One-loop contributions of super-partner particles to $e^-e^+ \to W^-W^+$ in the MSSM

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with

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- Sfermion one-loop effects on $e^-e^+ \to W^-W^+$
- In order to obtain trustworthy results, three tests for the one-loop calculation are performed.
- Size of the SUSY correction to the SM prediction is examined by taking into account the experimental constraints from

  the direct search results and

  the electroweak precision data.

1 Introduction

Study of Radiative Corrections $\oplus$ present/future Data

$\Rightarrow$ Information of NEW PHYSICS

The W^-W^+ pair production from e^-e^+ collision

Precise measurements at LEP 2
also at Future Linear Colliders (JLC, NLC, TESLA)

Radiative corrections [redacted] to $e^-e^+ \to W^-W^+$
can be used to probe not only the SM
but also models for new physics

2 In this Talk

SUSY-particle one-loop contributions to $e^-e^+ \to W^-W^+$ in the MSSM

- Sfermions (Squarks and Sleptons)
- Inos (Charginos, Neutralinos and Gluinos)
- extra Higgs bosons (H^0, A^0 and $H^\pm$)

We here concentrate on Sfermion-loop effects

Calculation of $e^-e^+ \to W^-W^+$

Subtle gauge-theory cancellation takes place!.

$$\Downarrow$$

Incomplete treatment of higher order terms leads artificially large corrections

Three tests of the one-loop calculation:

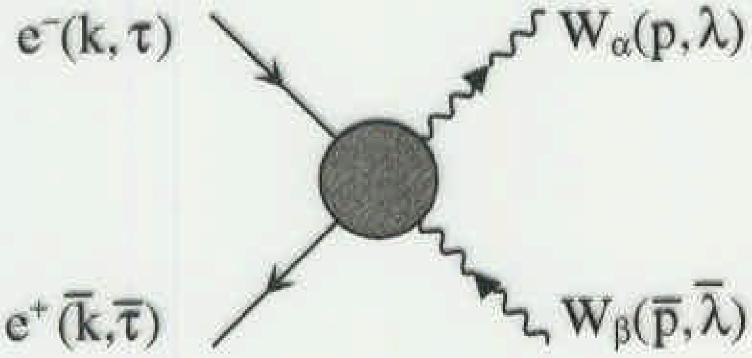
1. The BRS identity Alam, Hagiwata, Kanemura, Szalapski and Umeda
2. The Decoupling Theorem Appelquist and Carazzone
3. High Energy behaviors

Size of the sfermion correction is studied by taking into account parameter constraints from

- Sfermion direct search results,
- [redacted] precision data. PDG
  Cho, Hagiwara

3 Form-factor Decomposition

The process



helicities $\quad$ scalar W

$$\lambda, \bar{\lambda} = (0, -1, +1, S)$$

3 physical polarizations

The helicity amplitudes

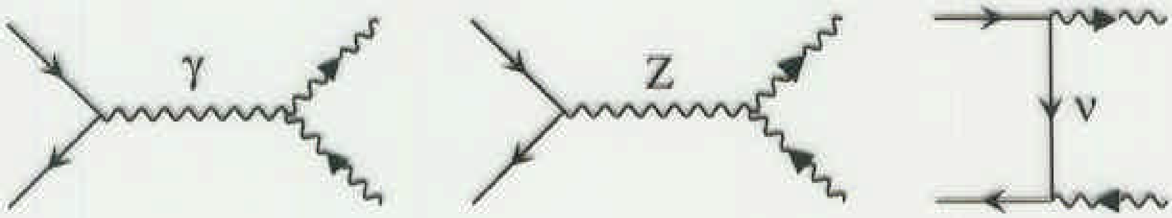
$$\mathcal{M}_\tau^{\lambda\bar{\lambda}} = \sum_{i=1}^{16} F_{i,\tau}(s,t)\, j_\mu(k,\bar{k},\tau)\, T_i^{\mu\alpha\beta}\, \epsilon^*_\alpha(p,\lambda)\, \epsilon^*_\beta(\bar{p},\bar{\lambda})$$

↑ Form Factors

↑ 16 basis tensors

$\lambda \otimes \bar{\lambda} = 16$

Tree level diagrams



$\sim \dfrac{s}{m_W^2}$ $\quad$ $\sim \dfrac{s}{m_W^2}$ $\quad$ $\sim \dfrac{s}{m_W^2}$ $\quad \rightarrow O(1)$

We also calculate $e^-e^+ \to w^-W^+$ to make the BRS test.
(w^-: the charged Nambu-Goldstone boson)

4 One-loop calculation

Tarasov et.al.
Chetyrkin et.al.

$\boxed{\text{Renormalization: } \overline{\text{MS}} \text{ scheme}}$

Input SM parameters: $(m_W^2, \hat{e}^2, \hat{s}^2)$ $\hat{e}^2 = \hat{g}^2 \hat{s}^2$

The W boson mass: $m_W = 80.41\text{GeV}$

The MSSM $\overline{\text{MS}}$ couplings:

$$\frac{1}{\hat{e}^2_{\text{MSSM}}(\mu)} = \frac{1}{\hat{e}^2_{\text{SM}}(\mu)} - \Delta\Pi_{T,\gamma}^{QQ}(0,\mu),$$
$$\frac{1}{\hat{g}^2_{\text{MSSM}}(\mu)} = \frac{1}{\hat{g}^2_{\text{SM}}(\mu)} - \Delta\Pi_{T,\gamma}^{3Q}(0,\mu)$$

↑
SUSY-loop contributions

The SM $\overline{\text{MS}}$ couplings are determined by using the SM RGE's and the experimental values for the effective charges

$$1/\overline{\alpha}(m_Z^2) = 128.75 \pm 0.09 \qquad \text{for } m_t = 175\text{GeV}$$
$$\overline{s}^2(m_Z^2) = 0.23035 \pm 0.00023 \qquad m_{H_{\text{SM}}} = 100\text{GeV}$$

5 The sfermion sector

Sfermions: Squarks $\oplus$ Sleptons

$$\tilde{Q}^i = \begin{bmatrix} \tilde{u}^i_L \\ \tilde{d}^i_L \end{bmatrix}, \qquad \tilde{L}^i = \begin{bmatrix} \tilde{\nu}^i_L \\ \tilde{e}^i_L \end{bmatrix}$$

$$\tilde{u}^i_R, \quad \tilde{d}^i_R, \qquad \tilde{e}^i_R, \qquad (i = 1, 2, 3)$$

Mass matrices

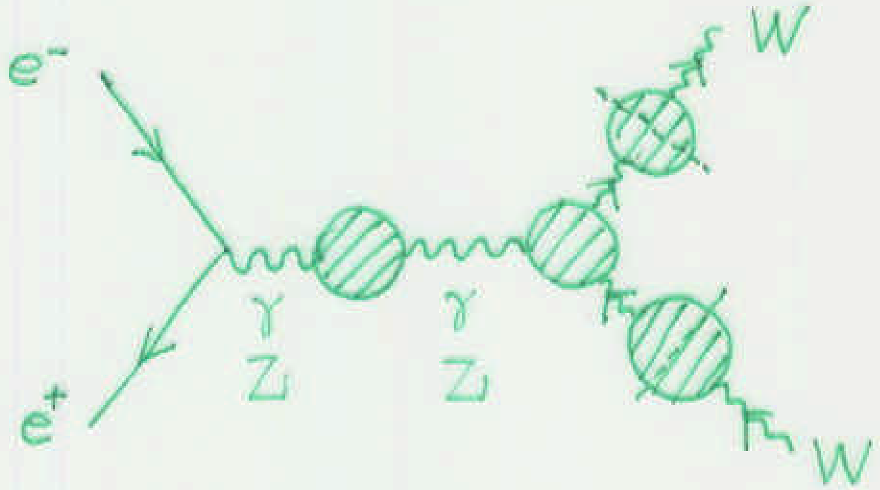
$$M^2_{\tilde{f}} = \begin{bmatrix} m^2_Q + m^2_Z \cos 2\beta (T^3_{f_L} - \hat{s}^2 Q_f) + m^2_f & -m_f A^{\text{eff}}_f \\ -m_f A^{\text{eff}*}_f & m^2_Q + m_Z \cos 2\beta \hat{s}^2 Q_f + m^2_f \end{bmatrix}$$

$$A^{\text{eff}}_{d,e} = A^*_{d,e} + \mu \tan\beta$$
$$A^{\text{eff}}_u = A^*_u + \mu \cot\beta$$

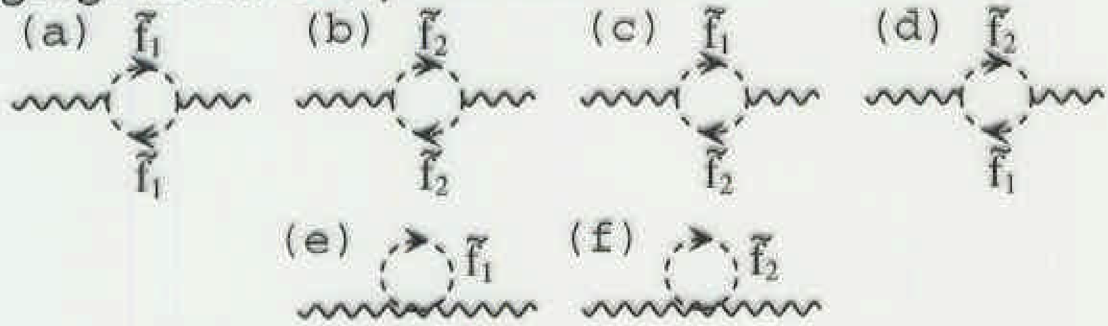
The $\tilde{t}_L$-$\tilde{t}_R$ mixing

Diagonalisation : $\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \longrightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$ mixing angle θ_t

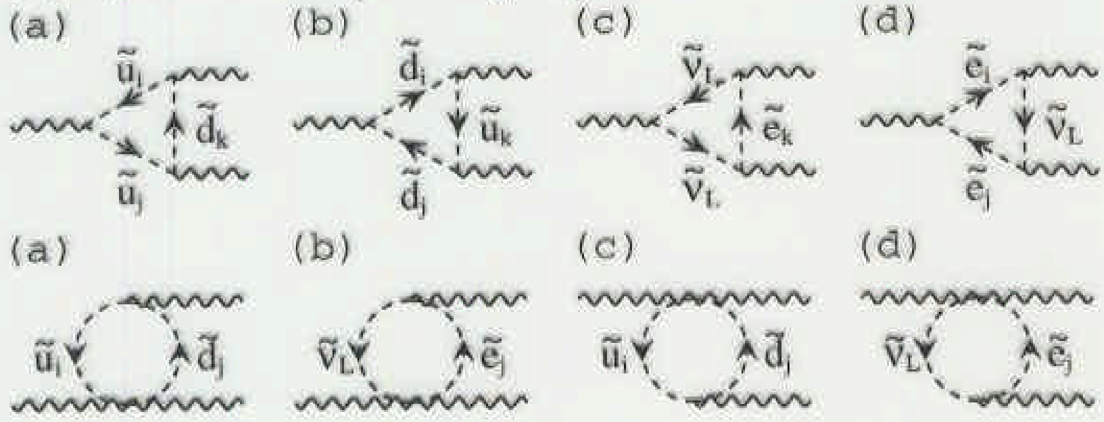
6 Sfermion one-loop diagrams



gauge boson two-point functions



VWW vertices ($V = \gamma,\, Z$)



7 The three tests of one-loop calculation

7.1 Test by using the BRS sum rules

$$Q_{\mathrm{BRS}}|\mathrm{phys}\rangle = \langle\mathrm{phys}|Q_{\mathrm{BRS}} = 0,$$
$$\{Q_{\mathrm{BRS}}, \hat{\bar{c}}^{\pm}\} = \partial^{\mu}\hat{W}^{\pm}_{\mu} + \hat{\xi}_W \hat{m}_W \hat{w}^{\pm}.$$

Becchi et al.

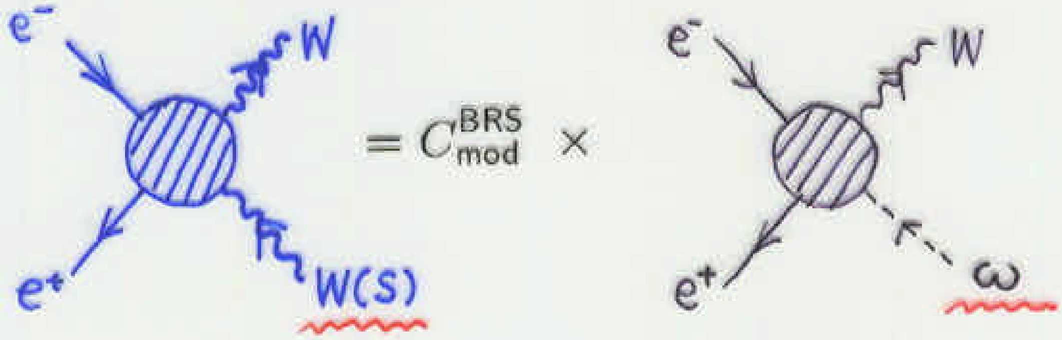
The BRS identity

$$\langle\mathrm{phys}'|(\partial^{\mu}\widehat{W}^{\pm}_{\mu} + \hat{\xi}_W \hat{m}_W \widehat{w}^{\pm})|\mathrm{phys}\rangle = 0\,.$$

Gaemers, Gounaris

Sum Rules among the form factors

$$\boxed{\sum_{j=1}^{16} \xi_{ij} F_{j,\tau}(s,t) = C^{\mathrm{BRS}}_{\mathrm{mod}} H_{i,\tau}(s,t) \quad (i = 1\text{--}3)}$$



Test by using the BRS sum rule $(i = 1,\ \tau = -1)$

$\sqrt{s}$	Left-hand-side $\xi_{1j} F_j(s,t)$ Right-hand-side $C_{\mathrm{mod}} H_i(s,t)$
200 GeV	$-1.385496590672218 \times 10^{-6}$ $-1.385496590672223 \times 10^{-6}$
1000GeV	$-6.682526871892199 \times 10^{-8}$ $-6.682526871892053 \times 10^{-8}$

More than 13 digits agreement

The one-loop form factors are tested by the BRS sum rules except for overall renormalization factors.

7.2 Test of the exact decoupling

The decoupling:

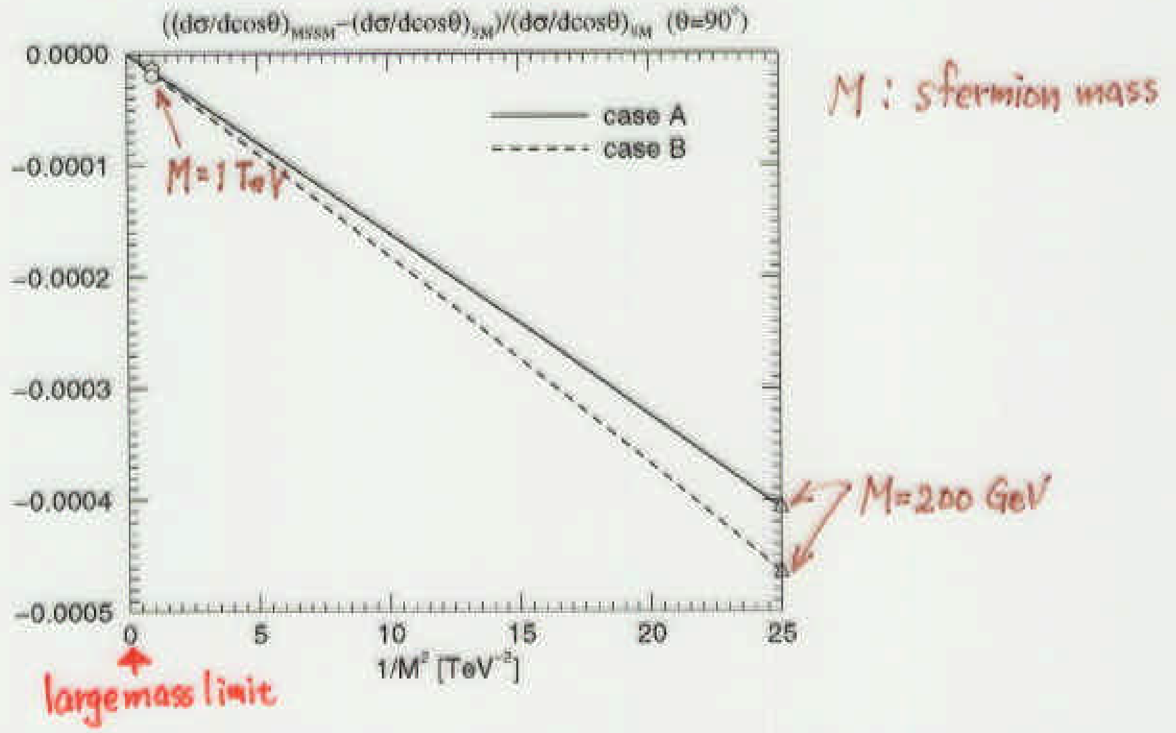
$$\sigma_{\mathsf{MSSM}} = \sigma_{\mathsf{SM}} + \Delta\sigma_{\mathsf{SUSY}}$$

$$\Delta\sigma_{\mathsf{SUSY}} \to \mathcal{O}\left(\frac{m_W^2}{M_{\mathsf{SUSY}}^2}\right), \qquad (M_{\mathsf{SUSY}}^2 \gg m_W^2)$$

The Decoupling Theorem (Appelquist and Carazzone)

This fact can be used for testing one-loop calculation.

For exact decoupling, we expand MSSM running couplings by those of SM, and take terms up to $\mathcal{O}(g_{\mathsf{SM}}^4)$.



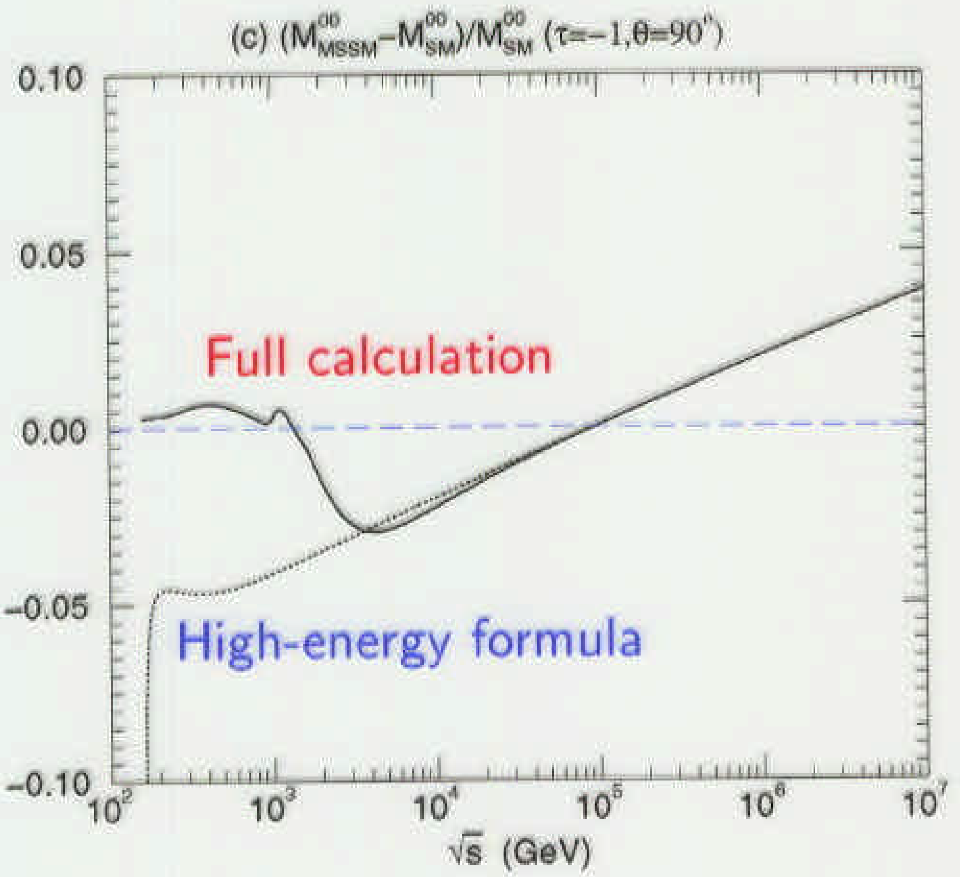
The overall renormalization factors have been tested, which cannot have been tested by the BRS test.

7.3 High energy behaviour

At high-energy, large gauge-theory cancellation takes place.

Test for numerical stability of the full computational program at high-energies.

High-energy analytic formulas of amplitudes
$(m_W^2/s \to 0,\ m_{\tilde{f}}^2/s \to 0)$



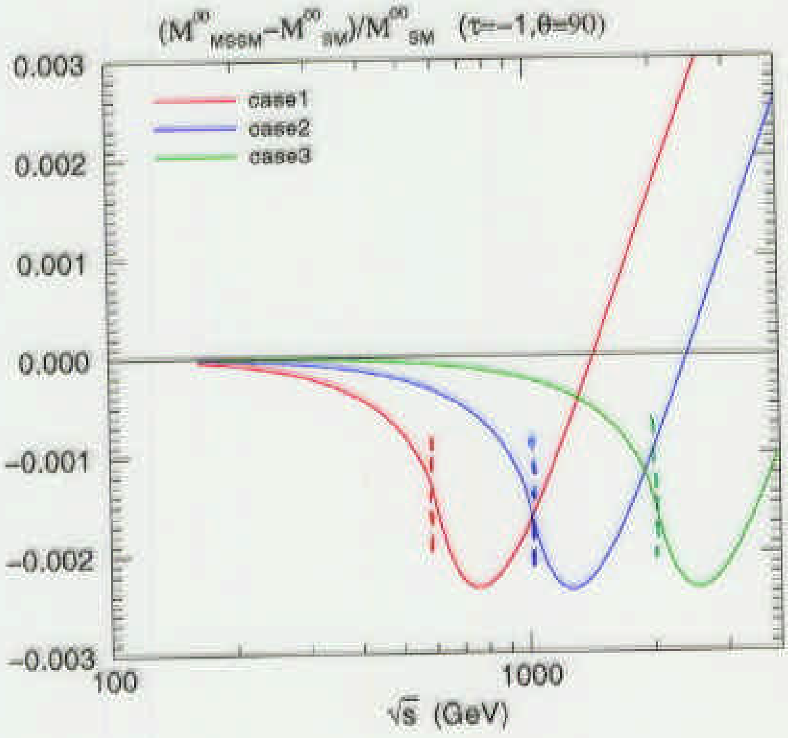
Complete agreement at high-energies.

8 Sfermion effects on $e^-e^+ \to W^-W^+$

Constraints on parameters:
- Direct Search Results
- EW Precision Data

8.1 Helicity amplitudes: Non $\tilde{f}_L$-$\tilde{f}_R$ mixing cases

First 2 generations:	Case 1	Case 2	Case 3
Input parameters			
$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}}$	300	500	1000
$A_{\tilde{f}}^{\rm eff}$	0	0	0
Output parameters			
$m_{\tilde{u}_1} = m_{\tilde{c}_1}$	297	498	999
$m_{\tilde{u}_2} = m_{\tilde{c}_2}$	298	499	999
$m_{\tilde{d}_1} = m_{\tilde{s}_1}$	304	502	1001
$m_{\tilde{d}_2} = m_{\tilde{s}_2}$	301	501	1000

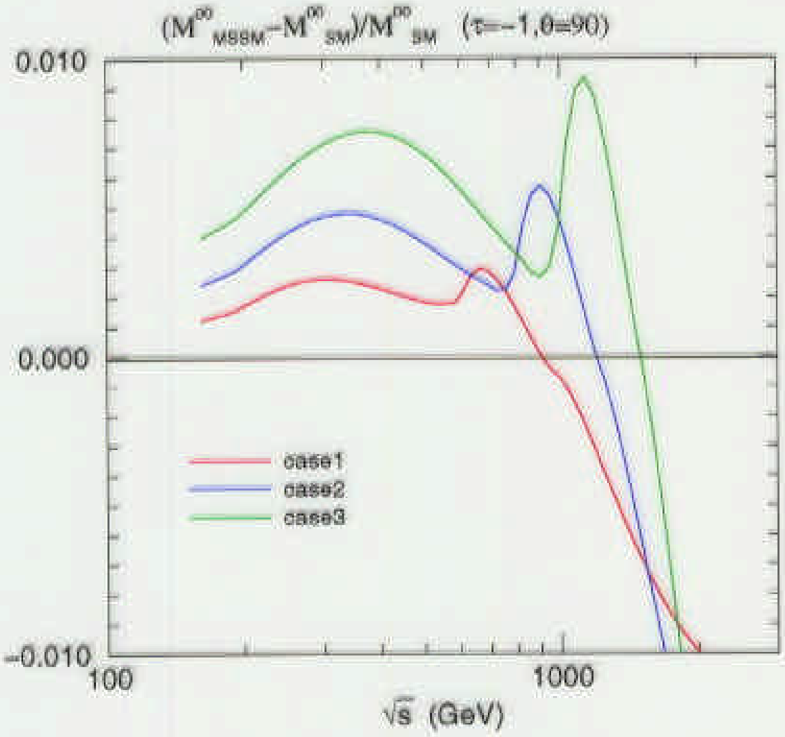


Corrections
- Negative
- $\sim$ a few $\times$ 0.1%

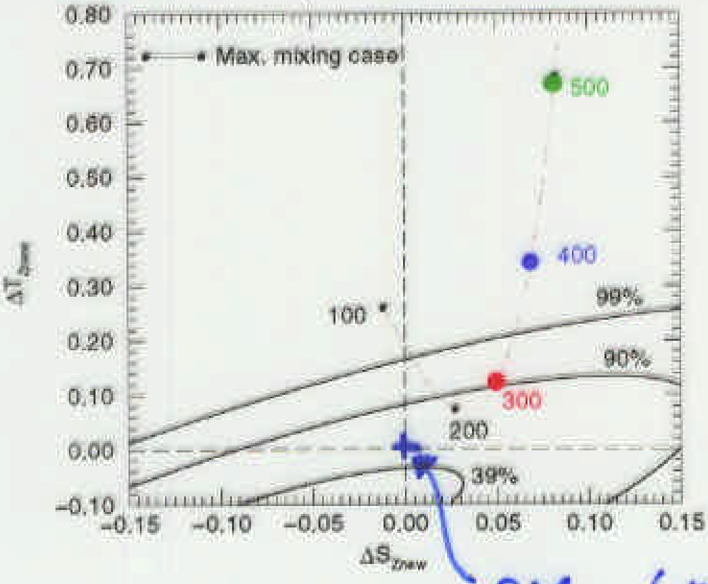
8.2 Helicity amplitudes: $\tilde{t}_L$-$\tilde{t}_R$ mixing cases

$\tilde{t}$-$\tilde{b}$ sector:	Case 1	Case 2	Case 3
Input parameters			
$m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}}$	300	400	500
$A^{\rm eff}_{\tilde{t}}$	625	1025	1539
Output parameters			
$m_{\tilde{t}_1}$	100	100	100
$m_{\tilde{t}_2}$	478	607	741
$m_{\tilde{b}_1}$	304	403	502
$m_{\tilde{b}_2}$	301	401	501
$\cos\theta_{\tilde{t}}$	0.708	0.708	0.707

← $\theta_t = 45°$

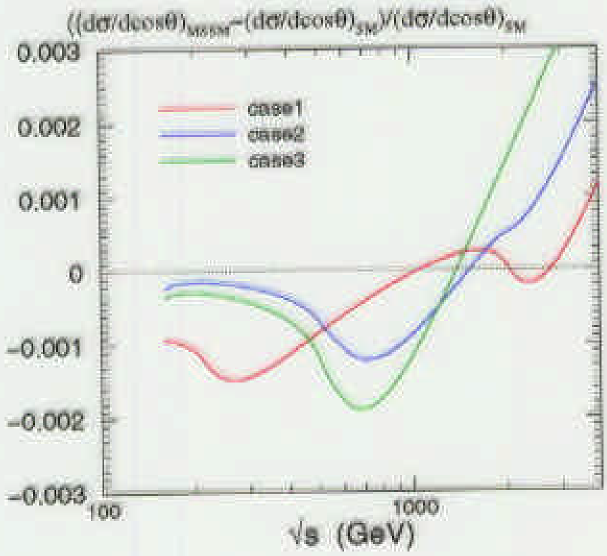


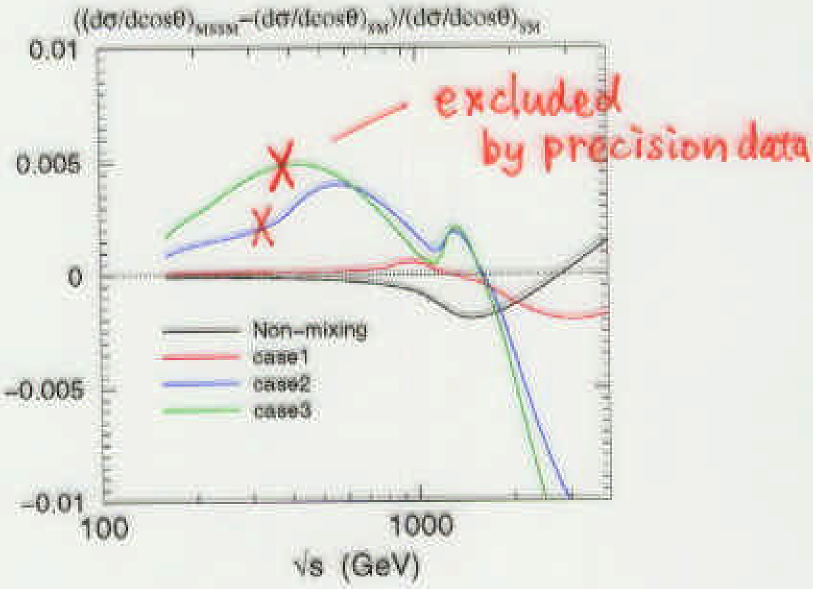
Constraints by the Precision Data (S-T fit)



SM ($m_t = 175$ GeV, $m_h = 100$ GeV)

8.3 Helicity-summed cross-sections





Case	1	2	3	4	5	6	7
Input							
$m_{\tilde{Q}}$	1000	250	250	600	600	600	600
$m_{\tilde{U}}=m_{\tilde{D}}$	1000	250	250	540	540	540	540
$m_{\tilde{L}}$	100	1000	250	540	540	540	540
$m_{\tilde{E}}$	100	1000	250	540	540	540	540
A_f^{eff}	0	0	0	0	1000	1800	1900
Output							
$m_{\tilde{t}_1}$	1014	302	302	624	421	196	111
$m_{\tilde{t}_2}$	1015	304	304	567	730	820	835
$m_{\tilde{b}_1}$	1001	254	254	602	602	602	602
$m_{\tilde{b}_2}$	1000	251	251	540	540	540	540
$\cos\theta_{\tilde{t}}$	1	1	1	1	0.637	0.668	0.671

9 Summary

Sfermion one-loop contributions to $e^- e^+ \to W^- W^+$.

Subtle gauge-theory cancellation
at each order of perturbation

$\Downarrow$

Three tests of the one-loop calculation.

1. BRS sum rules (one-loop form factors)
2. Decoupling property (overall renormalization factor)
3. High-energy behavior (high energy stability)

Numerical Results:

Constraints Direct search results
EW Precision data

- Sleptons and the first two generation of squarks

Corrections negative: a few $\times 0.1$ %.

- $\tilde{t}$-$\tilde{b}$ sector

Correction positive:

Larger $\tilde{t}_L$-$\tilde{t}_R$ mixings $\Rightarrow$ Larger corrections

$\uparrow$

Excluded by the EW precision data.

after all: a few $\times 0.1$ %.

The sfermion effects in this process is very small.

The other SUSY effects: work in progress.