Flavour, CP, RPV & neutrino physics at ILC

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Shrihari Gopalakrishna	:	B-physics and LC signatures of light stop and sbottom
Yeong Gyun Kim	:	Probing the Majorana Nature and CP Properties of neutralinos
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Introduction

In supersymmetry (SUSY) ...

scalar-quark sector can have non-trivial flavor structure

what if its not aligned with quark sector?

If new phases are big, 1st and 2nd generation squarks must be heavy

....in order to escape neutron EDM constraints

“Effective-SUSY” with only 3rd generation (right-handed) scalars light

We consider a scenario with sizable $(\mathcal{M}^2_{RL,RR,LL})_{32,23}$

...motivated by $U(2)$ flavor symmetry

[see: S.G & C.-P.Yuan, hep-ph/0410181, Phys.Rev.D71:035012, 2005]

Here, focus on the effective theory

What are the implications to rare B decays?

What are the collider signatures (ILC, LHC)?

Parameters

Define $\delta^{RL,RR,LL}_{32,23} \equiv \frac{(\mathcal{M}^2_{RL,RR,LL})_{32,23}}{m_0^2}$

Natural sizes: $\delta^{RL}_{32,23} = 6.82 \times 10^{-4}\, d^{RL}_{32,23}$ $\delta^{RR}_{32} = 0.02\, d^{RR}_{32}$

SUSY spectrum: (“effective” SUSY)

m_0	1000	$\tan\beta$	5
$m_{\tilde{b}_R,\tilde{t}_R}$	100	μ	$200\, e^{i\,2.2}$
$m_{\tilde{d}_R,\tilde{s}_R}$	1000	M_2	250
$m_{\tilde{q}_L}$	1000	$M_{\tilde{g}}$	300
A	1000	$m_{H^\pm}$	250
d^{LR}_{32}	$2\, e^{i\,3.2}$	d^{RR}_{32}	$1.75\, e^{i\,1.6}$

All masses are in GeV

Neutron EDM suppressed in effective SUSY in spite of new $\mathcal{O}(1)$ phases

B-meson (and K) FCNC

FCNC Effects in:

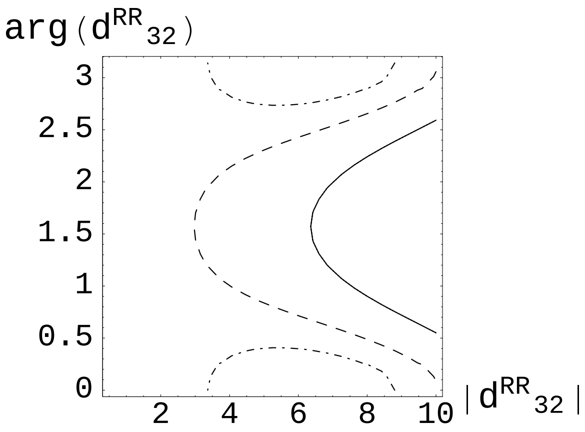
- $\Delta S = 2$:
  - $K^0 - \bar{K}^0$ mixing (ϵ_K)
- $\Delta B = 2$:
  - $B_d \bar{B}_d$ mixing (Δm_{B_d}), $B_d \to \psi K_s$ ($\sin 2\beta$)
  - $B_s \bar{B}_s$ mixing (Δm_{B_s})
- $\Delta B = 1$ (B.R. and C.P. Violation):
  - $B_d \to X_s \gamma$, $B_d \to X_s\, g$
  - $B_d \to X_s \ell^+ \ell^-$
  - $B_d \to \phi K_s$

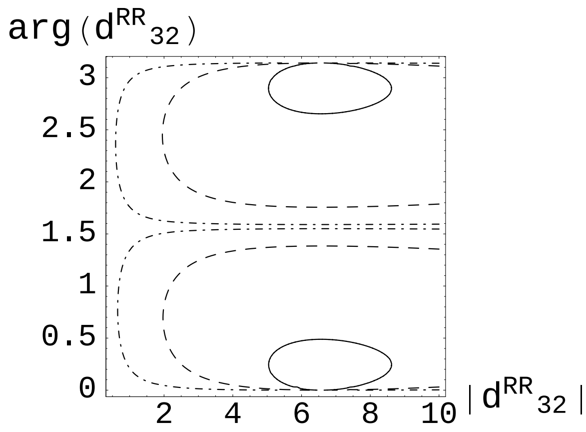
$\Delta B = 2$: $B_s\bar{B}_s$ *mixing*

Limit: $\Delta m_{B_s} > 14.4\, ps^{-1}$ @ 95% C.L. [PDG2004]
SM prediction: $14\ \mathrm{ps}^{-1} < \Delta m_{B_s} < 20\ \mathrm{ps}^{-1}$

Dilepton asymmetry: $A_{ll}^{B_q} \equiv \frac{N(B_q B_q) - N(\bar{B}_q \bar{B}_q)}{N(B_q B_q) + N(\bar{B}_q \bar{B}_q)}$ SM prediction: $A_{ll}^{B_s} \approx 10^{-4}$

(15, 25, 40) ps^{-1} contours of Δm_{B_s} (10^{-4}, 10^{-3} and 10^{-2}) contours of $|A_{ll}^{B_s}|$





Collider Signatures

usual expectations:

$$\tilde{t}_1 \to c\tilde{\chi}_1^0 \quad ; \qquad\qquad \tilde{b}_1 \to b\tilde{\chi}_1^0$$

However:

-$m_{\tilde{t}_1}$ in the range of electroweak baryogenesis (talk by C. Balazs)
- what about ν masses? ν_R can be light $\Rightarrow m_{\tilde{\nu}_R} = O(10\,\mathrm{GeV})$
- $\tilde{\nu}_R$ as LSP $\Rightarrow$

$$\tilde{t}_1 \to b\, l\, \tilde{\nu}_R \quad ; \qquad\qquad \tilde{b}_1 \to b\, \nu\, \tilde{\nu}_R$$

$$\Gamma \propto h_\nu^2$$

$\Rightarrow$ (extremely) long lived squarks

Probing the Majorana Nature and CP Properties of Neutralinos

Yeong Gyun Kim

(Korea University)

consider the decay

$$\tilde{\chi}^0_2(\hat{n}) \to \tilde{\chi}^0_1 l^+ l^-$$

in the $\tilde{\chi}^0_2$ rest frame

- lepton energy distributions
- lepton angular distributions
- lepton invariant mass and opening-angle distributions
- CP-odd triple spin/momentum product

- 100 % polarized $\tilde{\chi}^0_2$ from $\tilde{e}^{\pm}_L \to e^{\pm}\tilde{\chi}^0_2$
- detailed study of the decay $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \mu^+\mu^-$ in $\tilde{\chi}^0_2$ rest frame
-

$$\begin{aligned} d\Gamma &\propto F_0(x_-,x_+) + (\hat{q}_- \cdot \hat{n}) F_1(x_-,x_+) + (\hat{q}_+ \cdot \hat{n}) F_2(x_-,x_+) \\ &\quad + \hat{n} \cdot (\hat{q}_- \times \hat{q}_+) F_3(x_-,x_+) \\ x_\pm &= \frac{2E_\pm}{m_{\tilde{\chi}^0_2}} \end{aligned}$$

- CP invariance implies

$$\begin{aligned} F_0(x_-,x_+) &= +F_0(x_+,x_-) \\ F_1(x_-,x_+) &= -F_2(x_+,x_-) \\ F_3(x_-,x_+) &= -F_3(x_+,x_-) \end{aligned}$$

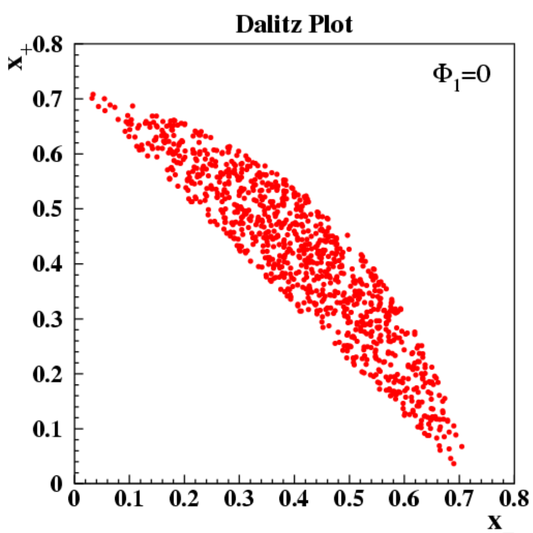
4.1 Lepton energy distribution

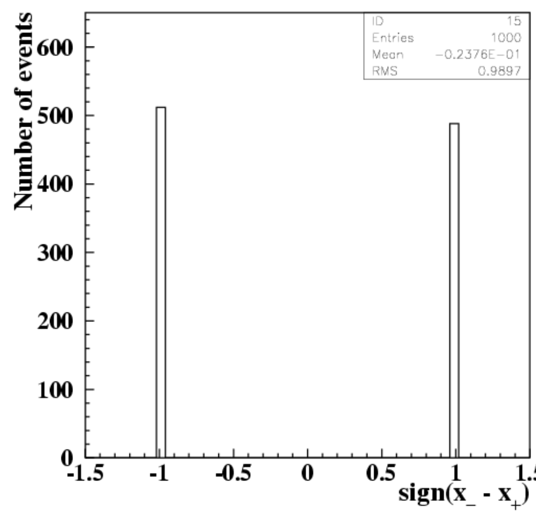
- $\frac{d^2\Gamma}{dx_- dx_+} \propto F_0(x_-, x_+)$ **where** $x_? = 2E_? / m_2$
- $F_0(x_-, x_+) = F_0(x_+, x_-)$ **to a good approximation (exactly in CP-invariant case)**

Majorana nature of neutralinos

⇓

Symmetric distribution of events on (x−,x+) Dalitz plane





$\mathrm{sign}(x_- - x_+)$

- ΔN_{ev} ? 24 **is within the expected error** $\sqrt{1000}$; 32

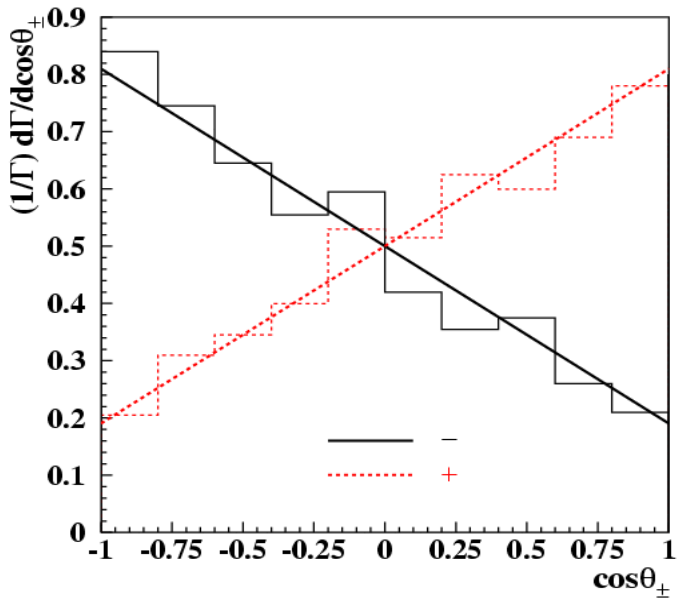
4.2 Lepton angular distribution

- **Lepton angle distribution** w.r.t **neutralino polarization vector**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{l^\pm}} = \frac{1}{2}(1 \pm \eta_l \cos\theta_\pm) \quad \textbf{with} \quad \cos\theta_l = \hat{q}_\pm \cdot \hat{n}$$

- $F_1(x_-, x_+) = -F_2(x_+, x_-) \Longrightarrow \eta_- = \eta_+$

Majorana nature of neutralino **the slope of the angle distribution**



$\Phi_1 = 0$

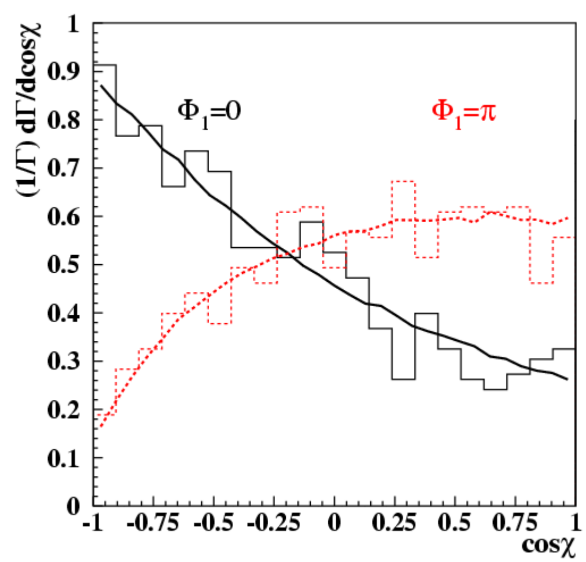
* **Selection rule of the orbital angular momentum by CP symmetry**

$$\eta_2 = \eta_1 (-1)^L$$ (L : orbital angular momentum of the final system

L=0 (steep S-wave) for $\eta_1 = \eta_2$ ($\Phi_1 = 0$ case)
L=1 (slow P-wave) for $\eta_1 = -\eta_2$ ($\Phi_1 = \pi$ case)

* **Decay distribution w.r.t. the opening angle between two lepton**

$$\cos\chi = \hat{q}_- \cdot \hat{q}_+$$



$$m_{ll}^2 = \frac{m_2^2}{2} x_+ x_- (1 - \cos\chi)$$

: maximum for $\cos\chi = -1$
for given x- and x+

Angular momentum conservation
forces L=0 for $\cos\chi = -1$

CP-odd and T-odd Asymmetries in Chargino and Neutralino Production and Decay

Stefan Hesselbach
High Energy Physics, Uppsala University

based on

Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, JHEP **0408** (2004) 038 [hep-ph/0406190]

Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, in preparation

Snowmass Workshop 2005

August 22, 2005

Comparison of real and complex scenarios

Scenario	$\lvert M_1\rvert$	ϕ_{M_1}	M_2	μ	ϕ_μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
real	180	0	300	335	0	3	300	180
complex	181	0.04π	305	328	1.91π	3.2	297	181

- CP-even observables at $\sqrt{s}$ = 500 GeV ILC:

Scenario	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ for $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ =		
			$(0, 0)$	$(-80\%, +60\%)$	$(+80\%, -60\%)$
real	170.0	254.2	18.3	20.2	34.0
complex	169.1	252.3	18.2	19.7	34.1

- CP-odd observables:

real: all CP-odd/T-odd asymmetries = 0

complex: A_T = 5.2% for $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-80\%, +60\%)$

A_{CP} = 4.1% (with transverse beam polarization)

T-odd triple product asymmetries

Chargino/neutralino production with subsequent three-body decays

$$e^+e^- \longrightarrow \tilde{\chi}_i + \tilde{\chi}_j \longrightarrow \tilde{\chi}_i + \tilde{\chi}_1^0 f \bar{f}^{(\prime)}$$

- Full spin correlation between production and decay

  [Moortgat-Pick, Fraas, ’97; Moortgat-Pick, Fraas, Bartl, Majerotto, ’98, ’99; Choi, Song, Song, ’99]

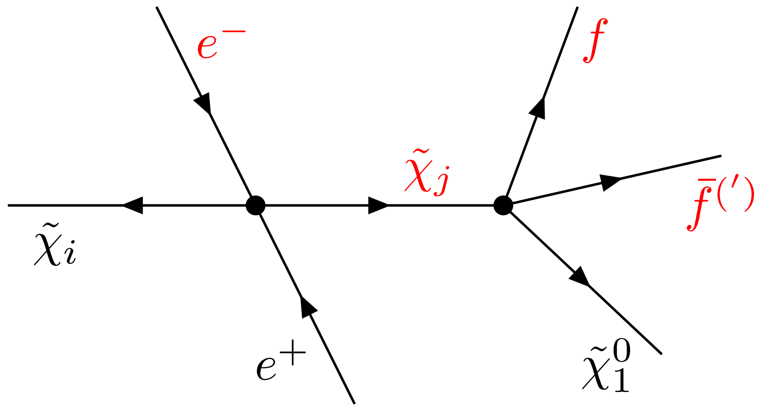
- Amplitude squared $|T|^2 = PD + \Sigma_P^a \Sigma_D^a$
- In Σ_P^a and Σ_D^a: products like $\boxed{i\epsilon_{\mu\nu\rho\sigma} p_i^\mu p_j^\nu p_k^\rho p_l^\sigma}$

  $\Rightarrow$ with complex couplings: real contributions to observables

  $\Rightarrow$ CP violation at tree level

T-odd triple product asymmetries

Triple products: $\boxed{\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{\bar{f}^{(\prime)}})}$ or $\boxed{\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f)}$



$\longrightarrow$ T-odd asymmetry:

$$\boxed{A_T = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)} = \frac{\int \text{sign}(\mathcal{T}) |T|^2 d\text{Lips}}{\int |T|^2 d\text{Lips}}}$$

$\longrightarrow$ CP-odd, if final state interactions and finite-widths effects can be neglected

T-odd asymmetry in $\tilde{\chi}^0$ sector

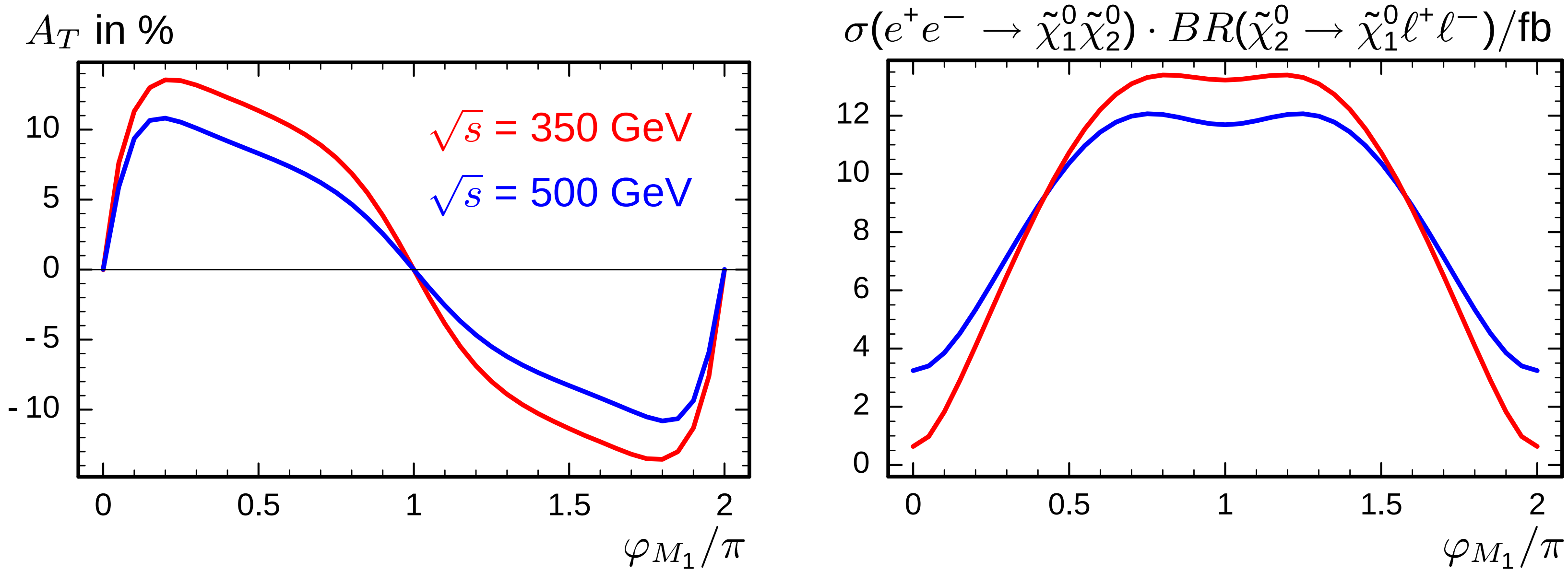
Asymmetry A_T for $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$

[Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, hep-ph/0406190]

- φ_{M_1} dependence

  $\tan\beta = 10$, $M_2 = 300$ GeV, $|M_1| = 150$ GeV, $|\mu| = 200$ GeV, $\varphi_\mu = 0$

  $m_{\tilde{e}_L} = 267.6$ GeV, $m_{\tilde{e}_R} = 224.4$ GeV, $\mathcal{P}_{e^-} = -0.8$, $\mathcal{P}_{e^+} = +0.6$



$\longrightarrow$ A_T larger closer to threshold (spin correlations)

Bilinearly broken R-parity

Is defined as MSSM $+ \epsilon_i \widehat{L}_i \widehat{H}_u + B_i \epsilon_i \widetilde{L}_i H_u$

Induced mixings: (leptons, charginos), (neutrinos, neutralinos), (Higgs bosons, sleptons)

Solves neutrino problems:
Atmospheric at tree level, solar at loop level

Negligible flavour violating decays of leptons:
BR$(\mu \to e\gamma) < 10^{-17}$, BR$(\tau \to e\gamma, \mu\gamma) < 10^{-16}$.

Leads to predictions for collider physics

Gravitino Dark Matter

GMSB: light gravitino LSP, $\tilde{\chi}_1^0$ of $\tilde{l}_R$ NLSP

Standard thermal history of the universe:

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{m_{3/2}}{100\,\text{eV}}\right)\left(\frac{100}{g_*}\right) \qquad (g_* \simeq 90 - 140)$$

Current data: $\Omega_M h^2 \simeq 0.134 \pm 0.006$, $\Omega_B h^2 \simeq 0.023 \pm 0.001$

$\Rightarrow m_{3/2} \simeq 100$ eV if DM candidate, warm dark matter
constraints from Lyman-α forest: $m_{WDM} \gtrsim 550$ eV
(M. Viel et al., arXiv:astro-ph/0501562)

$\Rightarrow$ assume additional entropy production, e.g. non-standard decays of messenger particles
(E. Baltz, H. Murayama, astro-ph/0108172; M. Fujii and T. Yanagida hep-ph/0208191)

Neutralino decays

dominant modes R-parity violating modes

$$\Gamma(\tilde{\chi}_1^0 \to W^\pm l_i^\mp) \;\propto\; \frac{\Lambda_i^2}{\det \mathcal{M}_{\tilde{\chi}^0}}$$

$$\Gamma(\tilde{\chi}_1^0 \to \sum_i Z\nu_i)$$

$$\Gamma(\tilde{\chi}_1^0 \to \nu\tau^+ l_i^-) \;\propto\; \frac{\epsilon_i^2}{\mu^2}$$

R-parity conserving mode

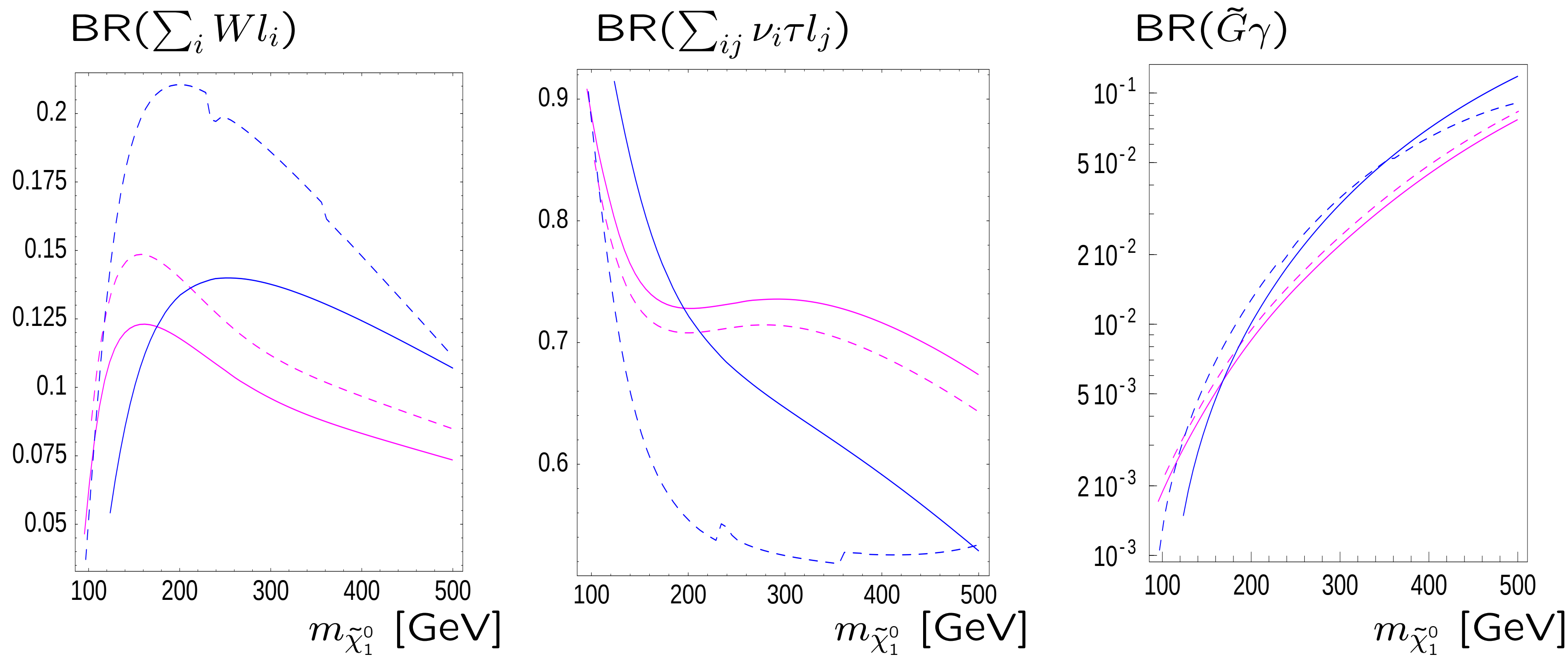
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) \;\simeq\; 1.2 \times 10^{-6} \kappa_\gamma^2 \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{eV}}{m_{3/2}}\right)^2 \mathrm{eV}$$

total width

$$\Gamma \simeq (10^{-4} - 10^{-2})\,\mathrm{eV}$$

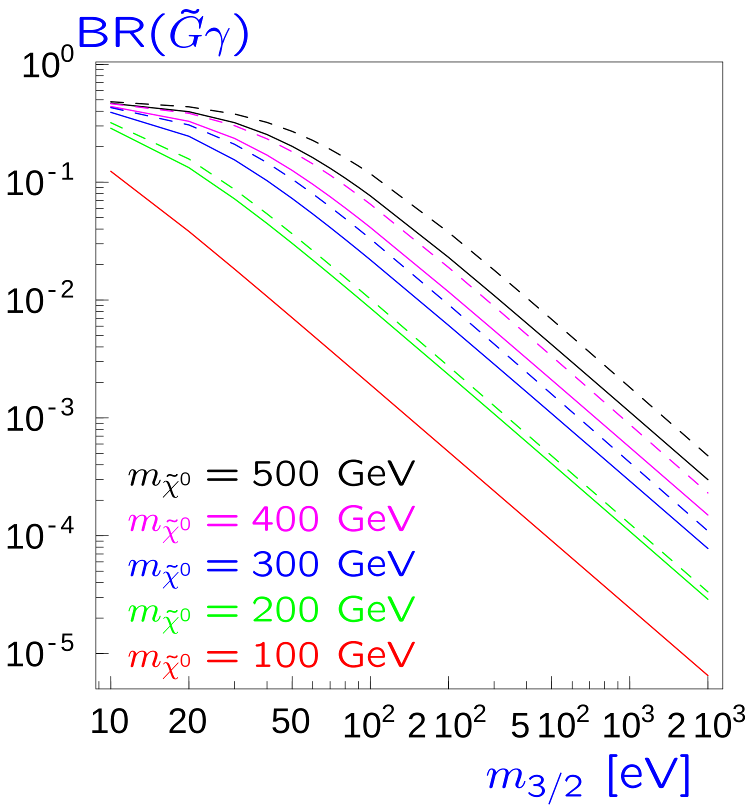
$\tan\beta = 10,\ \mu > 0$, - - $\tan\beta = 10,\ \mu < 0$

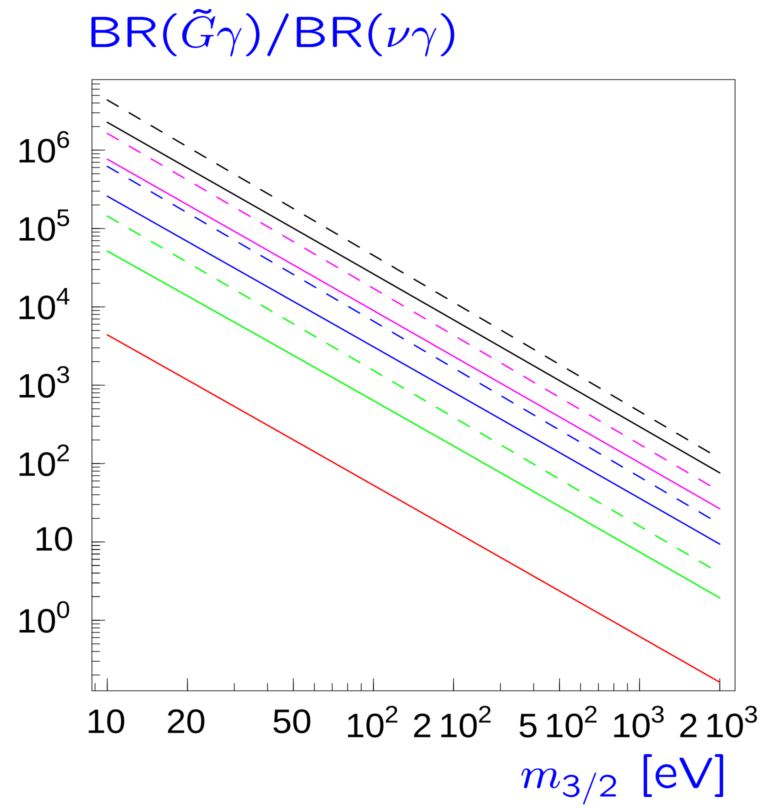
$\tan\beta = 35,\ \mu > 0$, - - $\tan\beta = 35,\ \mu < 0$



$m_{3/2} = 100$ eV, $n_5 = 1$

GMSB signals





$n_5 = 1$, $\tan\beta = 10$

Comments

- $$\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}^0_1}} \propto \frac{1}{\sqrt{n_5}}$$

  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}^0_1$ NLSP

- $\tilde{l}_R$ NLSPs: BR($l\nu$) $>$ BR($l\tilde{G}$)
- $n_5 = 2$: BR($\tilde{G}\gamma$) reduced by a factor 2-3
- $\tilde{G}$ decays via R-parity violating couplings, however:

  $$\Gamma(\tilde{G}) \simeq 3.5 \cdot 10^{-16} \frac{m_\nu[\mathrm{eV}]}{0.05\mathrm{eV}} \frac{m^3_{3/2}}{M^2_{Pl}} \quad \Rightarrow \tau(\tilde{G}) \sim O(10^{31})\mathrm{Hubbletimes}$$

Summary

Exploring flavour structures and CP properties of SUSY particles will be an important task at an ILC