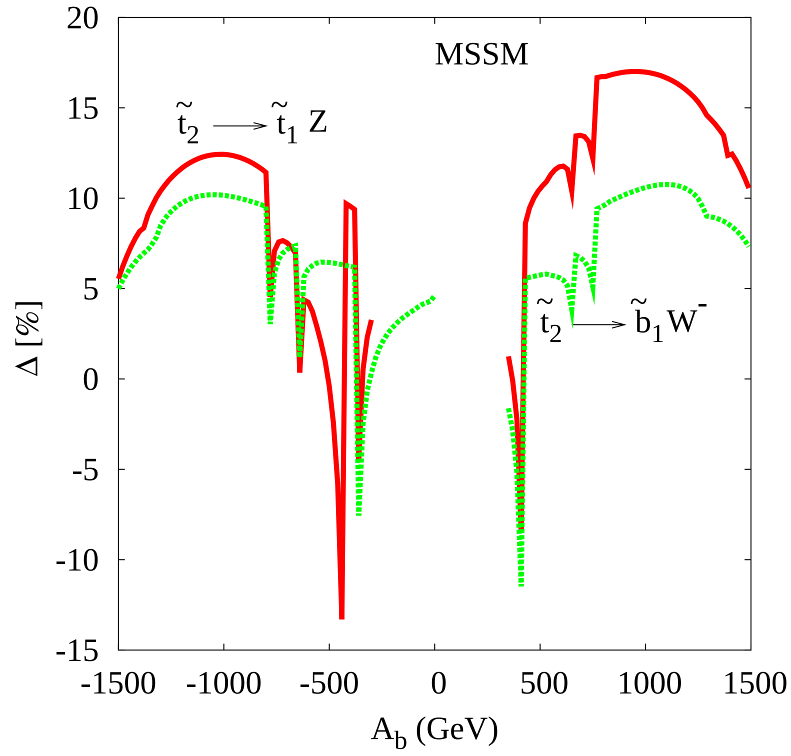




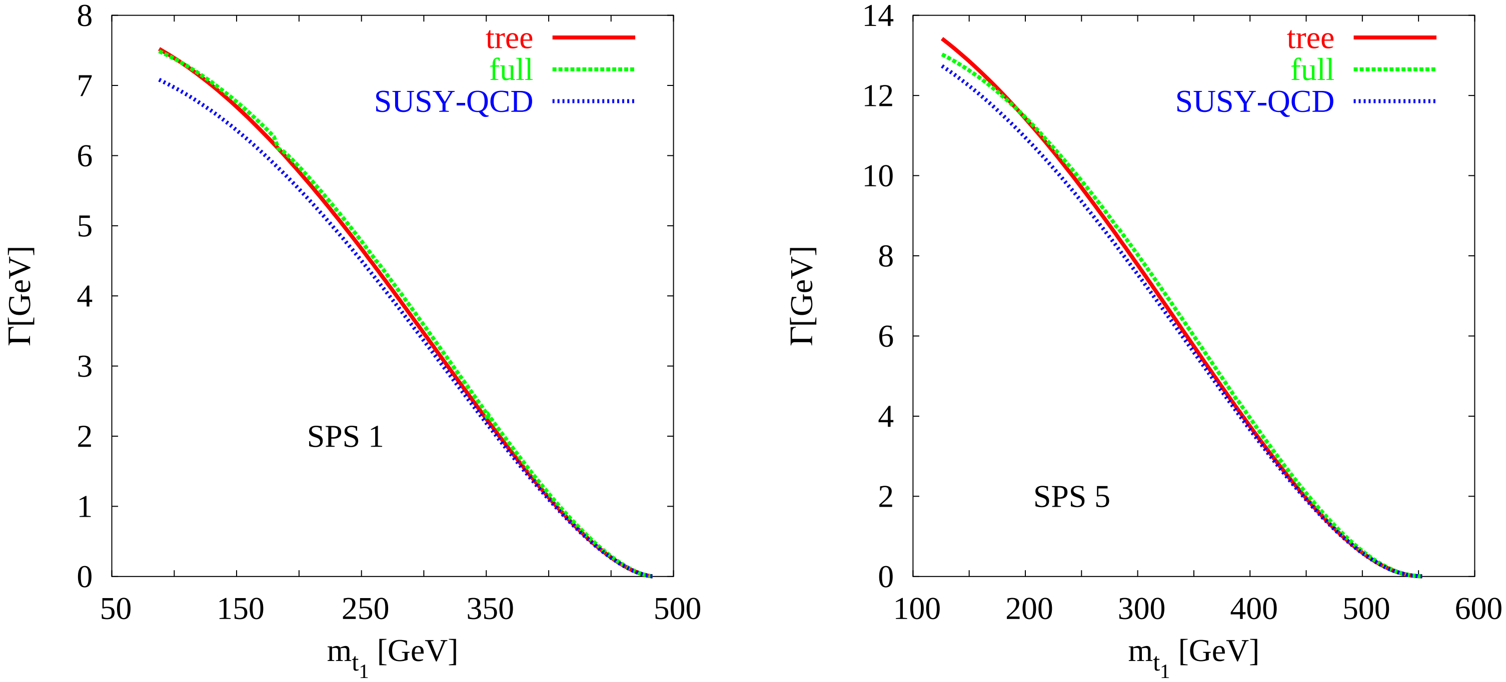
$\tilde{t}_2 \to \tilde{t}_1 Z$ and $\tilde{b}_1 \to \tilde{t}_1 W$ at 1-loop







Relative correction to $\widetilde{b}_2 \to \widetilde{t}_1 W$ in SPS1 (left) and $\widetilde{t}_2 \to \widetilde{t}_1 Z$, $\widetilde{b}_2 \to \widetilde{t}_1 W$ (right) as function of $A_t = A_b$ in general MSSM for $\mu = 500$ GeV, $M_2 = 130$ GeV, $M_A = 200$ GeV and $\tan\beta = 60$



Tree and one loop decay width of $\tilde{t}_2 \to \tilde{t}_1 Z$ as function of $m_{\tilde{t}_1}$

MSSM with CP violating phases

- In the SM, the amount of $\not{CP}$ in CKM, may be enough to explain the observed size of $\not{CP}$ in B and K meson system.
- However, it is too small to generate the observable Baryon Asymmetry in the Universe. Therefore, models with extra CP violating phases are welcome [A.D. Sakharov '67] .
- In principle, the MSSM admits a large number of CP violating phases which can not be rotated away and hence provide new sources of $\not{CP}$[J.Ellis et al'82, B. Grinstein et al '85].
- Those large CP violating phases can give contributions to the EDM which exceed the experimental upper bound.

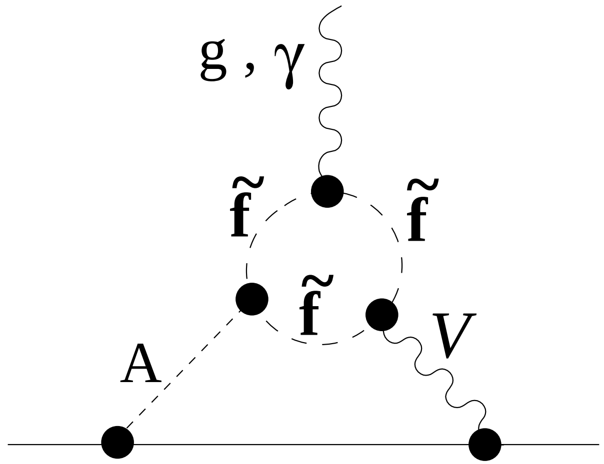
Evading EDM constraints without suppressing CP violating phases:

i) 1st and 2nd sfermions very heavy [Y.Kizukuri et al, PRD'92]

ii) Cancellation mechanism among the different EDM contribution, [T.Ibrahim et al PLB'98, M.Brhlik et al PRD'99]

iii) Non universality of the soft-trilinear Yukawa couplings: $A_f = (0, 0, A_t = A_b = A_0)$ and $\mathrm{Arg}(\mu) < 10^{-2}$, [S.Abel et al '97]

iv) 2-loop Barr-Zee type contribution to EDM requires: $\tan\beta \lesssim 30$ for large $A_{t,b}$ [D.Chang et al PRL'99]



Probing CP violation from $pp \to t\bar{t}$ at LHC

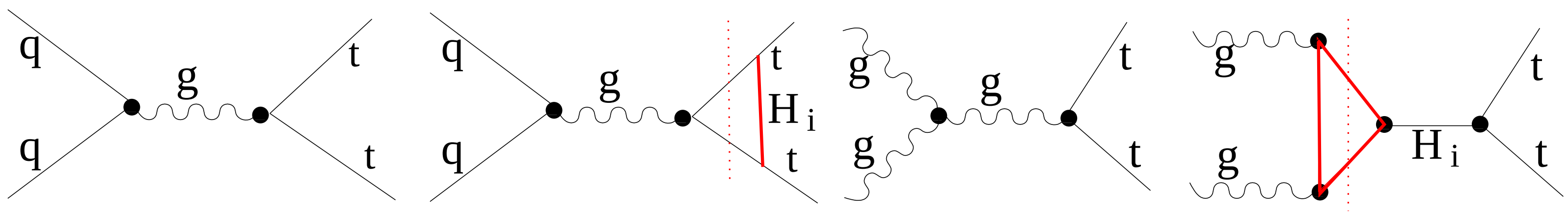
- [Schmidt-Peskin'92] propose a signature for $\not{C}P$ in $t\bar{t}$ production:

$$pp(\bar{p}) \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}l^+l^-\bar{\nu}_l\nu_l$$

$$\Gamma^V_\mu = v_V\gamma^\mu + a_V\gamma^5 + EDM_V\sigma^{\mu\nu}\gamma^5\frac{(p+p')_\nu}{2m_t}$$

$$\Delta N_{LR} = \frac{N(t_L\bar{t}_L) - N(t_R\bar{t}_R)}{all \quad t\bar{t}} \neq 0 \quad (\mathrm{CP} \ : \ \mathrm{t_L\bar{t}_L} \leftrightarrow \mathrm{t_R\bar{t}_R})$$

$$a_E = \frac{< E_{l^+} > - < E_{l^-} >}{< E_{l^+} > + < E_{l^-} >} \quad : \text{ Lepton energy asymmetry}$$



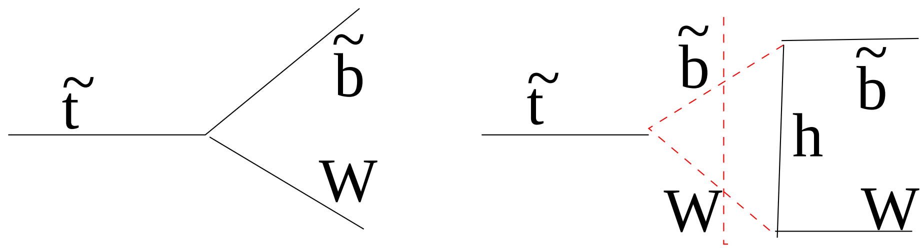
Non vanishing contribution to a_E and $\Delta N_{LR} \approx 10^{-3}$ comes from Absorptive part and complex coupling $H_i t\bar{t} = a_i + ib_i\gamma_5$

$\not{C}P$ in stops/sbottom decays: $\widetilde{t}_2 \to W^{\pm}\widetilde{b}_1$

- If SUSY particles are found, it will be necessary to measure the CP-violating properties of their couplings in order to get a complete picture of the SUSY model.
- CPV in $\widetilde{t}_i \to t\widetilde{\chi}^0_j$: T-odd asymmetries, by looking to triple product correlations [A. Bartl et al PRD70 2004]; CPA of the order 20 - 40%
  $t \to bW^+ \to bl\nu(bcs) \quad , \quad \widetilde{\chi}^0_j \to \widetilde{l}^-_n l^+_1 \to \widetilde{\chi}^0_1 l^+_1 l^-_2 \quad ,$
  $\widetilde{\chi}^0_j \to \widetilde{l}^+_n l^-_1 \to \widetilde{\chi}^0_1 l^-_1 l^+_2$
- CPV in $\widetilde{b}_i \to t\widetilde{\chi}^-_j$: T-odd asymmetries, by looking to triple product correlations [A. Bartl et al JHEP 2006]; CPA up to 30%
  $t \to bW^+ \to bl^+\nu(bcs) \quad , \quad \widetilde{\chi}^-_j \to \widetilde{\nu}_n l^- \to \widetilde{\chi}^0_1 l^-_1 \bar{\nu} \quad ,$
  $\widetilde{\chi}^+_j \to \widetilde{l}^-_n \bar{\nu} \to \widetilde{\chi}^0_1 l^-_2 \bar{\nu}$
- CPV in $\widetilde{t}_i \to \widetilde{t}_j H^*_i \to \widetilde{t}_j \tau^+\tau^-$: sigle-spin Asymmetry and triple product asymmetry, [D. London et al PRD74 2006];

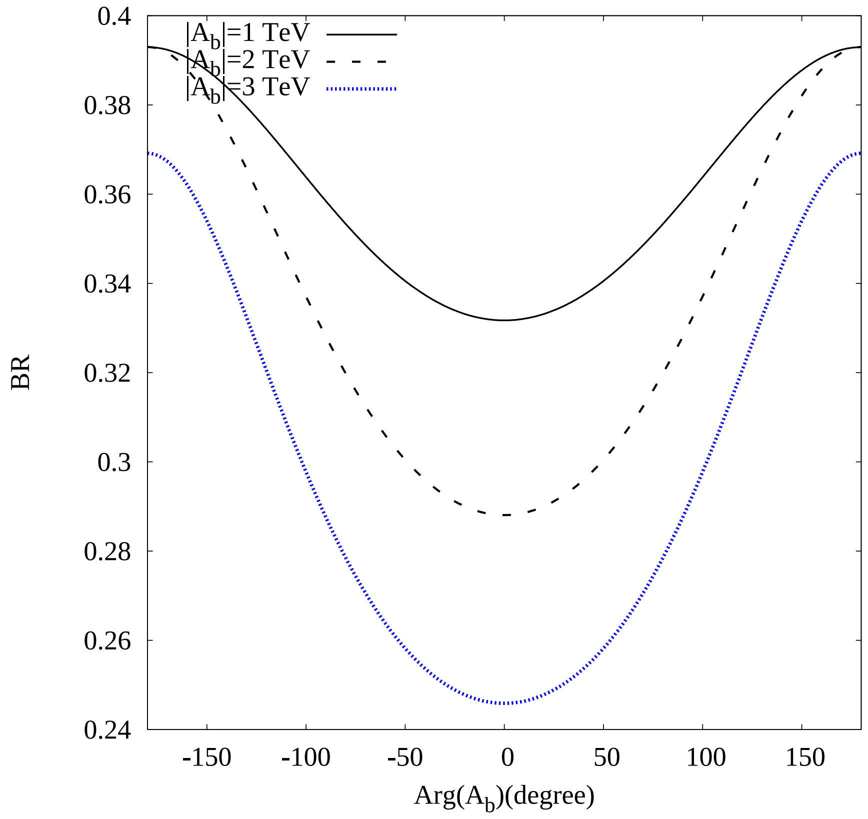
CP Asymmetry in $\widetilde{t}_2 \to W^+\widetilde{b}_1^*$ and $\widetilde{t}_2^* \to W^-\widetilde{b}_1$

$$\mathcal{A}^{CP} = \frac{\Gamma(\widetilde{t}_2 \to W^+\widetilde{b}_1^*) - \Gamma(\widetilde{t}_2^* \to W^-\widetilde{b}_1)}{\Gamma(\widetilde{t}_2 \to W^+\widetilde{b}_1^*) + \Gamma(\widetilde{t}_2^* \to W^-\widetilde{b}_1)}$$

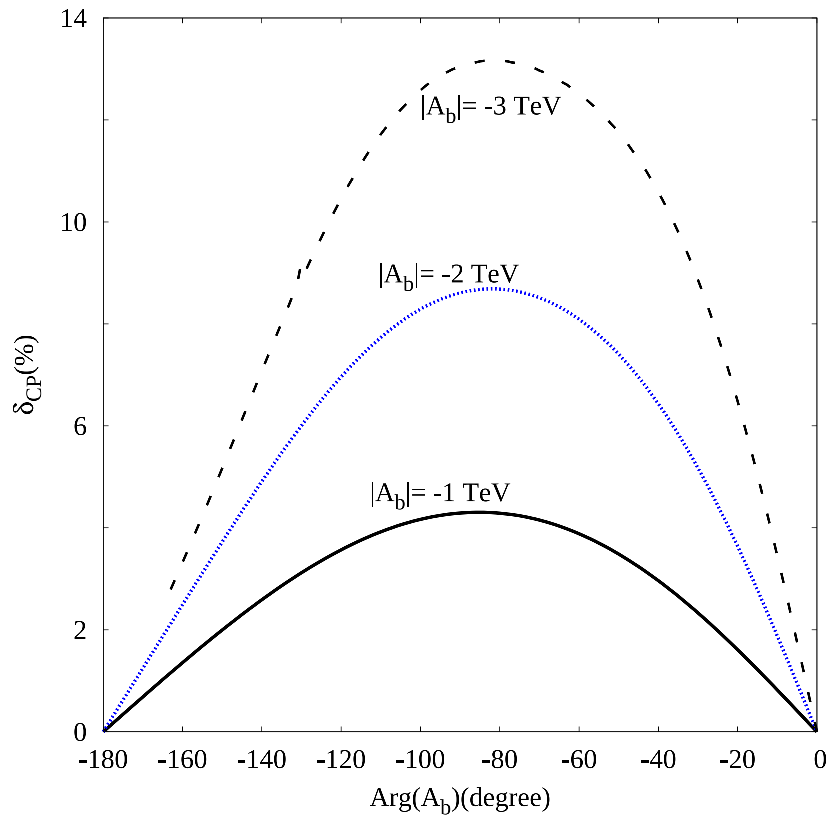


both complex couplings $\tilde{b}\tilde{b}h$, $\tilde{t}\tilde{b}W$ and absorptive part are needed to generate $\mathcal{A}^{CP} \neq 0$

$\mathrm{Br}(\widetilde{t}_2 \rightarrow W\widetilde{b}_1)$



Rate asymmetry for $\widetilde{t}_2 \to W^{\pm}\widetilde{b}_1$



Conclusions

- Scalar quarks can be copiously produced at LHC if not too heavy
- Sfermions production at ILC useful for masses and mixing anlges measurements
- Both QCD and EW corrections are important, total corrections can reach $\approx \pm 15\%$
- In MSSM with CP phases, CPA in $\tilde{t}_2 \to W^\pm \tilde{b}_1^*$ can be of the order 15%
- If SUSY masses are low and model is not too complicated, LHC will discover SUSY and ILC will be "LEP for SUSY"