Phenomenology of Split Supersymmetry
&
Splitting Split Supersymmetry

Kingman Cheung SUSY 2005, Durham, July 2005

(with Wai-Yee Keung PRD)
(with Cheng-Wei Chiang PRD and in progress)
(with Jeonghyeon Song hep-ph/0507113)

Why split SUSY, split split SUSY or Supersplit SUSY?

The magic word: Landscape!!

In reality, Why Not!! These scenarios are not impossible

Outline

- Split SUSY, neutralino and chargino production & decay
- Splitting split SUSY (i) high-μ split
- Splitting split SUSY (ii) low-μ split
- Conclusions

Fine Tuning Principle

We have been guided or sometimes bored by fine tuning.

- New physics comes in around TeV, e.g., technicolors.
- Weak scale supersymmetry.
- Large extra dimension models.
- Little Higgs models
- ... ...

Guiding Principles

What if fine tuning is NO LONGER a guiding principle?

Strongly interacting models at TeV scale, weak-scale supersymmetry, ... are not necessary. SM seems good. But there are observations that cannot be explained by the SM.

Guiding principles:

- dark matter constraint
- gauge coupling unification
- neutrino mass (by a see-saw mechanism at high scale, also good for leptogenesis)
- proton decay constraint
- cosmological constant (accepting the fine tuning as a fact)

Split Supersymmetry

(Arkani, Dimopoulos 2004)

Scenario

- All scalars are super heavy, except for a light SM-like Higgs boson

$$\tilde{m} \sim 10^{9-16}\ \mathrm{GeV}$$

- Gauginos and Higgsinos are $O(\mathrm{TeV})$.

Split Supersymmetry

Properties:

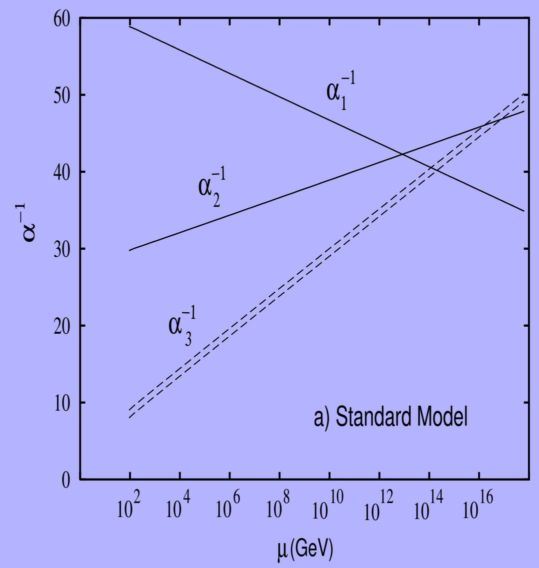
- Gauge coupling unification
- Light SM-like Higgs boson
- Super heavy scalars ⇒ safe FCNC, CP-violation, EDM, but there is still one possible source
- Relatively light gauginos, Higgsinos, μ parameter

  ⇒ Dark Matter

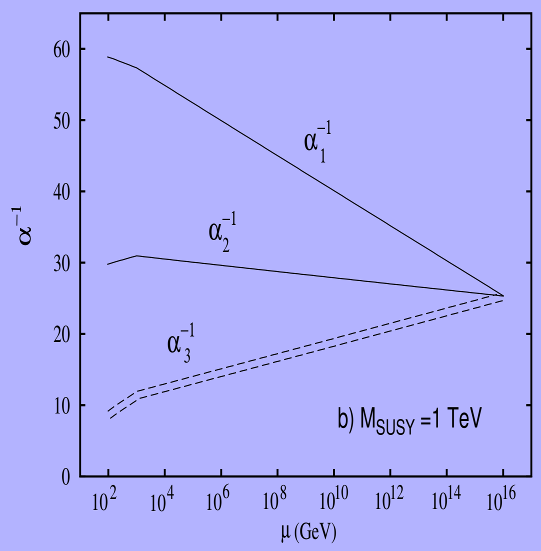
- Stable gluino, gluinonium signature

Gauge Coupling Unification

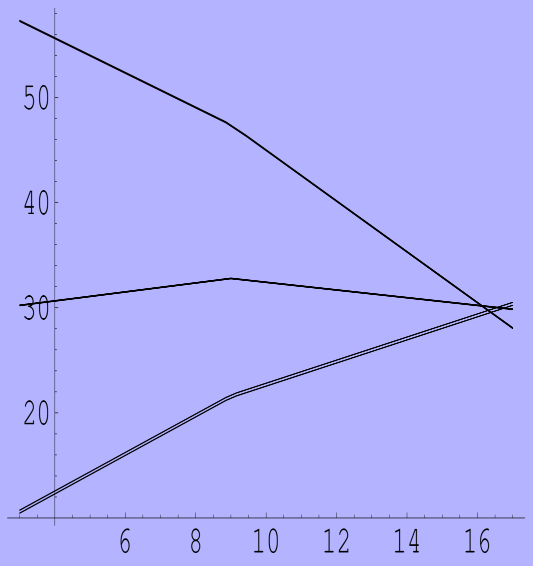
SM



Weak Scale SUSY



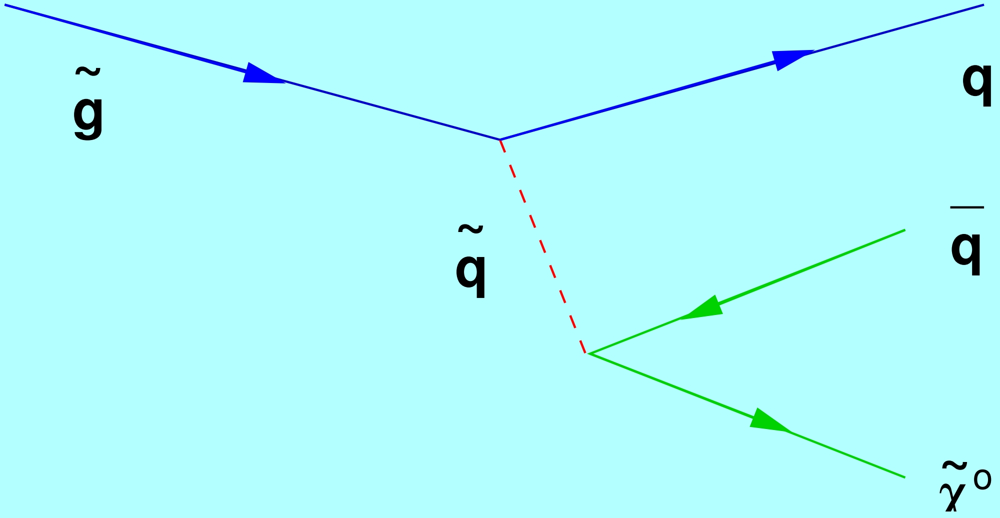
Split SUSY



Ellis, Kelly, Nanopoulos (1991); Arkani, Dimopoulos 2004

Gluino Signature

Decay of gluino has to go through a squark:



$$\tilde{m} \sim 10^{9-16}\ \mathrm{GeV} \Rightarrow \tau_{\tilde{g}} \gtrsim 10^{-2} - 10^{14}\mathrm{s}$$

Gluino is stable within particle detectors.

Gluino Life time

(Arvanitaki, Davis, Graham, Pierce, Wacker; Gambino, Giudice, Slavich)

Life time of the gluino (TeV) should be less than the age of the Universe, 14 Gyr:

$$\tilde{m} < 10^{13}\ \mathrm{GeV}$$

A TeV mass gluino must have a lifetime < 100 sec, so as not to alter the abundance of D and ^{6}Li.

$$\tau_{\tilde{g}} < 100\ \mathrm{s} \qquad \Rightarrow \qquad \tilde{m} \lesssim 10^9\ \mathrm{GeV}$$

Stable gluino-hadron

- Hadronize into a massive stable particle.
- Electrically either neutral or charged, depending on the mass spectrum.
- The heavy neutral particle will go through the detector unnoticed, very small energy loss.
- Charged particles also undergo ionization energy loss, via which it can be detected. It happens in central vertex detector and also in muon chamber.

(Kilian et al.; Hewett et al.; Anchordoqui et al.; KC and Keung)

Experimentally, the massive stable charged particle will produce a track in the central tracking and/or silicon vertex system, where dE/dx and p can be measured.

$$\beta\,\gamma = \frac{p}{E}\,\frac{E}{M} = \frac{p}{M} \lesssim 0.85$$

The particle is required to penetrate to the outer muon chamber.

$$0.25 - 0.5 \lesssim \beta\,\gamma$$

c.f. CDF Coll. used a criteria: $0.26 - 0.5 \lesssim \beta\gamma \lesssim 0.86$, but it is for a particle of mass of $50 - 500$ GeV only.

Cross sections at the LHC.

$\sigma_{1\mathrm{MCP}}$, $\sigma_{2\mathrm{MCP}}$ denote requiring the detection of 1, 2 massive stable charged particles (MCP) in the final state.

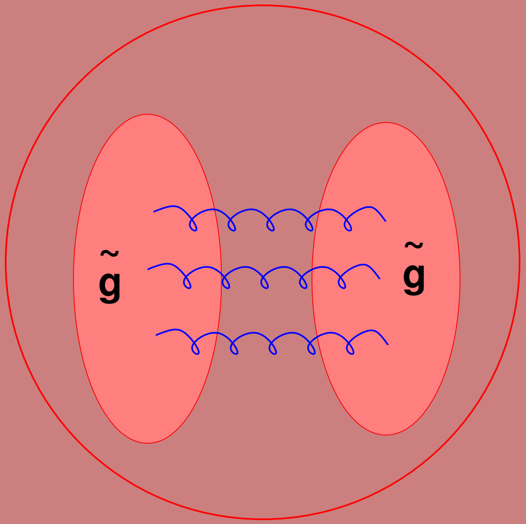
$m_{\tilde g}$ (TeV)	$\sigma_{1\mathrm{MCP}}$ (fb) $P = 0.5$	$\sigma_{2\mathrm{MCP}}$ $P = 0.5$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.5$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.1$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.01$
0.5	4050	620	4670	1040	105
1.0	67	13	80	18	1.9
1.5	3.7	0.91	4.6	1.1	0.11
2.0	0.3	0.09	0.39	0.09	0.0096

$P \equiv$ probability that $\tilde g$ fragments into charged R-hadron

Gluinonium

(KC and Keung)

Gluinos are stable, exchange gluons to form a bound state.



$$\begin{aligned} \text{Color} \quad &: \quad \mathbf{8} \otimes \mathbf{8} = \mathbf{1} + \mathbf{8}_S + \mathbf{8}_A + \mathbf{10} + \overline{\mathbf{10}} + \mathbf{27} \\ \text{S-wave, Spin} \quad &: \quad {}^1S_0(\text{antisymmetric}),\ {}^3S_1(\text{symmetric}) \end{aligned}$$

Possible configurations: ${}^1S_0(\mathbf{1})$, ${}^1S_0(\mathbf{8}_S)$, and ${}^3S_1(\mathbf{8}_A)$

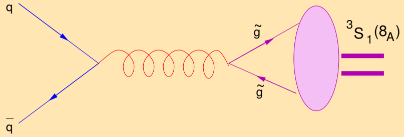
Hadronic Production of Gluinonium $^3S_1(\mathbf{8}_A)$

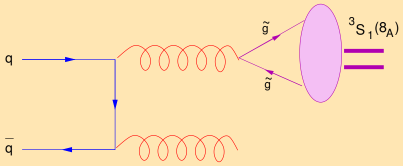
The lowest order process for $^3S_1(\mathbf{8}_A)$

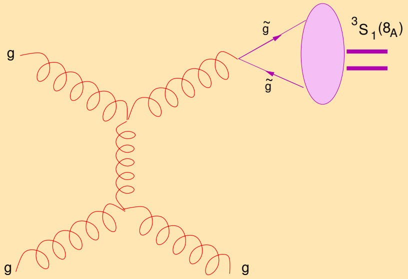
$$q\bar{q} \to ^3 S_1(\mathbf{8}_A)$$

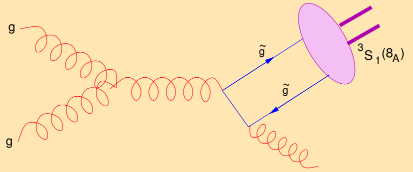
The next order include

$$\begin{aligned} q\bar{q} &\to {}^3S_1(\mathbf{8}_A) + g \\ qg &\to {}^3S_1(\mathbf{8}_A) + q \\ gg &\to {}^3S_1(\mathbf{8}_A) + g \end{aligned}$$

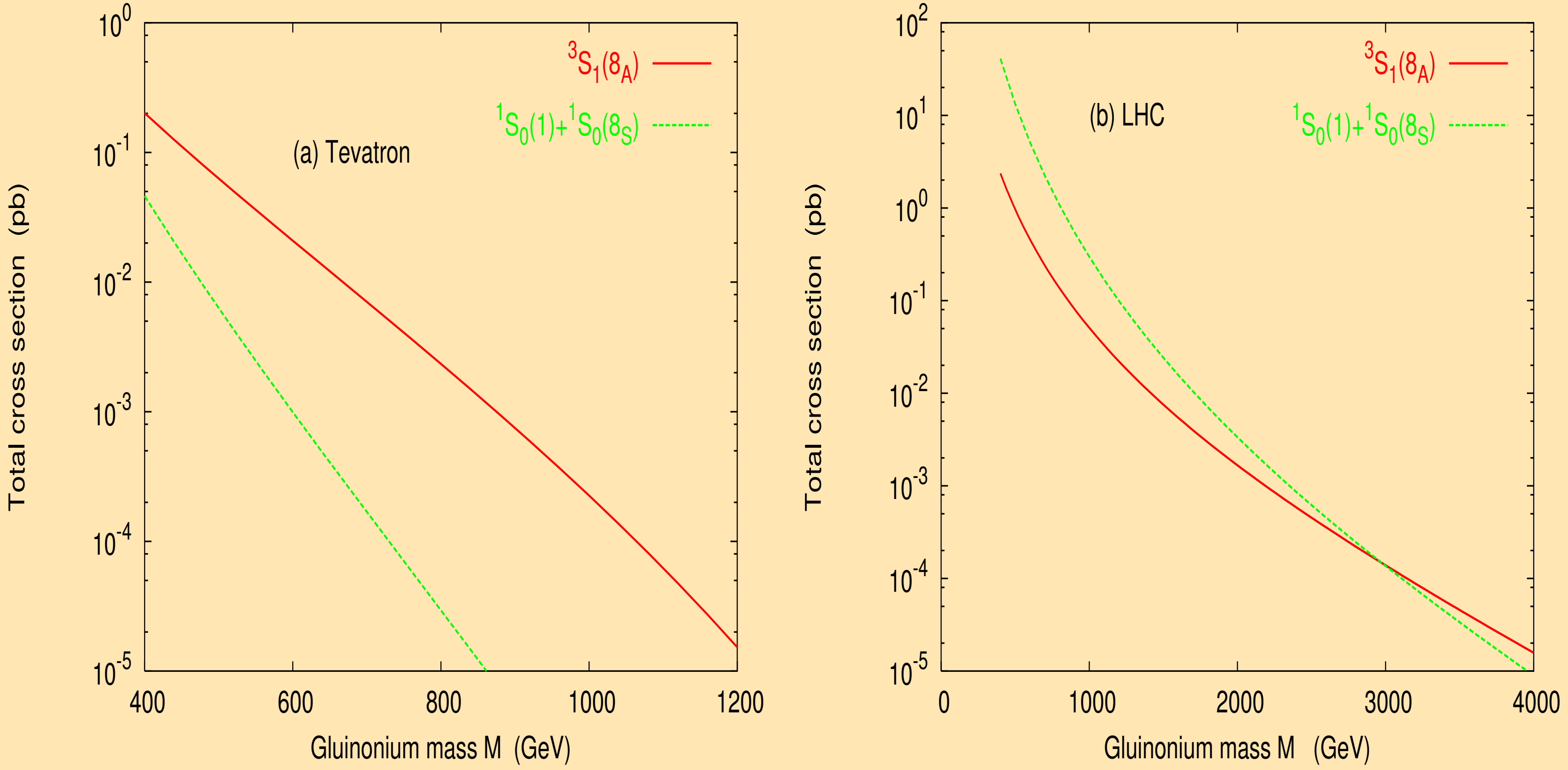








Hadronic Production of Gluinonium ...



Detection & Background analysis

$$\begin{aligned} {}^1S_0(\mathbf{1},\mathbf{8}_S) &\longrightarrow gg \\ {}^3S_1(\mathbf{8}_A) &\longrightarrow q\bar{q} \end{aligned}$$

buried under huge QCD background.

$$ {}^3S_1(\mathbf{8}_A) \to t\bar{t},\ b\bar{b} $$

have the potential feasibility for observation.

Irreducible background comes from QCD $t\bar{t}$ or $b\bar{b}$

Dark Matter

(Pierce; Masiero, Profumo and Ullio; Giudice, Romanino)

Dark matter constraint

$$0.094 < \Omega_{\rm DM} h^2 < 0.129$$

Preferred regions of split SUSY

1. Bino-like with $M_1 \sim \mu$
$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to Z^* \to f \bar{f}$$
2. Higgino-like with $M_{1,2} \gg \mu$. Annihilate via Z^*.
3. Wino-like with $M_2 < M_1, \mu$. Large annihilation rates mean heavier wino mass $(2 - 2.5$ TeV) to satisfy the DM.

Neutralinos and Charginos

(KC and J. Song, hep-ph/0507113)

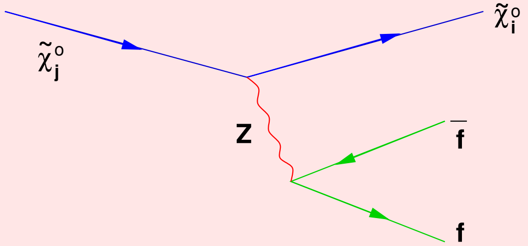
- Production and decay via intermediate $\tilde{f}$ disappear.
- Direct production via Drell-Yan-like processes (γ, Z^*, W^*).
- Neutralino decays via

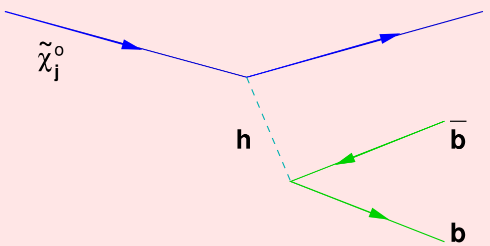
$$\begin{aligned}
\widetilde{\chi}^0_j &\rightarrow \widetilde{\chi}^0_i Z^* \rightarrow \widetilde{\chi}^0_i f \bar{f} \\
\widetilde{\chi}^0_j &\rightarrow \widetilde{\chi}^\pm_i W^* \rightarrow \widetilde{\chi}^0_i f \bar{f}' \\
\widetilde{\chi}^0_j &\rightarrow \widetilde{\chi}^0_i h^* \rightarrow \widetilde{\chi}^0_i b\bar{b} \\
\widetilde{\chi}^0_j &\xrightarrow{\widetilde{\chi}^+ W^- loop} \tilde{\chi}^0_i \gamma
\end{aligned}$$

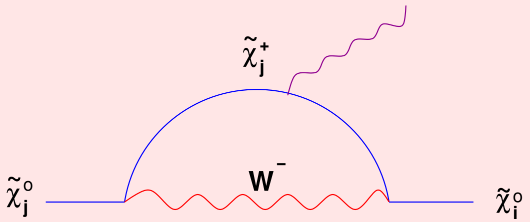
- Chargino decays via

$$\tilde{\chi}^+_j \rightarrow \tilde{\chi}^0_i W^* \rightarrow \tilde{\chi}^0_i f \bar{f}'$$

Decays of Neutralinos







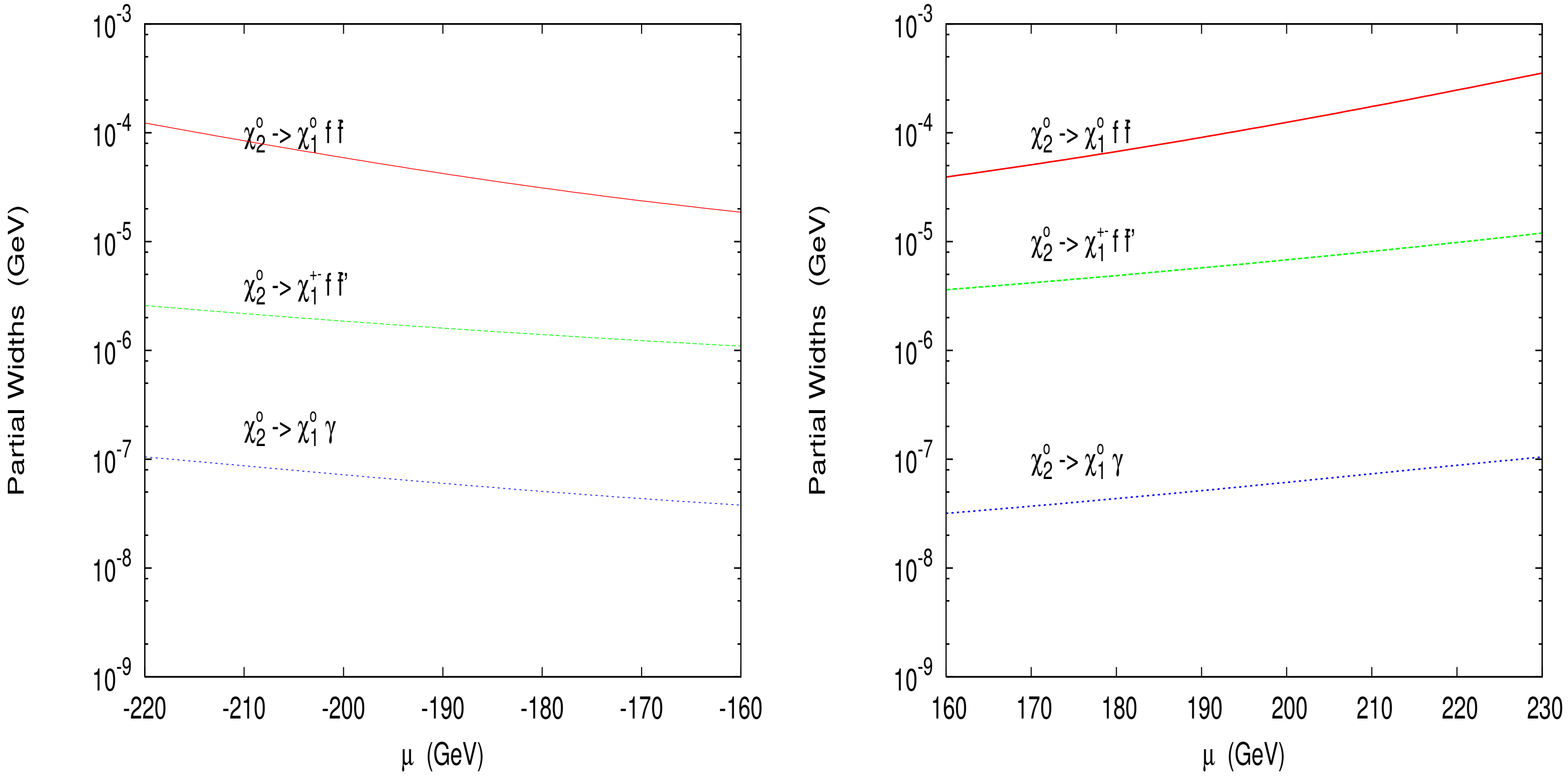
Aim: to enhance the $\tilde\chi^0_j \to \tilde\chi^0_i + \gamma$ by suppressing the $Z - \tilde\chi^0_j - \tilde\chi^0_i$ couplings:

$$O''^L_{ij} = -O''^R_{ij} = \frac{1}{2}(N_{i4}N^*_{j4} - N_{i3}N^*_{j3})$$

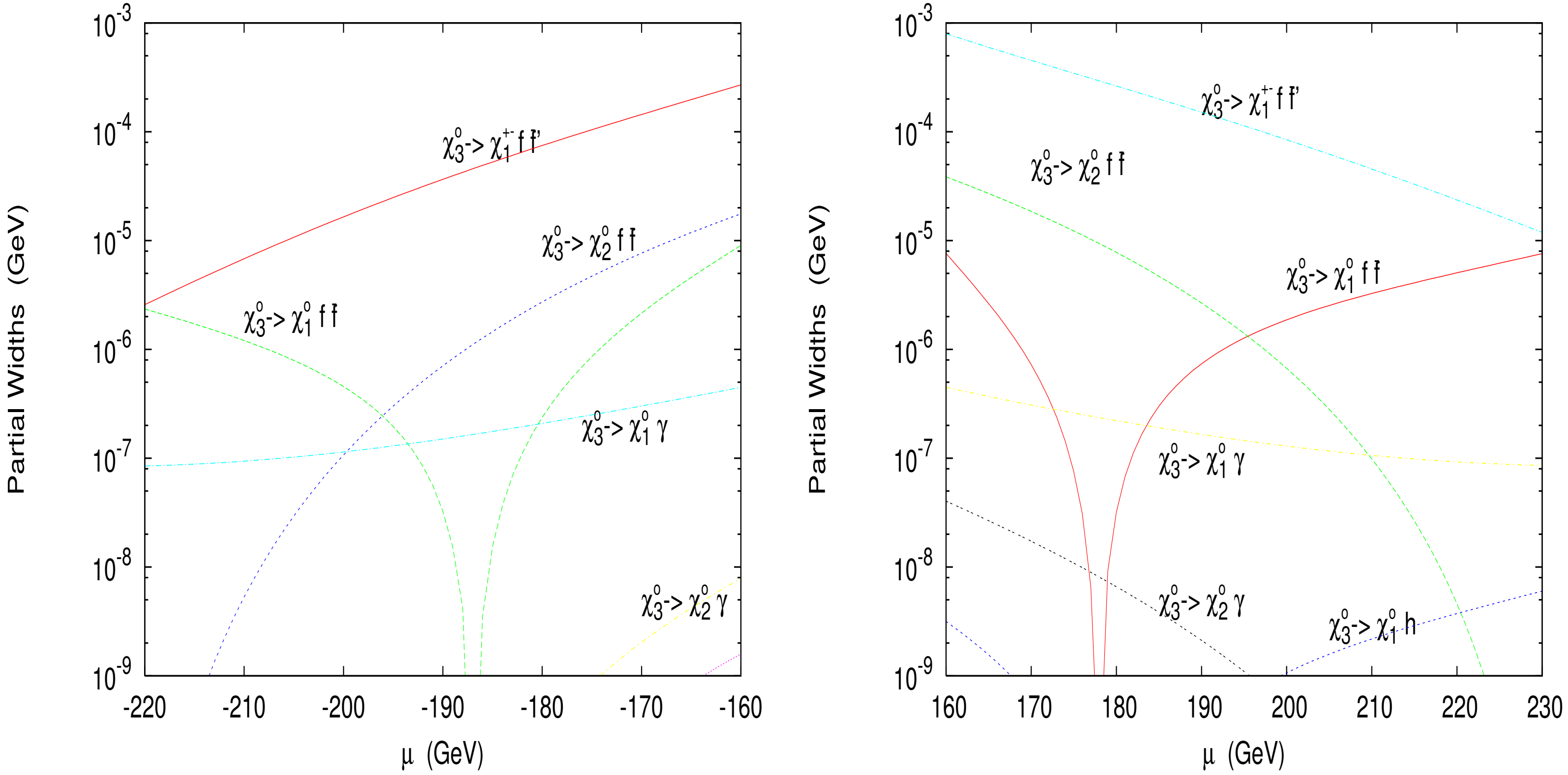
It is possible but needs fine tuned relation between μ and M_1. Specifically, need

$$M_1 \sim |\mu|$$

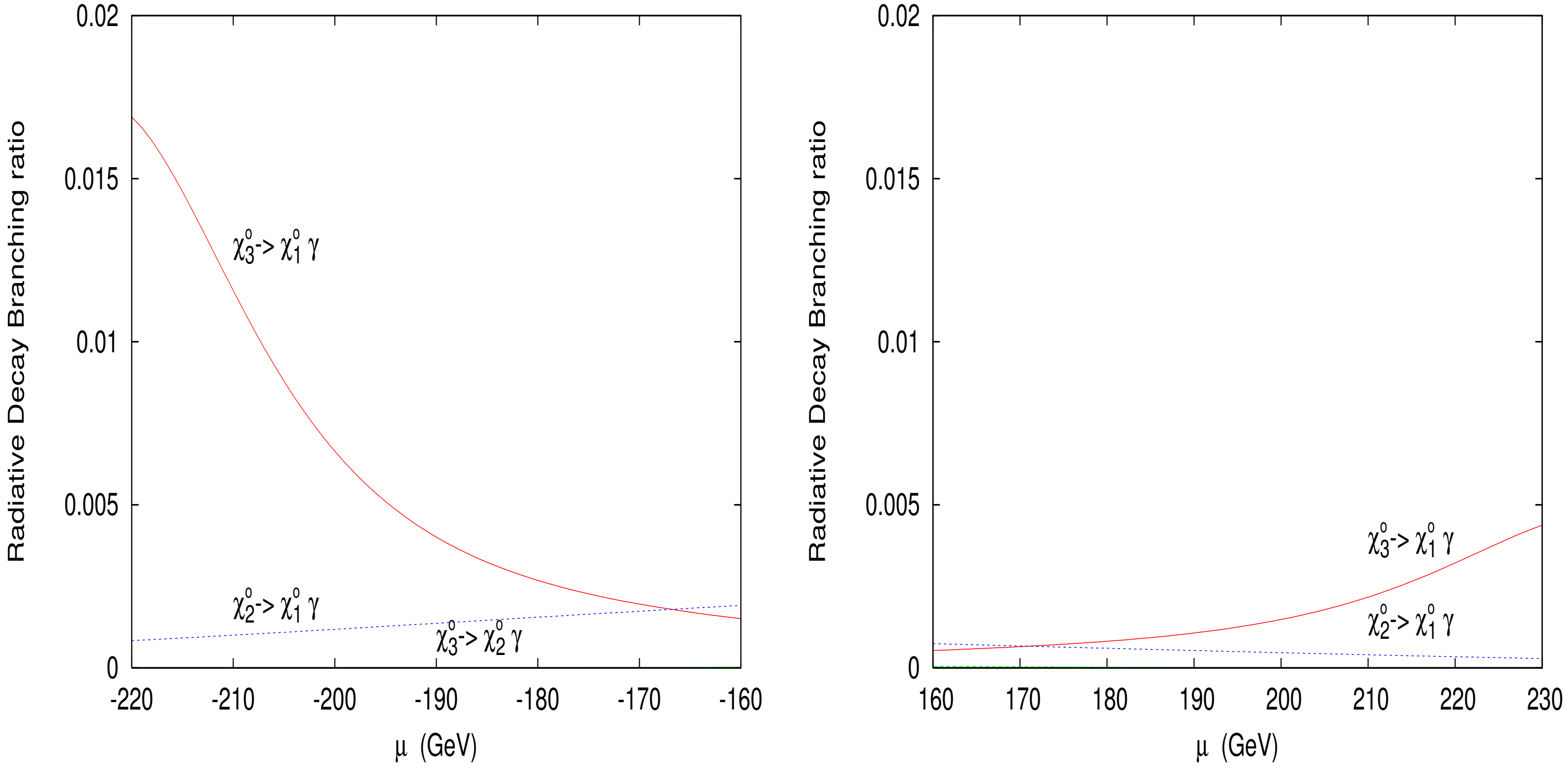
Potentially, observe mono-photon plus missing energy signature at hadron colliders.



$\widetilde{\chi}_2^0$ decay widths, $M_1 = 200$ GeV



$\widetilde{\chi}_3^0$ decay widths, $M_1 = 200$ GeV

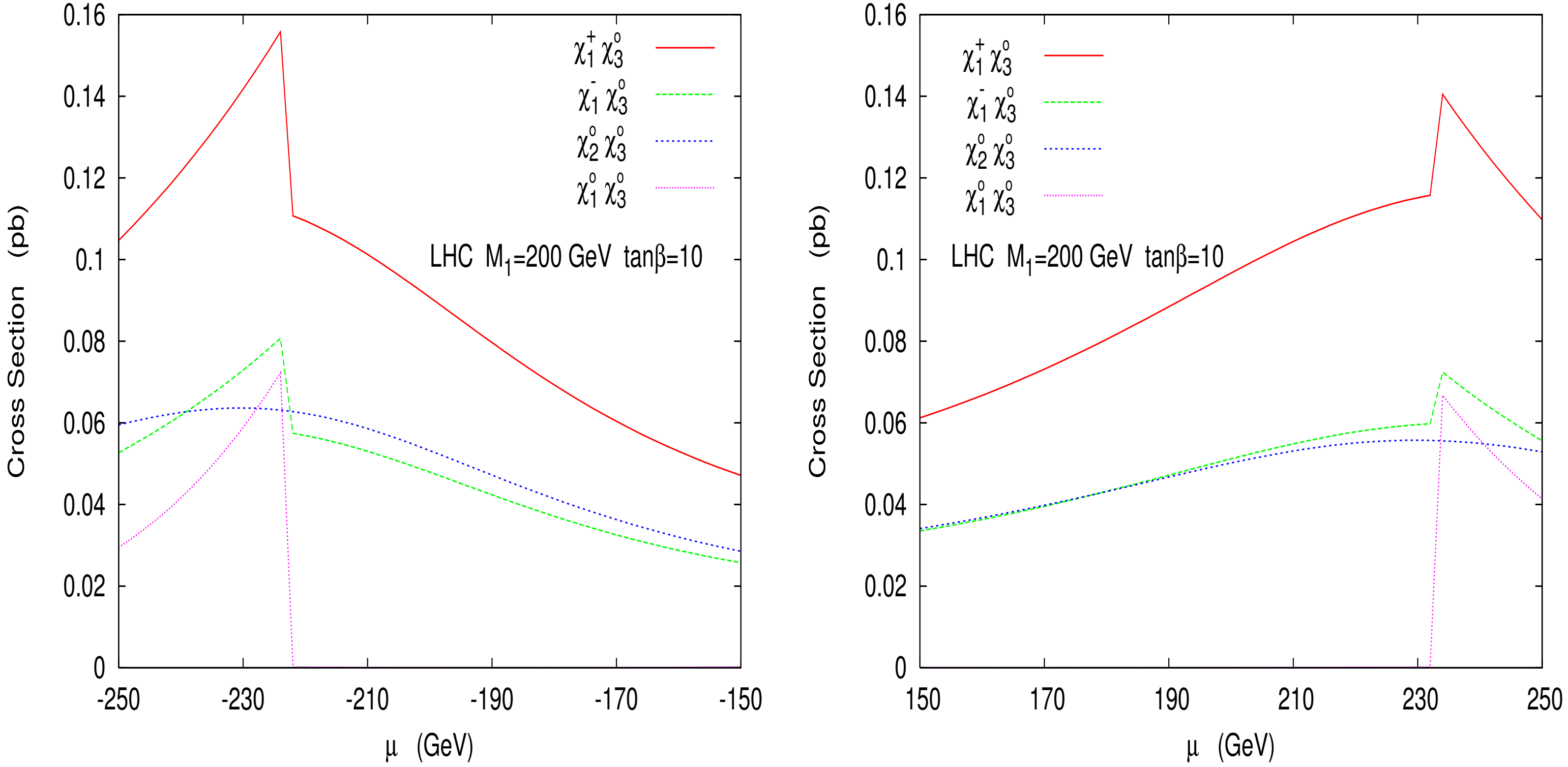


$\widetilde{\chi}^0_{3,2}$ radiative decay branching ratios

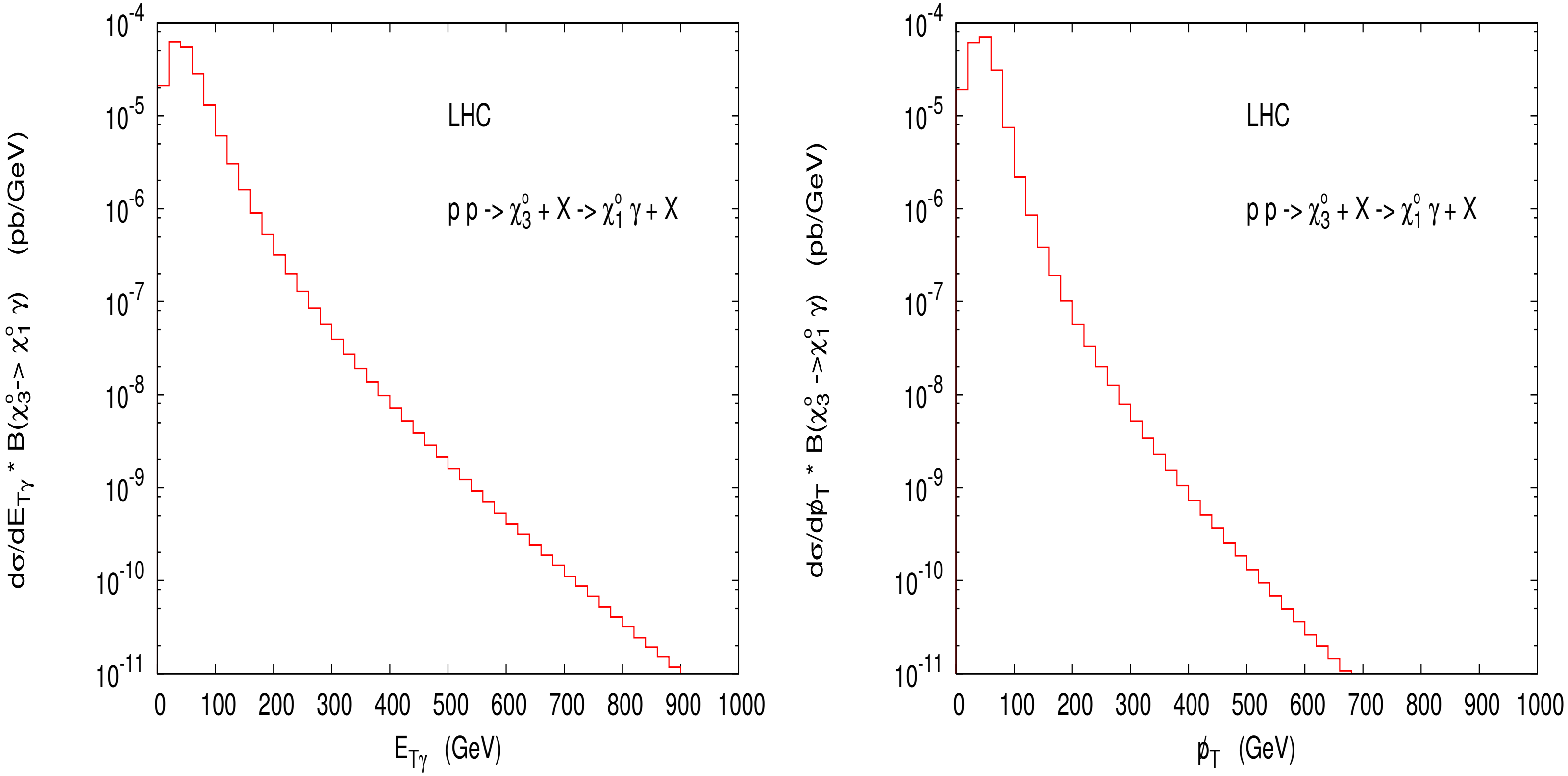
Production of Neutralinos and Charginos

$$
\begin{aligned}
q+\overline{q} &\xrightarrow{Z^*} \widetilde{\chi}_i^0+\widetilde{\chi}_j^0 \\
q+\overline{q} &\xrightarrow{\gamma, Z^*} \widetilde{\chi}_i^- +\widetilde{\chi}_j^+ \\
q+\overline{q}' &\xrightarrow{W^*} \widetilde{\chi}_i^\pm +\widetilde{\chi}_j^0 \\
e^-e^+ &\xrightarrow{\gamma, Z^*} \widetilde{\chi}_i^+ +\widetilde{\chi}_j^- \\
e^-e^+ &\xrightarrow{Z^*} \widetilde{\chi}_i^0+\widetilde{\chi}_j^0
\end{aligned}
$$

(Zhu; Kilian et al.; KC and Song)



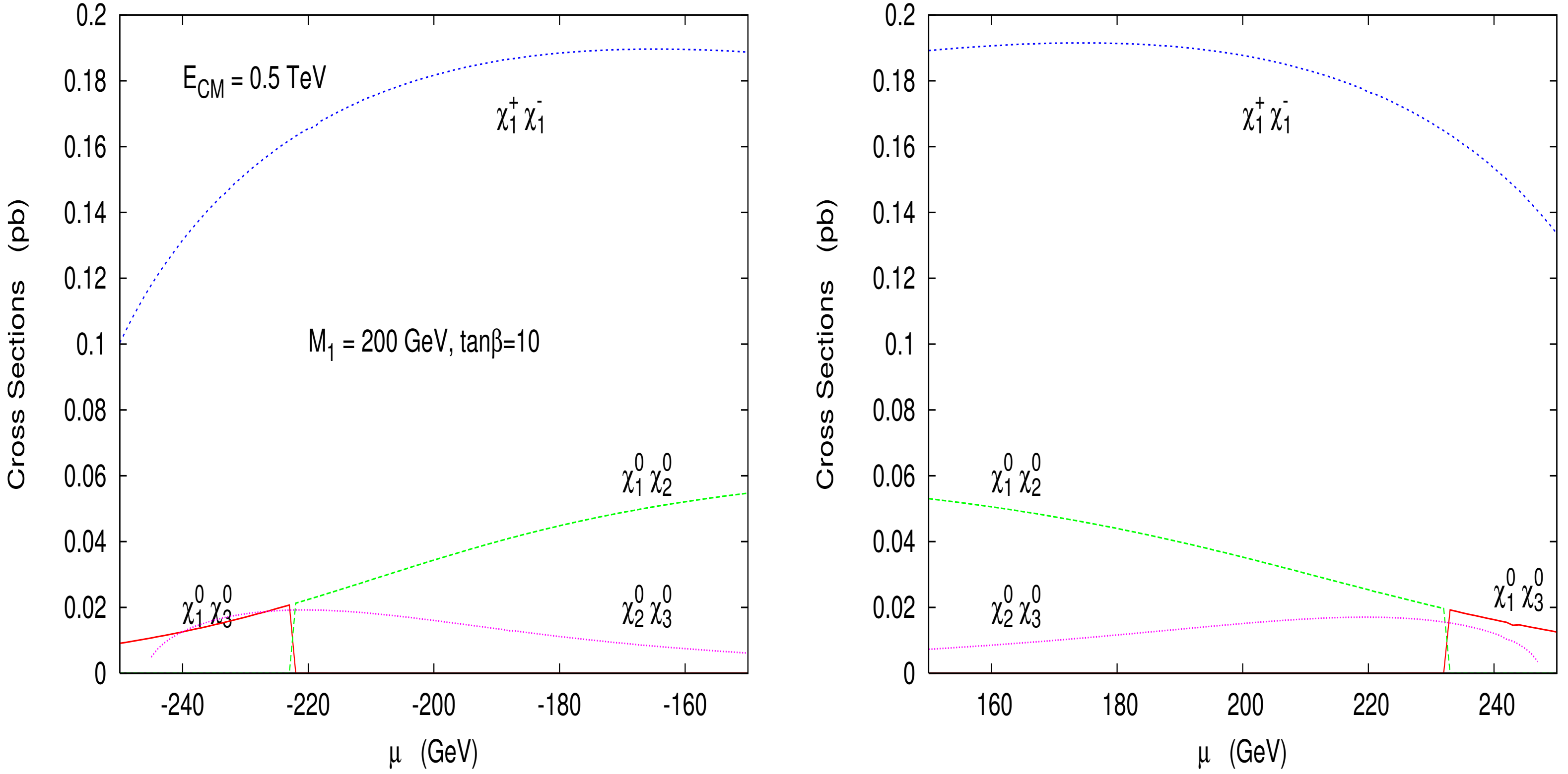
$\widetilde{\chi}_3^0$ production, $M_1 = 200$ GeV



$M_1 = 200$ GeV, $M_2 = 400$ GeV, $\mu = -220$ GeV

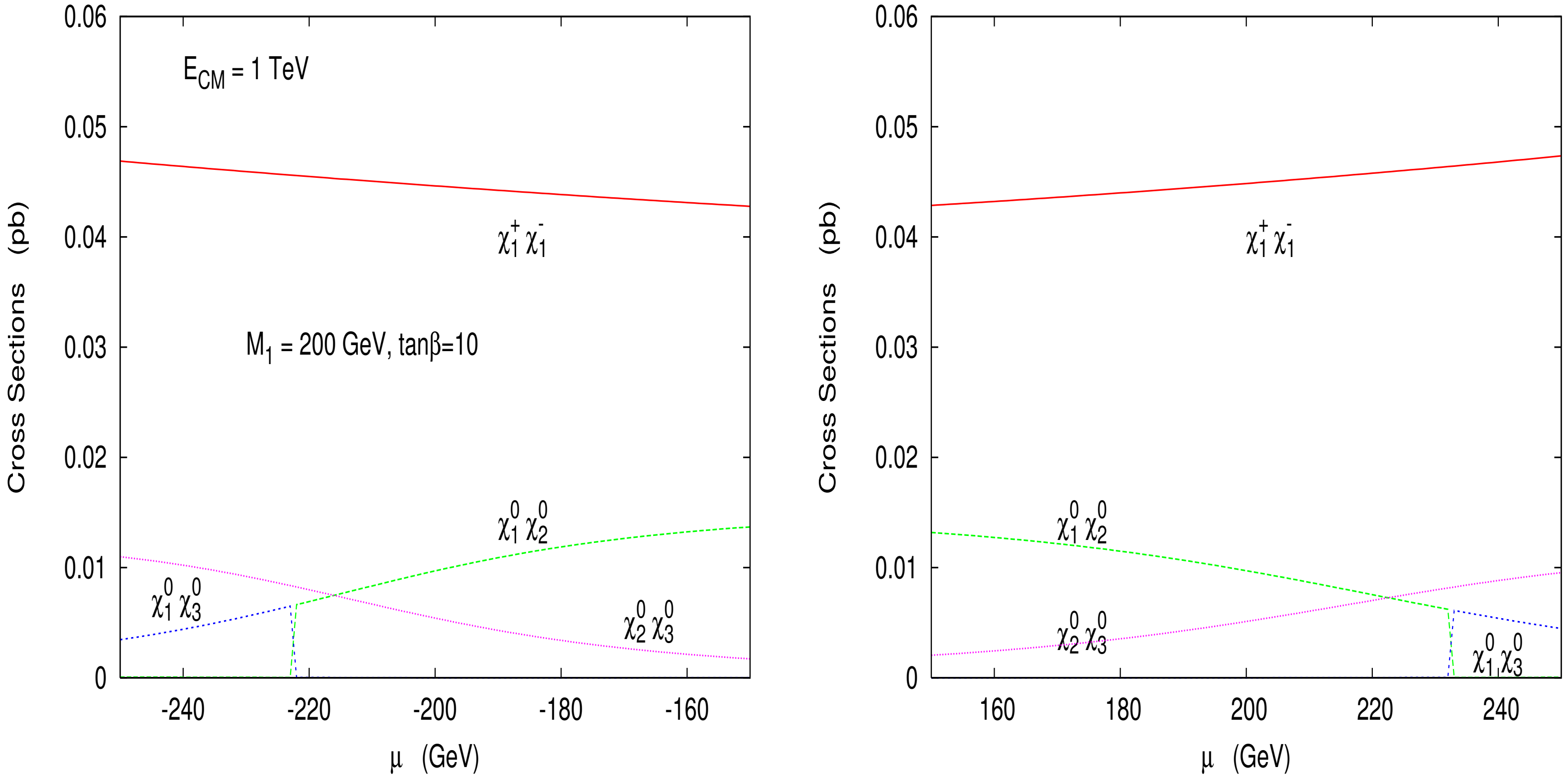
$B(\widetilde{\chi}^0_3 \to \widetilde{\chi}^0_1 \gamma) = 0.016$

Production at 0.5 TeV e^+e^- ILC



$$M_1 = 200 \text{ GeV},\ M_2 = 400 \text{ GeV},\ \tan\beta = 10$$

Production at 1 TeV e^+e^- ILC



$$M_1 = 200 \text{ GeV}, \; M_2 = 400 \text{ GeV}, \; \tan\beta = 10$$

Splitting split SUSY

(Cheung and Chiang, PRD and work in progress)

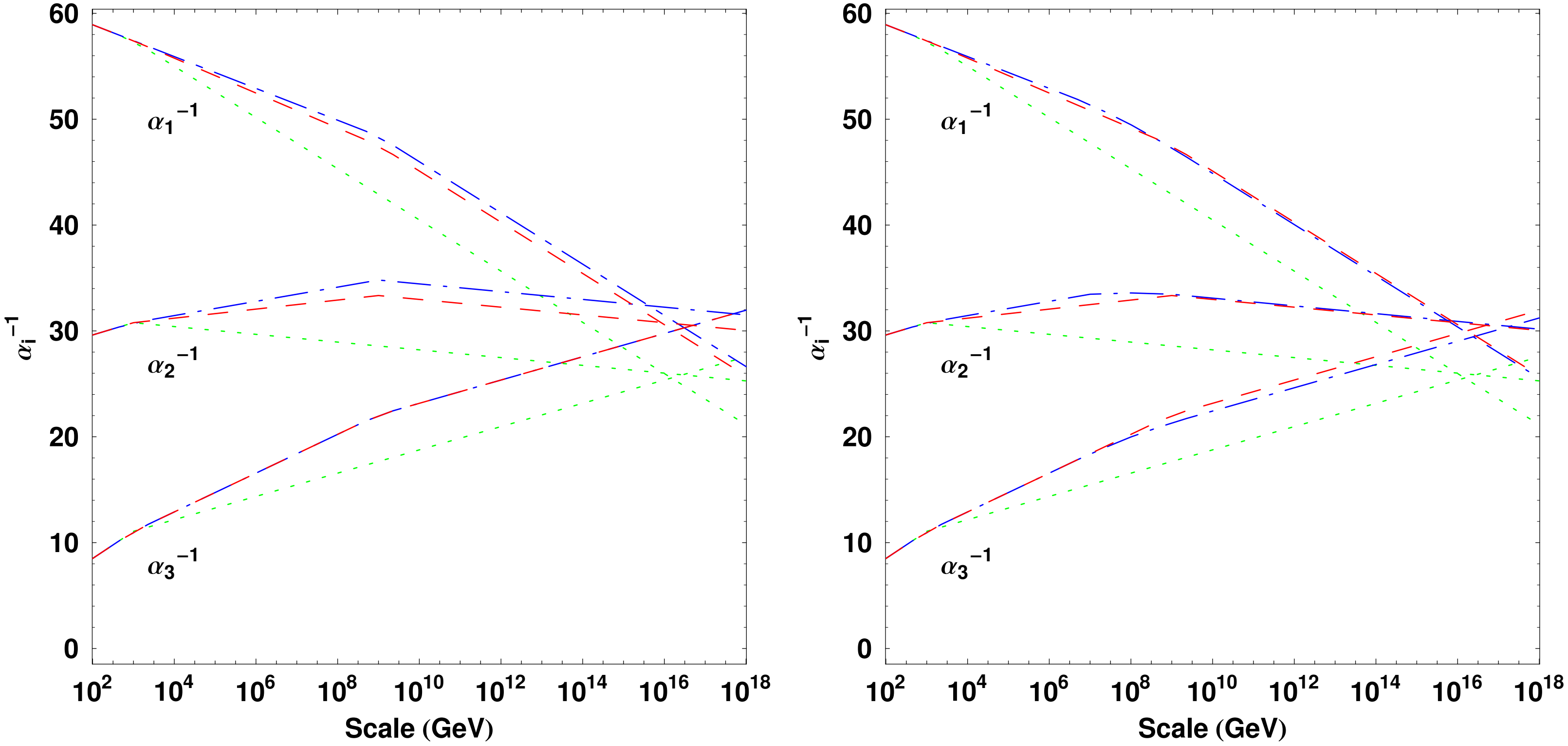
Scenarios:

- high-μ split SUSY
  Only gauginos are light, and a light Higgs boson.
  The Higgsino mass parameter μ is heavy $\sim \tilde{m}$.
  No μ problem
- low-μ split SUSY
  Only the Higgsino mass parameter μ is light. Two light Higgsinos only.

Features of these scenarios

- Gauge coupling unification
- Dark matter constraint, dark matter signal
- Chargino and neutralino pair production, detection

Gauge Coupling Unification



$\mu, \tilde{m} = 10^9$ GeV

$\mu = 10^7,\ \tilde{m} = 10^9$ GeV

Dark Matter

- $M_1 < M_2 < M_3$: is ruled out. The bino annihilation too small. (or $M_1 \lesssim M_2$)

- $M_2 < M_1 < M_3$: neutral wino is the LSP. Wino has a large annihilation cross section into W pairs. It only constituents a small fraction of the dark matterm unless the wino mass is of order 2 TeV. The relic density of wino LSP is

$$\Omega_{\widetilde{\chi}^0} h^2 \approx (0.02 - 0.05) \left(\frac{M_2}{\mathrm{TeV}} \right)^2$$

- $M_3 < M_2 < M_1$: the gluino LSP. Only when $M_{\tilde{g}} \sim 2 - 3$ TeV, it can be substantial fraction of the dark matter (as neutral R-hadron).

- Other nonthermal sources: e.g., decaying moduli in AMSB, the wino is the LSP. But the main source of wino is the moduli (Moroi and Randall, 1999).

- Wino dark matter detection:

$$\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \;\to\; \gamma\gamma,\;\; \gamma Z$$

gives monochromatic photon lines. The annihilation cross section is large for pure wino (via the W-$\widetilde{\chi}_1^+$ loop).

$$v\,\sigma(\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \;\to\; \gamma\gamma) \simeq 14\times 10^{-28}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

for $M_{\widetilde{\chi}_1^0} = 0.5 - 2$ TeV. (c.f. for pure higgsino case, $v\sigma \sim 1\times 10^{-28}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$)

The photon flux is

$$\begin{aligned} \phi_\gamma &\simeq 1.87\times 10^{-11}\left(\frac{N_\gamma v\sigma}{10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{10\,\mathrm{GeV}}{M_{\widetilde{\chi}^0}}\right)^2 J(\psi)\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \\ &\sim 2\times 10^{-10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \end{aligned}$$

for $M_{\widetilde{\chi}^0} \sim 500$ GeV, $N_\gamma = 2$, $J(\psi) = 100$.

Future ACT experiments have sensitivity of $10^{-13} - 10^{-14}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $\Delta\Omega \sim 10^{-3}$.

Neutralino and Chargino

Couplings:

- Z-$\widetilde{\chi}^0_{1,2}$-$\widetilde{\chi}^0_{1,2}$ $\to 0$ as $\mu \to \infty$. Same for H-$\widetilde{\chi}^0_{1,2}$-$\widetilde{\chi}^0_{1,2}$
- W^--$\widetilde{\chi}^0_1$-$\widetilde{\chi}^+_1$ coupling has the gaugino part, higgsino part goes to zero.
- W^--$\widetilde{\chi}^0_2$-$\widetilde{\chi}^+_1$ vanishes.
- $\gamma(Z)$-$\widetilde{\chi}^+_1$-$\widetilde{\chi}^-_1$ remains.
- H-$\widetilde{\chi}^+_1$-$\widetilde{\chi}^-_1$ vanishes.

The only relevant couplings for collider phenomenology are

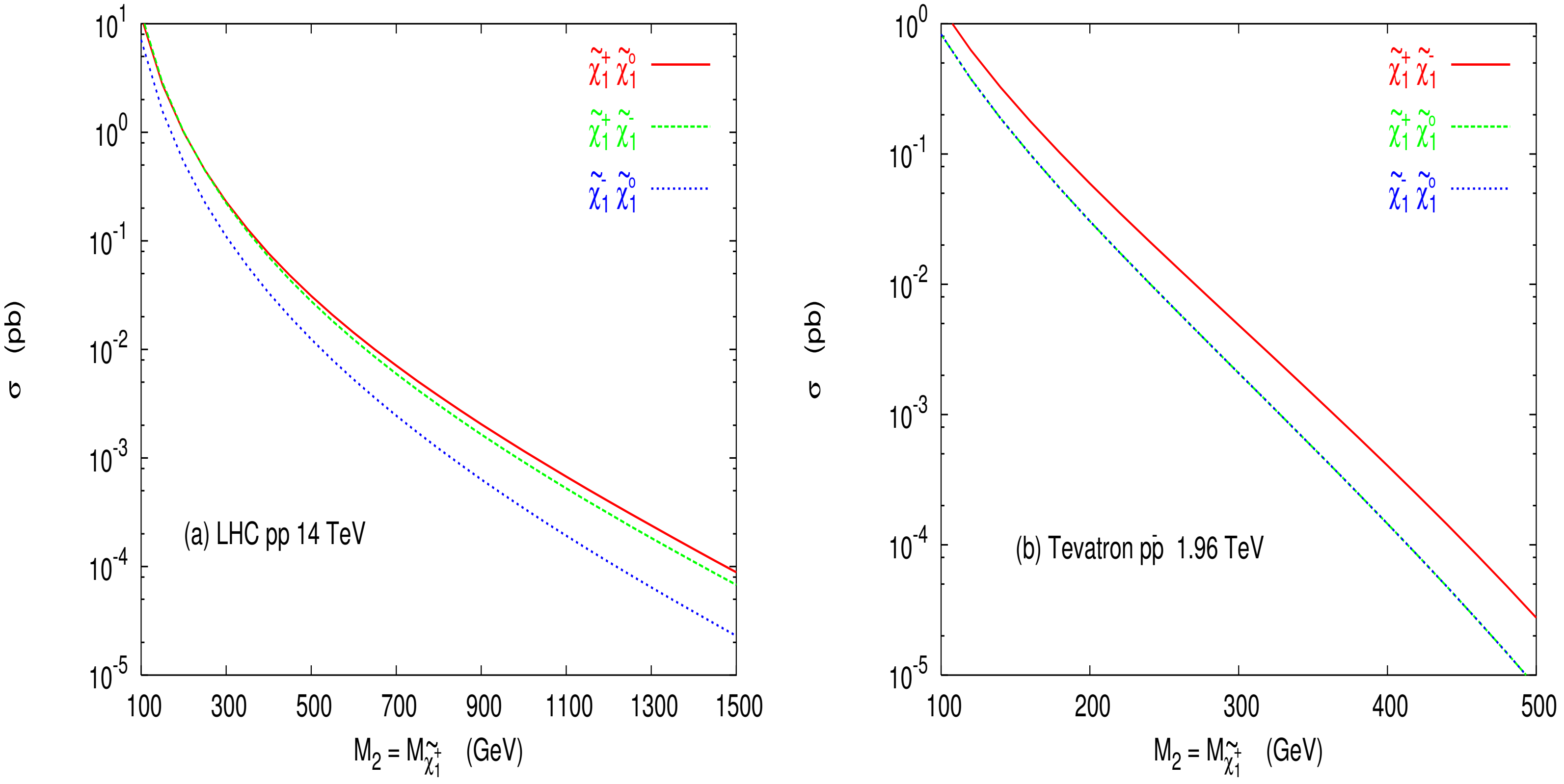
$$W^- - \widetilde{\chi}^0_1 - \widetilde{\chi}^+_1 , \qquad \gamma(Z) - \widetilde{\chi}^+_1 - \widetilde{\chi}^-_1$$

The only pair production at hadronic colliders:

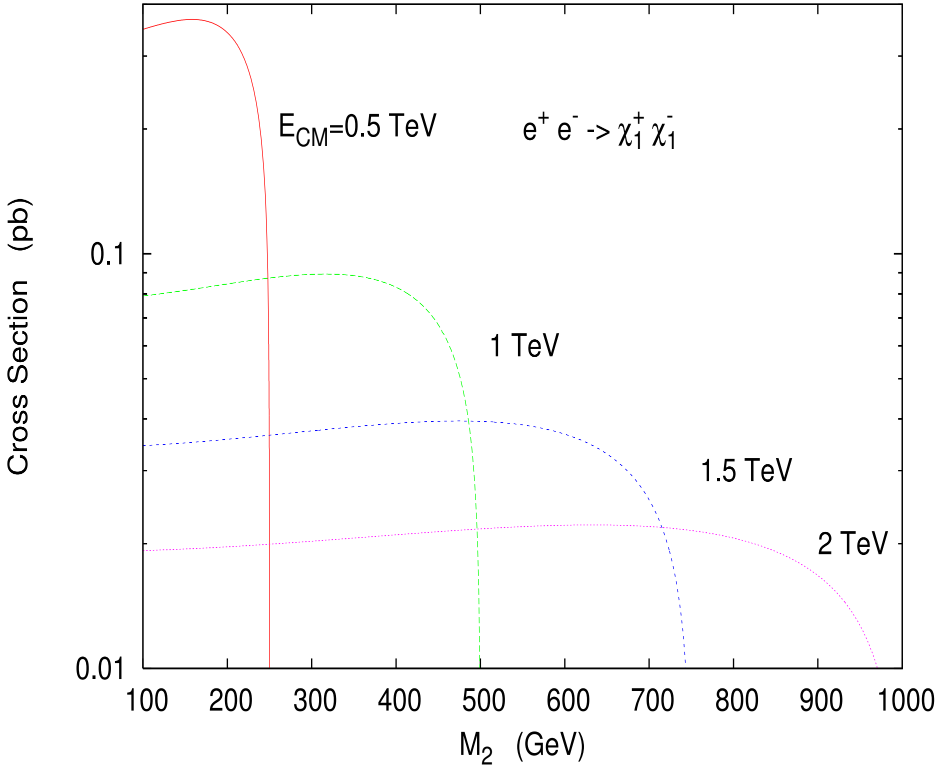
$$\widetilde{\chi}^+_1 \widetilde{\chi}^-_1 , \qquad \widetilde{\chi}^0_1 \widetilde{\chi}^\pm_1$$

Note the LSP-N scattering is zero at tree-level. Non-zero 1 loop contribution (Hisano et al.)

Neutralino and Chargino Pair Production



Chargino Pair Production at ILC



Only chargino pair production is possible at e^+e^-

Chargino Decay and detection

The decay of $\widetilde{\chi}_1^+ \to \widetilde{\chi}_1^0 W^+$ depends critically on $\Delta M \equiv M_{\widetilde{\chi}_1^+} - M_{\widetilde{\chi}_1^0}$.

- $m_\pi < \Delta M < 1$ GeV:

The most difficult region that depends on how many layers of silicon that the chargino can travel before decays, and the momentum resolution to tell the non-pointing pion.

- $1 - 2$ GeV $\lesssim \Delta M$:

The decay is prompt. If ΔM is large enough to have energetic leptons and jets, it is easy for detection. If the decay products are too soft, have to rely on other methods. E.g.

$$e^+ e^- \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \gamma$$

Chen, Gunion, Drees.

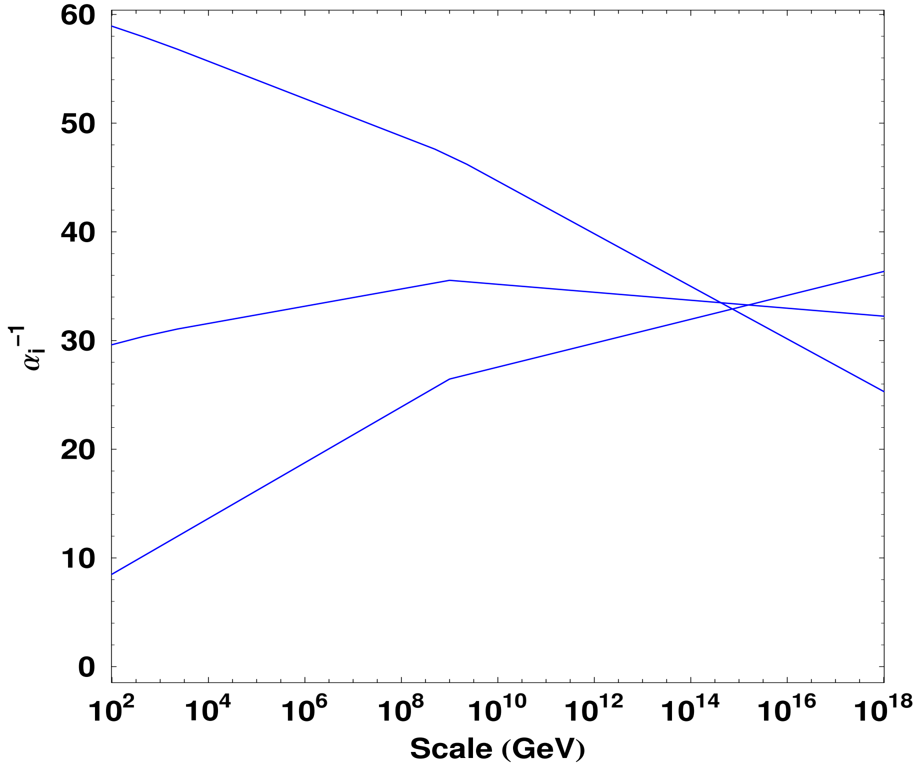
- $\Delta M >$ a few GeV:

charged lepton and jets are detectable.

Low-μ split SUSY

(Cheung, Chiang and Song in progress)

Gauge coupling unification is as good as MSSM, but at a lower GUT scale ($\sim 10^{14}$) GeV (Arkani, Dimopoulos)



μ, Higgsinos at TeV, all other gauginos and sfermions at 10^9 GeV

- Higgsino dark matter, degenerate neutralinos(1,2) and chargino(1). Strong annihilation, need $O(TeV)$ mass if the relic density comes from thermal source.

Strong annihilation into WW, ZZ, diphotons, plus nonzero $\widetilde{\chi}^0_1$-N scattering via the Higgsino-Higgsino-Z coupling.

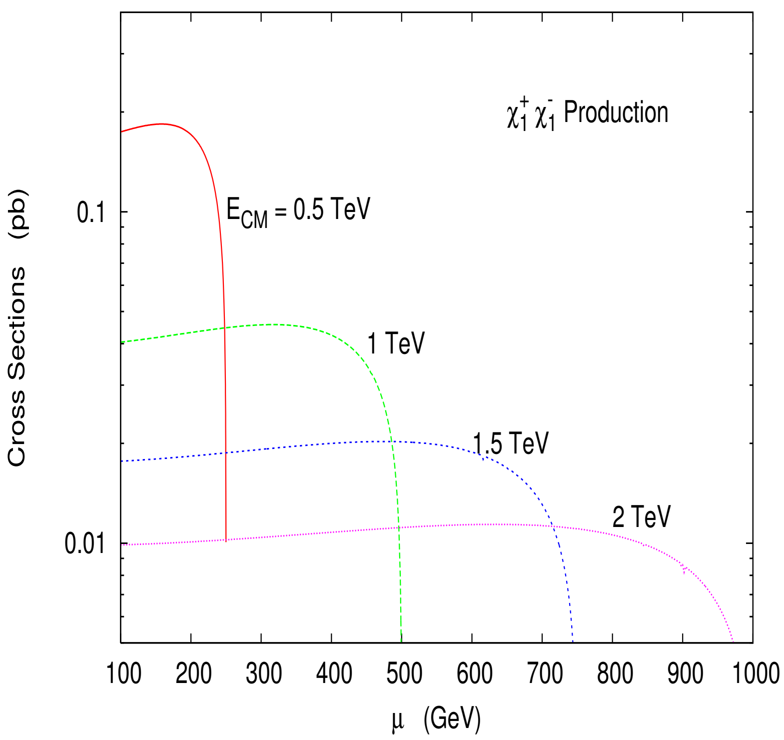
- Only Higgsino-Higgsino-gauge interactions are relevant for collider phenomenology:

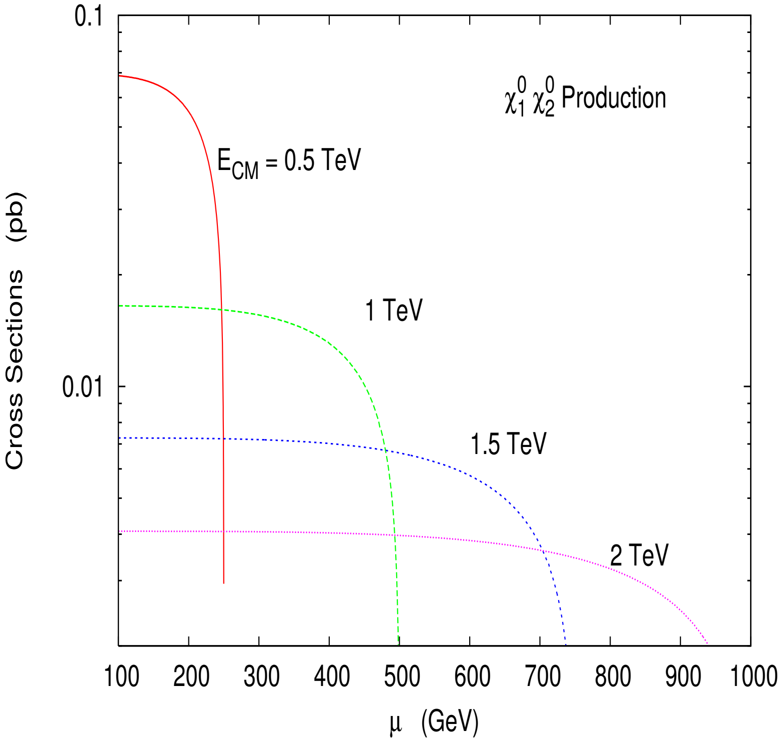
$$Z - \widetilde{\chi}^0_{1,2} - \widetilde{\chi}^0_{1,2}, \qquad W^- - \widetilde{\chi}^0_{1,2} - \widetilde{\chi}^+_1, \qquad \gamma(Z) - \widetilde{\chi}^+_1 - \widetilde{\chi}^-_1$$

At e^+e^- colliders, both neutralino and chargino pair production is possible

- Degeneracy among neutralino(1,2) and chargino(1), long decays or soft decays for the chargino and the neutralino(2).

Neutralino and Chargino Pair Production at ILC





both neutralino and chargino pair production are possible at e^+e^-

Conclusions

- High scale supersymmetry is possible and may be acceptable.
- Split SUSY: light gauginos and higgsinos, guided by gauge coupling unification and dark matter.
- Long-lived gluino and gluinonium are the most distinct features of the scenario.
- At hadron colliders, we may see signals of single-γ plus missing energy due to $\widetilde{\chi}_3^0 \to \widetilde{\chi}_1^0 + \gamma$.

Conclusions

- High-μ split SUSY: (i) only gauginos are light. Wino is the LSP. Wino DM has strong signal of monochromatic photons and near-zero LSP-N scattering. Long decays of charginos in detectors. e^+e^- colliders only produce chargino pairs.
- Low-μ split SUSY (ii) only Higgsinos are light. Neutal Higgsino is the LSP. DM has strong signal of annihilation into WW,ZZ, and diphotons, and nonzero LSP-N scattering. Long decays of chargino(1) and neutralino(2) in detectors. e^+e^- colliders produce chargino and neutralino pairs.