Susy Search at Supercolliders

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§1. Introduction

- Purpose of this talk:

(1) Study possibilities offered by multi-TeV colliders to discover susy.

(2) Study the role that the multi-TeV colliders could play in case any of the susy particles were discovered at present or near future collider experiments (such as TEVATRON, SLC, LEP and HERA).

(Note) (This talk mainly discusses susy search at $e^- e^+$ TeV collider as an example of multi-TeV collider susy physics.)

§2. Brief summary of susy phonomenology

* Minimal Content of SUSY Models

J = 1 (boson)	J = $\frac{1}{2}$ (fermion)	J = 0 (boson)
gluon (g)	○ gluino ($\tilde{g}_{\frac{1}{2}}$)	
	quark (q)	○ squark ($\tilde{q}_0$)
	lepton (ℓ)	○ slepton ($\tilde{\ell}_0$)
photon (γ)	○ photino ($\tilde{\gamma}_{\frac{1}{2}}$)	
$W^\pm$	○ Wino ($\tilde{W}_{\frac{1}{2}}$)	
Z^0	○ Zino ($\tilde{Z}_{\frac{1}{2}}$)	
	○ shiggs ($\tilde{h}_{\frac{1}{2}}$) (or higgsino)	higgs (h)
	○ Goldstino ($\tilde{G}_{\frac{1}{2}}$)	

↗ Nambu-goldstone fermion of SUSY breaking (massless until eaten by gravitino in local SUSY)

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        2.5                 I I I            I
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        2.1               I I III     I I I  I
        2                 I I III     I I I  I
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        1.8               I I III     I I I  I
        1.7               I I III     I I I  I
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        1.1               0 I I0I     0 0 0  I
        1                 I I III     I I I  I
         .9               I I III     I I I  I
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* ENTRIES =          13       * ALL CHANNELS =  0.1391E-09      * UNDERFLOW =  0.0          * OVERFLOW =  0.0
* BIN WID = 0.2000E+02        * MEAN VALUE   =  0.3977E+03      * R . M . S =  0.1290E+03    * ABNOR CHA=  0.0
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W-pair Background

$\mathcal{L} = 10^{38}$

(entry = 13)

Fig. 19

- *Key-ingredients of susy phenomenology*

(i) Ordinary particles and its super partner have

<u>different</u> <u>spin</u> and <u>mass</u> (<u>the only unknown!</u>)
but
<u>same</u> <u>coupling</u> strength!

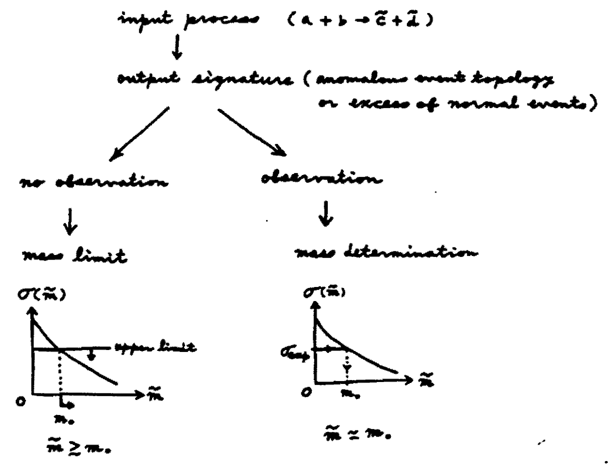
(ii) Experimental signature of susy interactions is dramatic:

<u>large missing energy</u> and <u>large p_T unbalance</u>

(due to the production of inactive "ν-like" susy particles, namely, $\tilde{\gamma}$, $\tilde{h}^0$, $\tilde{\nu}$ or $\tilde{G}$.)

Since all susy particles inevitably produce $\tilde{\gamma}, \tilde{h}^0, \tilde{\nu}$ or $\tilde{G}$ in their decays (due to R-invariance), we have a fairly unambiguous signal for susy interactions!

《Priciple of susy phenomenology》



§3. Susy search at TeV e^-e^+ collider

§3-1 Simple picture (no gaugino-higgsino mixing case)

(Ref.: Ellis-Pauss and Dionisi-Dittmar, "Proc. of the Workshop on Physics at Future Accelerators", La Thuile and Geneva, 1987 (CERN 87-07).)

- Simple picture:

× Physical susy particles

$\underbrace{\tilde{l}, \tilde{q}}_{\text{smatters}}$ $\quad$ $\underbrace{\tilde{g}, \tilde{W}^{\pm}, \tilde{Z}^0, \tilde{\gamma}}_{\text{gauginos}}$

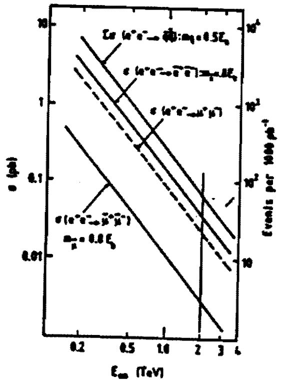
(with no mixing with higgsinos)

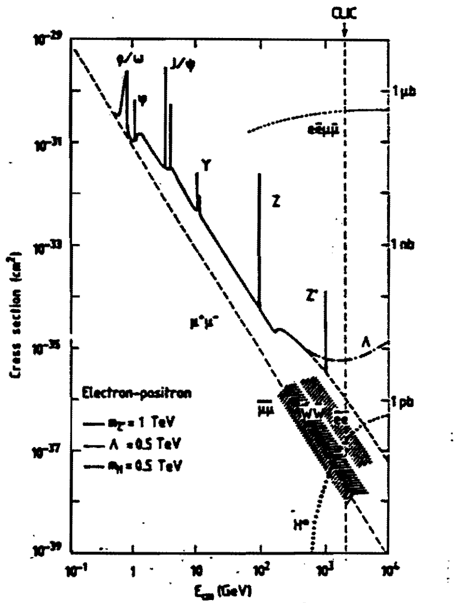
× Susy particle decay

$\tilde{l} \to l\tilde{\gamma}$
$\tilde{q} \to q\tilde{\gamma}$ or $q\tilde{g}$

$\tilde{g} \to q\bar{q}\tilde{\gamma}$
$\tilde{W}^{\pm} \to W^{\pm}_{m}\tilde{\gamma}$
$\tilde{Z}^0 \to f\bar{f}\tilde{\gamma}$ ($f = l$ or q)
$\tilde{\gamma}$: stable

- Typical size of σ_{susy} :





$$\downarrow$$

$$\boxed{\sigma_{\tilde{s}\bar{\tilde{s}}} \sim \sigma_{\mu\mu}} \quad (\text{for } m_{\tilde{s}} \lesssim 0.8\, E_{beam})$$

$(\tilde{s} = \tilde{\ell}, \tilde{q}, \tilde{w})$

$$\downarrow$$

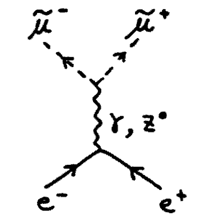
$$\boxed{\sim O(10^{2\text{-}3})\, \tilde{s}\bar{\tilde{s}} \text{ events}} \left(\text{for } 10\, fb^{-1} \text{ at } \sqrt{s} = 2\, \text{TeV}\right)$$

$$\left(LT = 10^{33}(cm^{-2}sec^{-1}) \cdot 10^{7}(sec) = 10\, fb^{-1}\right)$$

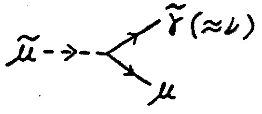
(1) $e^- e^+ \rightarrow \tilde{\mu}^- \tilde{\mu}^+$, $\tilde{\mu}^+ \rightarrow \mu^+ \tilde{\gamma}$, $\tilde{\mu}^- \rightarrow \mu^- \tilde{\gamma}$

- Signature :

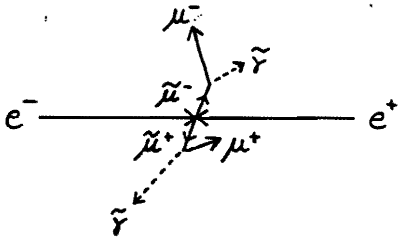
($\tilde{\mu}$ prod.)

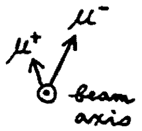


($\tilde{\mu}$ decay)



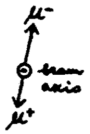
(Signature)





$$\boxed{\text{signature : accoplanar } \mu^- \mu^+ + \text{large } \not{P}_T}$$

- Backgrounds:



$\mu^-\mu^+$
(i) $e^-e^+ \to \mu^-\mu^+\gamma$ ($\gamma \to$ × (forward detector gap)) (almost coplanar $\mu^-\mu^+$ & small $\not{p}_T$)
(ii) $e^-e^+ \to e^-e^+\mu^-\mu^+$ ($e^-e^+ \to$ × (f.d. gap)) (almost coplanar $\mu^-\mu^+$ & small $\not{p}_T$)

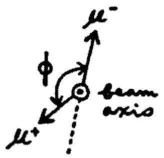
$\tau^-\tau^+$
(iii) $e^-e^+ \to \tau^-\tau^+$ ($\tau^+ \to \mu^+\nu\bar{\nu}$, $\tau^- \to \mu^-\nu\bar{\nu}$) (almost coplanar $\mu^-\mu^+$)
(iv) $e^-e^+ \to \tau^-\tau^+\gamma$ ($\gamma \to$ × (f.d. gap), $\tau^+ \to \mu^+\nu\bar{\nu}$, $\tau^- \to \mu^-\nu\bar{\nu}$) (almost coplanar $\mu^-\mu^+$)
(v) $e^-e^+ \to e^-e^+\tau^-\tau^+$ ($\tau^+ \to \mu^+\nu\bar{\nu}$, $\tau^- \to \mu^-\nu\bar{\nu}$, $e^-e^+ \to$ × (f.d. gap)) (almost coplanar $\mu^-\mu^+$)

WW
(vi) $e^-e^+ \to W^+W^-$ ($W^- \to \mu^-\nu$, $W^+ \to \mu^+\nu$) (almost coplanar $\mu^-\mu^+$)
($\because m_W \ll E_W \approx 1\,\text{TeV}$)
(vii) $e^-e^+ \to W^+W^-\gamma$ ($\gamma \to$ × (f.d. gap), $W^- \to \mu^-\nu$, $W^+ \to \mu^+\nu$) (almost coplanar $\mu^-\mu^+$)
(viii) $e^-e^+ \to e^-e^+W^+W^-$ ($W^- \to \mu^-\nu$, $W^+ \to \mu^+\nu$, $e^-e^+ \to$ × (f.d. gap)) (almost coplanar $\mu^-\mu^+$)

↓

All of these backgrounds can be eliminated (or suppressed) by imposing

- × $\not{p}_T$ cut
- × acoplanarity angle (ϕ) cut



without any significant loss of the signal events $e^-e^+ \to \tilde{\mu}^-\tilde{\mu}^+ \to \mu^-\mu^+\tilde{\gamma}\tilde{\gamma}$!

- Selection cut:

Scatter plot of MC events in ($\Sigma E_{vis}, \cos\phi$) plane

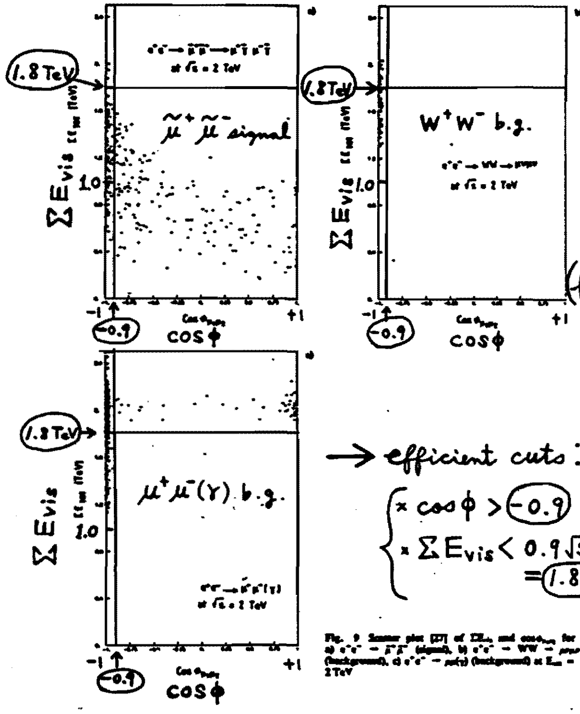
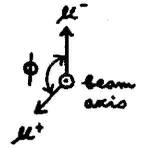


Fig. 9 Scatter plot [27] of ΣE_{vis} and $\cos\phi_{\mu\mu}$ for a) $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (signal), b) $e^+e^- \to WW \to \mu\nu\mu\nu$ (background), c) $e^+e^- \to \mu\mu(\gamma)$ (background) at E_{cm} = 2 TeV



(for $m_{\tilde{\mu}} = 0.5$ TeV)

→ efficient cuts:

- × $\cos\phi > -0.9$
- × $\Sigma E_{vis} < 0.9\sqrt{s} = 1.8$ TeV

at $\sqrt{s} = 2$ TeV

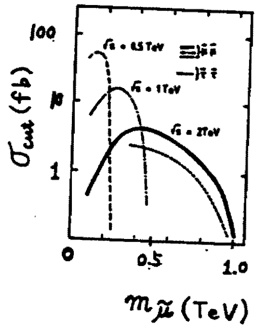
Selection cuts:

- Production angle cut: $\theta_{\mu^\pm} > 30°$
- Energy cut: $E_{\mu^\pm} > 30\,\mathrm{GeV}$
- Visible energy cut: $\sum E_{vis} < 0.9\sqrt{s} = 1.8\,\mathrm{TeV}$
- Acoplanarity angle cut: $\cos\phi > -0.9$
- $\not{p}_T$ cut: $\not{p}_T > 100\,\mathrm{GeV}$

↓

- Only 40 ~ 50 % reduction of signal events for $m_{\tilde{\mu}} > 500\,\mathrm{GeV}$.
- Background cross section becomes negligiblly small!
  (e.g., $\sigma_{cut}(ee \to eeWW \to ee\mu\mu\nu\nu) < 1\,fb$)

- Cross section after selection cuts:



(assume: $B(\tilde{\mu} \to \mu\tilde{\gamma}) = 100\%$)

$\sigma_{cut}(e^-e^+ \to \tilde{\mu}^-\tilde{\mu}^+ \to \mu^-\mu^+\tilde{\gamma}\tilde{\gamma})$

↓

- Discovery limit:

(assuming $B(\tilde{\mu} \to \mu\tilde{\gamma}) = 100\%$)

$\boxed{m_{\tilde{\mu}} \lesssim 0.9\, E_{beam} = 0.9\,\mathrm{TeV}}$ (if $m_{\tilde{\gamma}} \ll m_{\tilde{\mu}}$)

(for $50\,fb^{-1}$ at $\sqrt{s} = 2\,\mathrm{TeV}$)

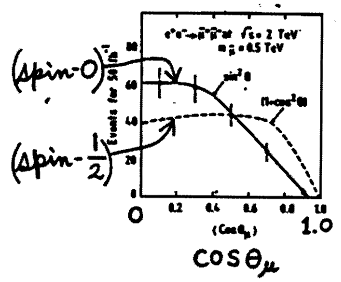
- $\tilde{\mu}$ spin determination:

$$\begin{cases} \dfrac{d\sigma}{d\cos\theta_{\tilde{\mu}}} \propto \underline{\sin^2\theta_{\tilde{\mu}}} & (\text{for } \underline{\text{spin-0}}\ \tilde{\mu}) \\ \qquad\quad \propto \underline{1+\cos^2\theta_{\tilde{\mu}}} & (\text{for } \underline{\text{spin-}\tfrac{1}{2}}\ \tilde{\mu}) \end{cases}$$

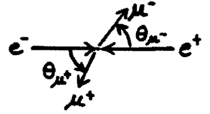
$$\downarrow$$

($\tilde{\mu}$ spin determination by using correlation between $\tilde{\mu}$ and decay μ momentum directions)

decay μ angular distrib.



- after selection cuts
- I : expected error for 50 fb^{-1} (190 ev.)
- $\cos\theta_\mu \equiv \dfrac{|\cos\theta_{\mu^-} + \cos\theta_{\mu^+}|}{2}$



→ (Can distinguish between spin-0 and spin-$\frac{1}{2}$!)

- $\tilde{\mu}$ mass determination:

$$\sigma_{\tilde{\mu}\tilde{\mu}} \propto \beta^3 = \left(1-\left(\frac{m_{\tilde{\mu}}}{E_{beam}}\right)^2\right)^{\frac{3}{2}}$$

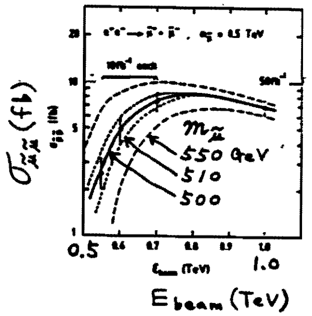
$$\downarrow$$

$\sigma_{\tilde{\mu}\tilde{\mu}}$ is very sensitive to $m_{\tilde{\mu}}$ near the threshold!

$$\downarrow$$

$m_{\tilde{\mu}}$ determination

$\sigma_{\tilde{\mu}\tilde{\mu}}$ v.s. E_{beam} near threshold



→ measurement of $\sigma_{\tilde{\mu}\tilde{\mu}}$ near threshold can determine $m_{\tilde{\mu}}$ with ~2% accuracy for $m_{\tilde{\mu}}$ ~ 500 GeV and 10 fb^{-1}

(2) $e^-e^+ \to \tilde{e}^-\tilde{e}^+$
↳ $e^+\tilde{\gamma}$
↳ $e^-\tilde{\gamma}$

- Analysis similar to $\tilde{\mu}^-\tilde{\mu}^+$

↓

- Discovery limit:

(<u>assuming</u> $B(\tilde{e} \to e\tilde{\gamma}) = 100\%$)

$\boxed{m_{\tilde{e}} \lesssim 0.9\, E_{\mathrm{beam}} = 0.9\ \mathrm{TeV}}$ $\left(\begin{array}{l}\text{if } m_{\tilde{\gamma}} \ll m_{\tilde{e}} \\ \ \& \ m_{\tilde{q}} \approx 1\ \mathrm{TeV}\end{array}\right)$

(for $50\ fb^{-1}$ at $\sqrt{s} = 2\ \mathrm{TeV}$)

(3) $e^-e^+ \to \tilde{\tau}^-\tilde{\tau}^+$
↳ $\tau^+\tilde{\gamma}$
↳ $\tau^-\tilde{\gamma}$

- Analysis similar to $\tilde{\mu}^-\tilde{\mu}^+$

↓

- Discovery limit:

(<u>assuming</u> $B(\tilde{\tau} \to \tau\tilde{\gamma}) = 100\%$)

$\boxed{m_{\tilde{\tau}} \lesssim 0.8\, E_{\mathrm{beam}} = 0.8\ \mathrm{TeV}}$ (if $m_{\tilde{\gamma}} \ll m_{\tilde{\tau}}$)

(for $50\ fb^{-1}$ at $\sqrt{s} = 2\ \mathrm{TeV}$)

(4) $e^-e^+ \to \tilde{q}\,\overline{\tilde{q}}$
↳ $\bar{q}\tilde{\gamma}$
↳ $q\tilde{\gamma}$

- Signature (for $m_{\tilde{q}} > m_{\tilde{g}}$):

$e^-e^+ \to \tilde{q}\,\overline{\tilde{q}}$
↳ $\bar{q}\tilde{\gamma}$
↳ $q\tilde{\gamma}$

$\boxed{\text{"acoplanar jet pair + large } \not{p}_T}$

- Background:

$e^-e^+ \to q\bar{q}(g)$ (main b.g.)
↳ $\bar{q}'\ell\nu$
↳ $q'\ell\nu$

<u>$\sigma_{\mathrm{signal}} \sim \sigma_{\mathrm{b.g.}}$</u> (for $m_{\tilde{q}} \lesssim 0.8\ \mathrm{TeV}$ at $\sqrt{s} = 2\ \mathrm{TeV}$)

↓

<u>Background is not serious</u>!

- Discovery limit: (<u>assuming $B(\tilde{q} \to q\tilde{\gamma}) = 100\%$</u>)

$\boxed{m_{\tilde{q}} \lesssim 0.9\, E_{\mathrm{beam}} = 0.9\ \mathrm{TeV}}$ (if $m_{\tilde{\gamma}} \ll m_{\tilde{q}}$)

(for $50\ fb^{-1}$ at $\sqrt{s} = 2\ \mathrm{TeV}$)

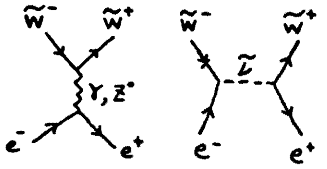
(5) $e^- e^+ \to \tilde{W}^+ \tilde{W}^-$

$\hookrightarrow W^- \tilde{\gamma}$

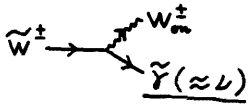
$\hookrightarrow W^+ \tilde{\gamma}$

- *Signature:*

($\tilde{w}$ *prod.*)

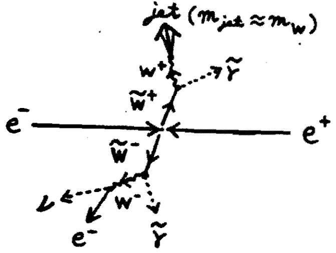


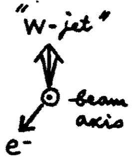
($\tilde{w}$ *decay*)



(*dominant if* $m_{\tilde{w}} < m_{\tilde{\ell}}$ & $m_{\tilde{q}}$)

(*Signature*)





Signature: *acoplanar* (e^- - *jet*) *pair* + *large* $p\!\!\!/_T$
($m_{jet} \approx m_W$)

- *Backgrounds:*

(i) $e^- e^+ \to W\,W$, $W \hookrightarrow e\nu$, $W \hookrightarrow jet$

(*almost coplanar* e-jet with $E_{jet} \approx E_{beam}$)

(ii) $e^- e^+ \to \underbrace{e^- e^+}_{} W^+ W^-$, $W^- \hookrightarrow e\nu$, $W^+ \hookrightarrow jet$ (*almost coplanar* e-jet)

$\hookrightarrow$ (forward detector gap)

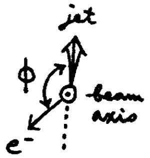
(iii) $e^- e^+ \to e\,\nu\,Z^0\,W$, $W \hookrightarrow e\nu$, $Z^0 \hookrightarrow jet$ (*acoplanar* e-jet)

$e \hookrightarrow$ (f.d. gap)

$\downarrow$

All of these backgrounds can be eliminated (or suppressed) by imposing

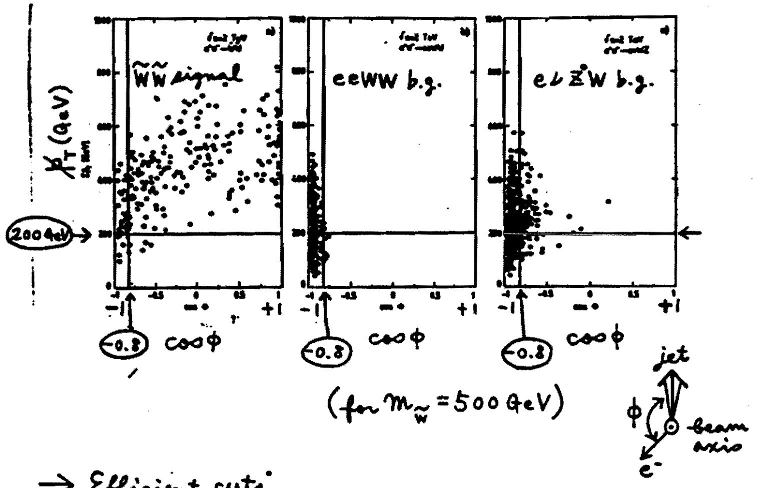
- × $p\!\!\!/_T$ cut
- × acoplanarity angle (ϕ) cut



without any significant loss of the signal events $e^- e^+ \to \underline{\tilde{w}^- \tilde{w}^+} \to \underline{e^-\ jet}\,\nu\,\tilde{\gamma}\,\tilde{\gamma}$!

- Selection cut:

Scatter plot of MC events in $(\not{p}_T, \cos\phi)$ plane



(for $m_{\tilde{W}} = 500$ GeV)

→ Efficient cuts:

$$\begin{cases} \times\ \cos\phi > \boxed{-0.8} \\ \times\ \not{p}_T > \boxed{200\ \mathrm{GeV}} \end{cases}$$

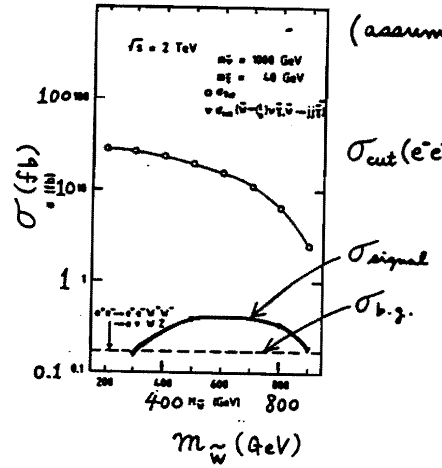
Selection cuts:

- Production angle cut: $\cos\theta < 0.87$ (lepton)
  < 0.94 (jet)
- Energy cut: E_e & $E_{jet} > 100$ GeV
  $E_{jet} < 0.7\, E_{beam}$ (to eliminate $e^-e^+ \to W^+W^-$ b.g.)
- $\not{p}_T$ cut: $\not{p}_T > 200$ GeV
- acoplanarity angle cut: $\cos\phi > -0.8$

↓

- $\sigma^{\tilde{W}\tilde{W}}_{signal} \approx 0.34$ fb (for $m_{\tilde{W}} = 800$ GeV)
  $\vee$
- $\sigma_{b.g.} \lesssim 0.2$ fb
  (at $\sqrt{s} = 2$ TeV)

- Cross section after selection cuts:



(assume: $B(\tilde{w} \to W\tilde{\gamma}) = 100\%$)

$\sigma_{cut}(e^-e^+ \to \underline{\tilde{W}^+\tilde{W}^-} \to \underline{e^- jet}\, \nu\, \tilde{\gamma}\tilde{\gamma})$

σ_{signal}

$\sigma_{b.g.}$

↓

- Discovery limit:
  (assuming $B(\tilde{w} \to W\tilde{\gamma}) = 100\%$)

$$\boxed{m_{\tilde{W}} \lesssim 0.8\, E_{beam} = 0.8\ \mathrm{TeV}} \quad \left(\begin{array}{l} \text{if } m_{\tilde{\gamma}} \ll m_{\tilde{W}} \\ m_{\tilde{\nu}} \approx 1\ \mathrm{TeV} \end{array} \right)$$

(for $50\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 2$ TeV)

§ 3-2 Complication (gaugino-higgsino mixing case)

Refs.:
(1) Ahn et al., SLAC-Report-329 (1988)
(2) Baer et al., Univ. Wisconsin preprint MAD/PH/422 (1988)
(3) Gunion-Haber, P.R. D37, 2515 (1988)
(4) Baer et al., P.R. D36, 96 (1987)
(5) Barnett et al., P.R.L. 60, 401 (1988) and P.R. D37, 1892 (1988)
(6) Baer et al., Proc. of the SSC Workshop, Berkeley (1987) P210
(7) Baer et al., Florida State Univ. preprint FSU-HEP-890223 (1989)

- gaugino-higgsino mixing effect:

The mixing makes susy search very complicated and rich!

- gaugino-higgsino mixing (in MSSM):

$$\underbrace{\widetilde{W}^{\pm},\ \widetilde{H}^{\pm}_{1,2}}\ \text{(interaction eigenstates)}$$
$$\Big\downarrow \text{mixing}$$
$$\overbrace{\widetilde{W}^{\pm}_{(-)},\ \widetilde{W}^{\pm}_{(+)}}\ \text{(mass eigenstates)}$$
(2 charginos)

$$\underbrace{\widetilde{\gamma},\ \widetilde{Z}^{0},\ \widetilde{H}^{0}_{1},\ \widetilde{H}^{0}_{2}}\ \text{(interaction eigenstates)}$$
$$\Big\downarrow \text{mixing}$$
$$\overbrace{\underbrace{\widetilde{Z}^{0}_{1}}_{\uparrow\ \text{(LSP)}},\ \widetilde{Z}^{0}_{2},\ \widetilde{Z}^{0}_{3},\ \widetilde{Z}^{0}_{4}}\ \text{(mass eigenstates)}$$
(4 neutralinos)

- Basic mixing parameters:

$$\begin{cases} M\ (\equiv M_{\tilde{g}}): & \text{gaugino mass parameter} \\ \mu\ (\equiv 2m_1): & \text{higgsino mass parameter} \\ \dfrac{v_2}{v_1}\ (\equiv \tan\beta): & \text{ratio of vacuum expect. values of 2 higgs scalars } H_1^0 \text{ and } H_2^0 \end{cases}$$

These 3 parameters determine everything, i.e., masses and couplings of the charginos and neutralinos !!

- Basic parameters in MSSM:

$\left(M,\ \mu,\ \frac{v_2}{v_1},\ m_{H^{\pm}},\ m_{\tilde{q}}\right)$ determine everything of susy phenomenology including higgs scalars !!

(1) Chargino & neutralino decay

- Possible decays:

  (for $(m_{\tilde{q}}$ & $m_{\tilde{g}}) > (m_{\tilde{W}_i}$ & $m_{\tilde{Z}_i}) > (m_W$ & $m_Z)$)

(basic decay kernels)

$\tilde{W}_i \to W\,\tilde{Z}^0_j$

$\quad\to Z^0\,\tilde{W}_j$

$\quad\to H^0_i\,\tilde{W}_j$

$\qquad\hookrightarrow b\bar{b}\ (m_{H^0_i} < m_Z)$

,

$\tilde{Z}^0_i \to W\,\tilde{W}_j$

$\quad\to Z^0\,\tilde{Z}^0_j$

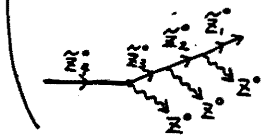
$\quad\to H^0_i\,\tilde{Z}^0_j$

$\qquad\hookrightarrow b\bar{b}$

$\downarrow$

($W^{\pm}_{on}$, Z^0_{on} in final state!)

(note) (Possible cascade decays:



$\to$ multi Z^0's in final state!

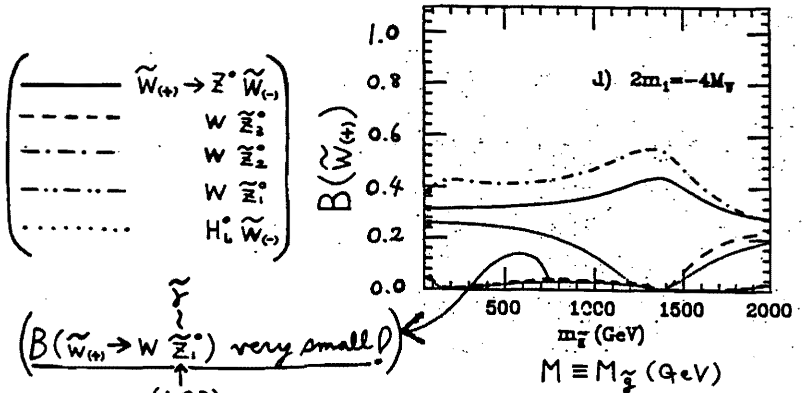
etc. etc. ⋯)

- Branching ratio:

  BR depend on details of mass spectrum and couplings of sparticles (, i.e., on the 5 basic parameters).

  For example;

  for $\begin{cases} M (\equiv M_{\tilde{g}}) \\ \mu (\equiv 2m_1) = -4\, m_W \\ \frac{v_2}{v_1} = 0.5 \\ m_{H^\pm} = 500 \text{ GeV} \end{cases}$



($B(\tilde{W}_{(+)} \to W\,\overset{\tilde{\gamma}}{\tilde{Z}^0_1})$ very small!)

(LSP)

(Cf. $B(\tilde{W} \to W\tilde{\gamma}) \simeq 100\%$ in simple picture)

- $\tilde{W}_i^{\pm}$ & $\tilde{Z}_i^0$ signature in e^-e^+ collider:

$e^-e^+ \to \tilde{W}_i^+ \tilde{W}_j^-$

$\quad \tilde{W}_j^- \to W^- \tilde{Z}_1^0$ } direct decay into LSP

$\quad \tilde{W}_j^- \to Z^0 \tilde{W}_k^-$, $\tilde{W}_k^- \to W^- \tilde{Z}_1^0$

$\quad \tilde{W}_j^- \to H_L^0 \tilde{W}_k^-$, $\tilde{W}_k^- \to W^- \tilde{Z}_1^0$, $H_L^0 \to b\bar{b}$ } cascade decays

$\quad \tilde{W}_i^+ \to$ (the same)

$e^-e^+ \to \tilde{Z}_i^0 \tilde{Z}_j^0$

$\quad \tilde{Z}_j^0 \to Z^0 \tilde{Z}_1^0$ } direct decay into LSP

$\quad \tilde{Z}_j^0 \to W \tilde{W}_k$, $\tilde{W}_k \to W \tilde{Z}_1^0$

$\quad \tilde{Z}_j^0 \to H_L^0 \tilde{Z}_k^0$, $\tilde{Z}_k^0 \to Z^0 \tilde{Z}_1^0$, $H_L^0 \to b\bar{b}$ } cascade decays

$\quad \tilde{Z}_i^0 \to$ (the same)

→ Typical signature: "(m-weak-bosons)+(n-jets)+$\not{p}_T$"
(m ≧ 2, n ≧ 0)

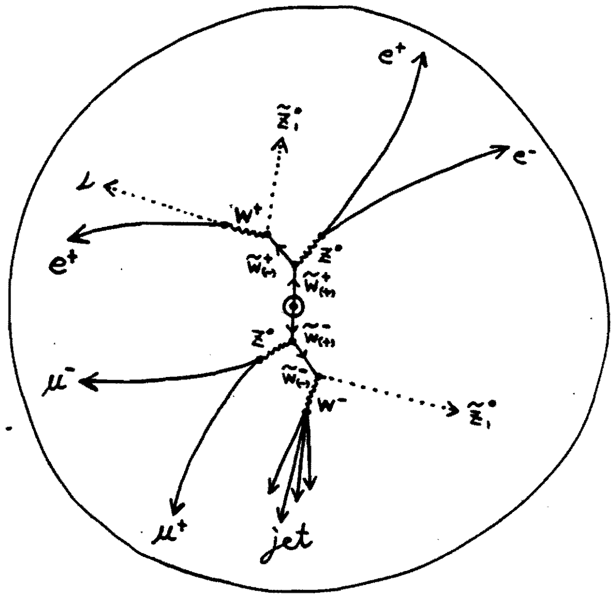
(Detailed MC analysis not yet done.)

For example;

$e^-\ e^+ \to \tilde{W}_{(+)}^+ \tilde{W}_{(+)}^-$

$\quad \tilde{W}_{(+)}^- \to Z^0 \tilde{W}_{(-)}^-$, $\tilde{W}_{(-)}^- \to W^- \tilde{Z}_1^0$

$\quad \tilde{W}_{(+)}^+ \to Z^0 \tilde{W}_{(-)}^+$, $\tilde{W}_{(-)}^+ \to W^+ \tilde{Z}_1^0$



(2) Slepton decay

- Possible decays:

(for large $m_{\tilde{e}}$)

$\tilde{e}_L \to e\,\tilde{Z}_1^0$ } direct decay into LSP

$\to e\,\tilde{Z}_i^0$

$\quad \hookrightarrow Z^0\,\tilde{Z}_1^0$ etc.

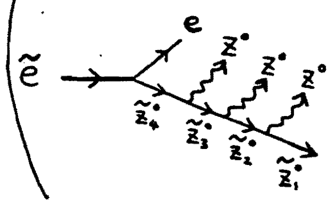
$\to \nu\,\tilde{W}_j$

$\quad \hookrightarrow W\,\tilde{Z}_1^0$ etc. } cascade decays

$\downarrow$

($W^\pm$, Z^0 in final state!)

(note) Possible cascade decays:



$\to$ multi Z^0's in final state!

etc. etc.

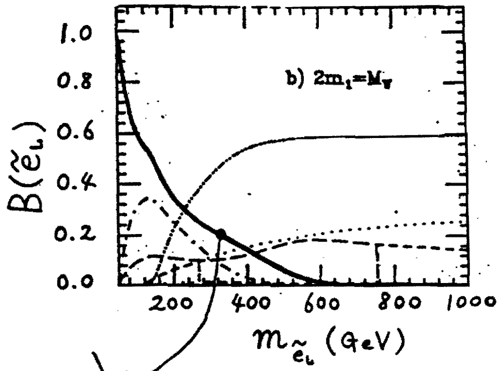
- Branching ratio:

BR depend on the basic parameters.

For example;

$$\text{for}\begin{cases} M(\equiv M_{\tilde{g}}) = m_{\tilde{e}} \\ \mu(\equiv 2m_1) = m_W \\ \dfrac{v_2}{v_1} = 0.5 \end{cases}$$

———	$\tilde{e}_L \to e\,\tilde{Z}_1^0$ (LSP)
– – – –	$e\,\tilde{Z}_2^0$
- - - - - -	$e\,\tilde{Z}_3^0$
·······	$e\,\tilde{Z}_4^0$
–·–·–	$\nu\,\tilde{W}_{(-)}$
–··–··–	$\nu\,\tilde{W}_{(+)}$



($B(\tilde{e}_L \to e\,\underset{\sim}{\tilde{\gamma}}\tilde{Z}_1^0)$ very small

for large $m_{\tilde{e}_L}$!)

- $\tilde{e}$ signature in $e^- e^+$ collider:

$$e^- e^+ \to \tilde{e}_L^- \tilde{e}_L^+$$

$\tilde{e}_L^+ \to e\,\tilde{Z}_1^0$ } direct decay into LSP

$\tilde{e}_L^+ \to e\,\tilde{Z}_i^0$
  $\hookrightarrow Z^0 \tilde{Z}_1^0$ etc.

$\tilde{e}_L^+ \to \nu\,\tilde{W}_j$
  $\hookrightarrow W \tilde{Z}_1^0$ etc.

} cascade decays

$\tilde{e}_L^- \to$ (the same)

$\downarrow$

Typical signature:

"(m-charged-leptons) + (n-weak-bosons) + $\not{p}_T$"

$(2 \geqq m \geqq 0,\ n \geqq 0)$

- Discovery limit:

$$\boxed{m_{\tilde{e}} \lesssim 0.8\,E_{beam} = 0.8\ \mathrm{TeV}}\ \text{(supposed)}$$

(for $10\ fb^{-1}$ at $\sqrt{s} = 2$ TeV)

(Detailed cut analysis not yet done.)

(3) Squark decay

- Possible decays
- Branching ratio
- $\tilde{q}$ signature in $e^- e^+$ collider

} similar to slepton.

(4) Gluino decay

- Possible decays:

$\tilde{g} \to q\bar{q}\,\tilde{Z}_1^0$(LSP) } direct decay into LSP

$\tilde{g} \to q\bar{q}\,\tilde{Z}_i^0$
  $\hookrightarrow Z^0 \tilde{Z}_1^0$ etc.

$\tilde{g} \to q\bar{q}'\,\tilde{W}_j$
  $\hookrightarrow W \tilde{Z}_1^0$ etc.

} cascade decays

- Cascade decay effect on CDF $m_{\tilde{g}}$ limit:

(cascade decay of $\tilde{g}$)

$\downarrow$

(softer LSP than usual direct decay $\tilde{g} \to q\bar{q}\tilde{\gamma}$)

$\downarrow$

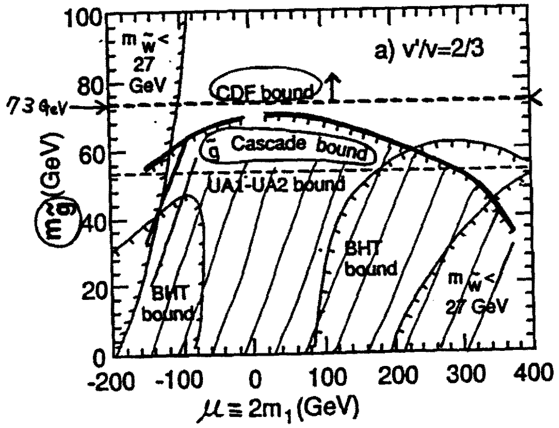
(smaller $\not{p}_T$ than usual ")

$\downarrow$

- (Reduce the CDF $m_{\tilde{g}}$ limit by as much as 30 GeV !)

$\boxed{(m_{\tilde{g}}, \mu) \text{ region excluded by CDF data}}$

(for $\frac{v_2}{v_1} = \frac{2}{3}$, $m_{\tilde{q}} = 2 m_{\tilde{g}}$, $m_{H^+} = 0.5$ TeV)



§4 Comments and Conclusion

(1) Susy physics reach at present and future colliders:

Physics reach at lower energy colliders

Measured and expected SUSY limits

Reactions	Mass limit (GeV)	LEP I $\sqrt{s}$ 110 GeV (GeV)	LEP II $\sqrt{s}$ = 190 GeV (GeV)	$p\bar{p}$ colliders (GeV)	Model assumptions
$e^+e^- \to \tilde{e}\tilde{e}$ $\tilde{e}e\tilde{\gamma}$ $\gamma\tilde{\gamma}\tilde{\gamma}$	$m_{\tilde{e}} \geq 22^{a)}$ $\geq 30^{a)}$ $(^*) \geq 58^{b)}$	≥ 50 ≥ 60 -	≥ 90 - -	- - -	$\tilde{e} \to e\tilde{\gamma}$ $m_{\tilde{\gamma}} = 0$ $m_{\tilde{\gamma}} = 0$
$e^+e^- \to \tilde{\mu}\tilde{\mu}$ $\tilde{\tau}\tilde{\tau}$	$m_{\tilde{\mu}} \geq 21^{a)}$ $m_{\tilde{\tau}} \geq 20^{a)}$	≥ 50 ≥ 50	≥ 85 ≥ 75	- -	$\tilde{\mu} \to \mu\tilde{\gamma}$ $\tilde{\tau} \to \tau\tilde{\gamma}$
$e^+e^- \to \tilde{q}\tilde{q}$ $p\bar{p} \to \tilde{q}\tilde{q}$	$m_{\tilde{q}} \geq 21^{a)}$ $m_{\tilde{q}} \geq 45^{c\,A)}$	≥ 50 -	≥ 85 -	- $100^{d)}$ $200^{e)}$	$\tilde{q} \to q\tilde{g}$ or $\tilde{q} \to q\tilde{\gamma}$ $m_{\tilde{g}}$ large
$p\bar{p} \to \tilde{g}\tilde{g}$	$m_{\tilde{g}} \geq 53^{c\,A)}$	-	-	$100^{d)}$ $200^{e)}$	$m_{\tilde{q}}$ large
$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$	$m_{\tilde{\gamma}} \geq 20^{a)}$	$50^{e)}$	$80^{e)}$	-	$\tilde{\gamma}$ unstable
$e^+e^- \to \tilde{W}\tilde{W}$ $\tilde{W}e\tilde{\nu}$ $\gamma\tilde{\nu}\tilde{\nu}$	$m_{\tilde{W}} \geq 22.5^{a)}$ $\geq 26^{a)}$ $(^*) \geq 57^{b)}$	≥ 50 ≥ 60 -	≥ 80 - -	≥ 50 from $p\bar{p} \to WX$ $\to \tilde{W}\tilde{\gamma}$	$\tilde{W} \to$ "W*" $\tilde{\gamma}$ $m_{\tilde{\nu}} = 0$ $m_{\tilde{\nu}} = 0$
$e^+e^- \to \tilde{Z}\tilde{\gamma}$	$m_{\tilde{Z}} \geq 35^{a)}$	≥ 60	≥ 90 ($\sqrt{s}$ = 160 GeV)		$m_{\tilde{\gamma}}$ small

a) Limits from PETRA experiments (CELLO, JADE, MARK J, TASSO).
b) Limits from PEP experiments (ASP, MAC, MARK II).
c) CERN $p\bar{p}$ Collider (A = UA1).
d) Fermilab $p\bar{p}$ Collider.
e) Educated guesses.
All limits are given with 95% CL [but (*) means 90% CL].

$$\longrightarrow \boxed{\tilde{m} \lesssim O(100)\ \text{GeV}}$$

$$\left(\because \sqrt{\hat{s}} \sim O(100)\ \text{GeV}\right)$$

Physics reach at multi-TeV colliders

Comparison of possible mass limits from the different accelerators

sparticle type	hh $\sqrt{s}$ = 17 TeV	ep $\sqrt{s}$ = 1.8 TeV	e^+e^- $\sqrt{s}$ = 2 TeV ($\int L\,dt$ = 500 fb^{-1})
slepton	$\tilde{e}, \tilde{\mu}$ 300 GeV	$\tilde{e}$ 350 GeV $m_{\tilde{e}} = m_{\tilde{q}}$	$\tilde{e}, \tilde{\mu}, \tilde{\tau}$ 850 GeV
squark	1 TeV $m_{\tilde{q}} < m_{\tilde{g}}$	700 GeV $m_{\tilde{e}}$ = 50 GeV 350 GeV $m_{\tilde{e}} = m_{\tilde{q}}$	850 GeV
wino*	*450 GeV* $m_{\tilde{W}} = m_{\tilde{q}}$	No useful limit	850 GeV
gluino	*1 TeV* $m_{\tilde{g}} < m_{\tilde{q}}$	No useful limit	No useful limit

The limits in italics need more study

$$\longrightarrow \boxed{\tilde{m} \lesssim O(1)\ \text{TeV}}$$

$$\left(\because \sqrt{\hat{s}} \sim O(1)\ \text{TeV}\right)$$

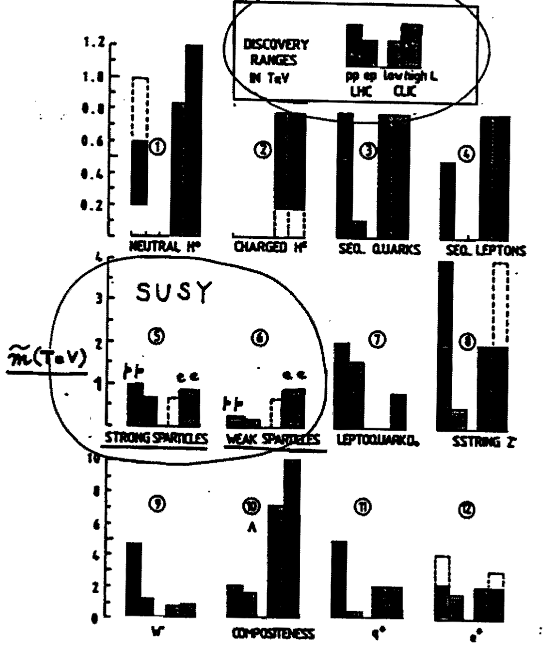


Fig. 15 Summary of the discovery limits expected for 12 different processes. The vertical scale is in TeV and changes by a factor of 4 (2.5) when passing from the first (second) to the second (third) line. The four dashed areas in each diagram refer to the following beam conditions, from left:
proton-proton at E_{cm} = 16 GeV with $L = 10^{34}\ cm^{-2}s^{-1}$;
electron-proton at 1.5 TeV with $L = 10^{32}\ cm^{-2}s^{-1}$;
electron-positron at 2 TeV with $L = 10^{33}\ cm^{-2}s^{-1}$ (indicated for simplicity as 'low' L);
electron-positron at 2 TeV with $L = 4 \times 10^{34}\ cm^{-2}s^{-1}$ ('high' L).
The detailed explanations of the 12 histograms are given in the text. Note that in working out the discovery limits and in compiling the figures, all the quoted luminosities have been taken for granted, even if the CLIC

(2) Beamstrahlung effect:

Beamstrahlung effect has to be taken into account in MC analysis of susy search at TeV e^-e^+ collider

↓

Have to convolute the susy and B.G. cross sections with beam energy spectrum!

(3) R parity violating susy model:

(Ref.: L. Hall, talk at HEP Conf., Munich, 1988)

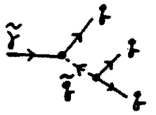
- Signature of sparticle production in R parity violating model:

$$\begin{cases} \text{not } \not p_T \\ \text{but } \Delta L \neq 0 \text{ or } \Delta B \neq 0 \text{ !!} \end{cases}$$

- Example:

LSP {

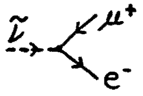
$\tilde{\gamma} \to qqq$



$\left(\dfrac{\Delta B \neq 0}{\text{no } \not p_T}\right)$

or

$\tilde{\nu} \to \mu^+ e^-$



$\left(\dfrac{\Delta L \neq 0}{\text{no } \not p_T}\right)$

(4) Conclusion:

(i) Discovery potential for $(\tilde{q}, \tilde{g})$

$$\begin{cases} \text{at SSC and LHC higher than} \\ \text{at TeV } e^-e^+ \text{ colliders.} \end{cases}$$

(But Cleanliness of susy events at TeV e^-e^+ colliders allows to determine susy parameters (spin, mass etc.) in more detail.)

(ii) Discovery potential for $(\tilde{l}, \tilde{W}_i, \tilde{Z}_i^\circ)$

$$\begin{cases} \text{at TeV } e^-e^+ \text{ colliders higher than} \\ \text{at SSC and LHC.} \end{cases}$$

(iii) Cascade decays of sparticles are expected for large $\tilde{m}$:

Large variety of possible susy signatures including multi-$W^\pm$, Z° in final state

→ $\boxed{\text{needs detailed MC analysis!}}$

(iv) Recall that susy theory expects, on the basis of the hierarchy argument, that all sparticles should weigh $\tilde{m} \lesssim O(1)$ TeV, which is well accessible to multi-TeV supercolliders!

PURELY STRINGY MODEL BUILDING WITH LOWER-RANK GAUGE GROUPS

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§1 INTRODUCTION

Compactification of 10-d heterotic string theory may provide a unified framework for all fundamental interactions in 4-d.

Compactification of 6 space dimensions

(1) Calabi-Yau manifold
    tensor product of minimal N=2 superconformal theories   Gepner

(2) Orbifold
- standard Z orbifold

$$E_8 \times E_8' \longrightarrow E_6 \times SU(3) \times E_8'$$

- orbifold with Wilson lines
  homomorphism of the space group defining the torus into $E_8 \times E_8$
  - gauge symmetry breaking
  - number of generations

  $\Big\} \Rightarrow$ realistic models

$$E_8 \times E_8'$$
$$\hookrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times [U(1)]^4$$

extra $U(1) \longrightarrow Z'$

Rank of the gauge group is not changed and many extra U(1)'s survive.