SUSY Search at Future Collider and Dark Matter Experiments

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Outline

- SUSY : Merits & Problems
- Nature of LSP : Bino, Higgsino or Wino
- DM Constraints on Bino, Higgsino & Wino LSP Scenarios (mSUGRA & mAMSB Models)
- Bino LSP Signals at LHC
- Higgsino & Wino LSP Signals at CLIC
- Bino, Higgsino & Wino LSP Signals in DM Expts
- Nonminimal Models for Higgsino, Wino & Bino LSP

WHY SUSY :

A. Natural Soln to the Hierarchy Problem of EWSB

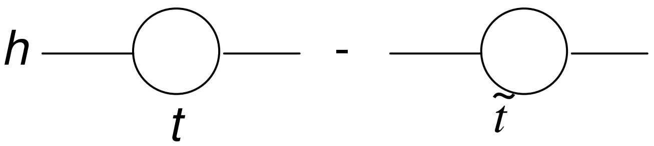
B. Natural (Radiative) Mechanism for EWSB

C. Natural Candidate for the cold DM (LSP)

D. Unification of Gauge Couplings @ GUT Scale

PROBLEMS WITH SUSY :

1. Little Hierarchy Problem



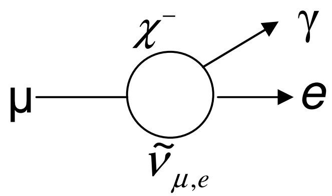
$m_h > 114$ GeV (LEP) $\Rightarrow m_{\tilde{t}} > 1$ TeV

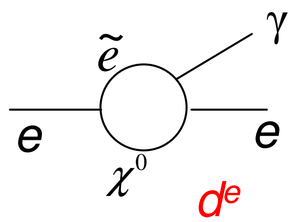
Split SUSY solves 2 at the cost of aggravating1.

$m_{\tilde{f}} >>> 1 TeV \Rightarrow No\ (A\ \&\ B)$

$m_{\chi^{\pm,o}} \approx 1 TeV \Rightarrow C\ \&\ D$

2. Flavour & CP Viol. Problem





$m_{\tilde{\nu}_{\mu,e}} > 10\,TeV$

$(m_{\tilde{\nu}_\mu} \cong m_{\tilde{\nu}_e})$

$m_{\tilde{e}} > 10 TeV$

$(\phi_{\mu,A} < 10^{-2})$

We shall consider a more moderate option, allowing

$m_{\tilde{f}} = 10 - 100 TeV$

Nature of the Lightest Superparticle (LSP) in the MSSM:

Astrophysical Constraints ⇒ Colourless & Chargeless LSP
Direct DM Detection Expts ⇒ LSP not Sneutrino

$$\therefore LSP \rightarrow \chi \equiv \chi_1^0 = c_1\tilde{B} + c_2\tilde{W} + c_3\tilde{H}_d + c_4\tilde{H}_u$$

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}$$

Diagonal elements : M_1, M_2, ±μ in the basis $\tilde{B}, \tilde{W}$ & $\tilde{H}_{1,2} = \tilde{H}_d \pm \tilde{H}_u$

Nondiagonal elements < M_Z

Exptl Indications ⇒ M_1, M_2, μ > $2M_Z$ in mSUGRA $\Rightarrow \chi \cong \tilde{B}, \tilde{W} or \tilde{H}$

Exception : $M_{ii} \approx M_{jj} \Rightarrow \tan 2\theta_{ij} = 2M_{ij} / (M_{ii} - M_{jj})$ large $\Rightarrow \chi = \tilde{B} - \tilde{H}, \tilde{W} - \tilde{H}$

"Well-tempered Neutralino Scenario" Arkani-Hamed, Delgado & Giudice

DM Relic Density Constraints on Bino, Higgsino & Wino LSP Scenarios

mSUGRA: SUSY Br in HS communicated to the OS via grav. Int.

$\Rightarrow$ m_0 , $m_{½}$, tanβ, A_0 , sign (μ) at GUT scale (A0 = 0 & +ve μ)

$\downarrow$ RGE (Weak Sc masses)

$$\tilde{B} : M_1 = (\alpha_1 / \alpha_G) m_{1/2} \approx 0.4 m_{1/2} \ \& \ \tilde{W} : M_2 = (\alpha_2 / \alpha_G) m_{1/2} \approx 0.8 m_{1/2}$$

Imp Weak Sc Scalar mass M_{Hu}

$$EWSB \Rightarrow \underset{||}{\mu^2} + M_Z^2 / 2 = \frac{M_{Hd}^2 - M_{Hu}^2 \tan^2\beta}{\tan^2\beta - 1} \approx -M_{Hu}^2 \ @ \tan\beta > 5$$

(LEP)

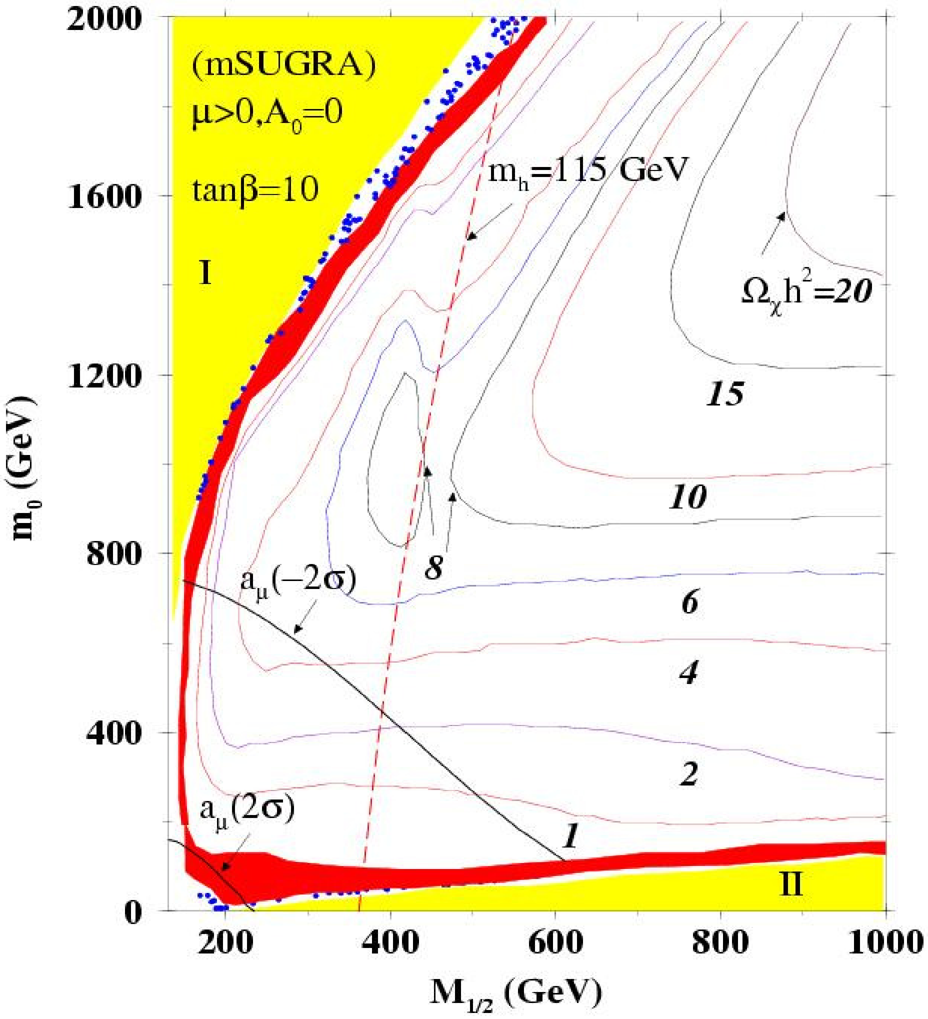
$$\text{RGE:} -M_{Hu}^2 = \underbrace{C_1}_{-\varepsilon}(\alpha_i, h_t, \tan\beta) m_0^2 + \underbrace{C_2}_{\approx 2}(\alpha_i, h_t, \tan\beta) m_{1/2}^2$$

Hyperbolic Br (tan β > 5) of μ^2:

$$m_0 \approx m_{1/2} \Rightarrow |\mu| > M_1 \Rightarrow \tilde{B} - LSP$$

$$m_0 >> m_{1/2} \Rightarrow |\mu| < M_1 \Rightarrow \tilde{H} - LSP$$

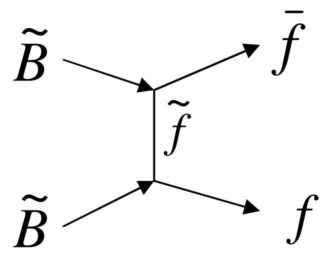
Chattopadhyay et al



$m_0 \sim m_{1/2} \rightarrow$ TeV (Bino LSP)

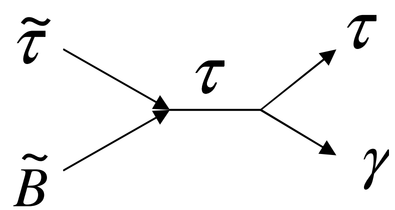
$m_h > 115$ GeV $\Rightarrow m_{1/2} > 400$ GeV ($M_1 > 2M_Z$)
$\Rightarrow$ also large sfermion mass

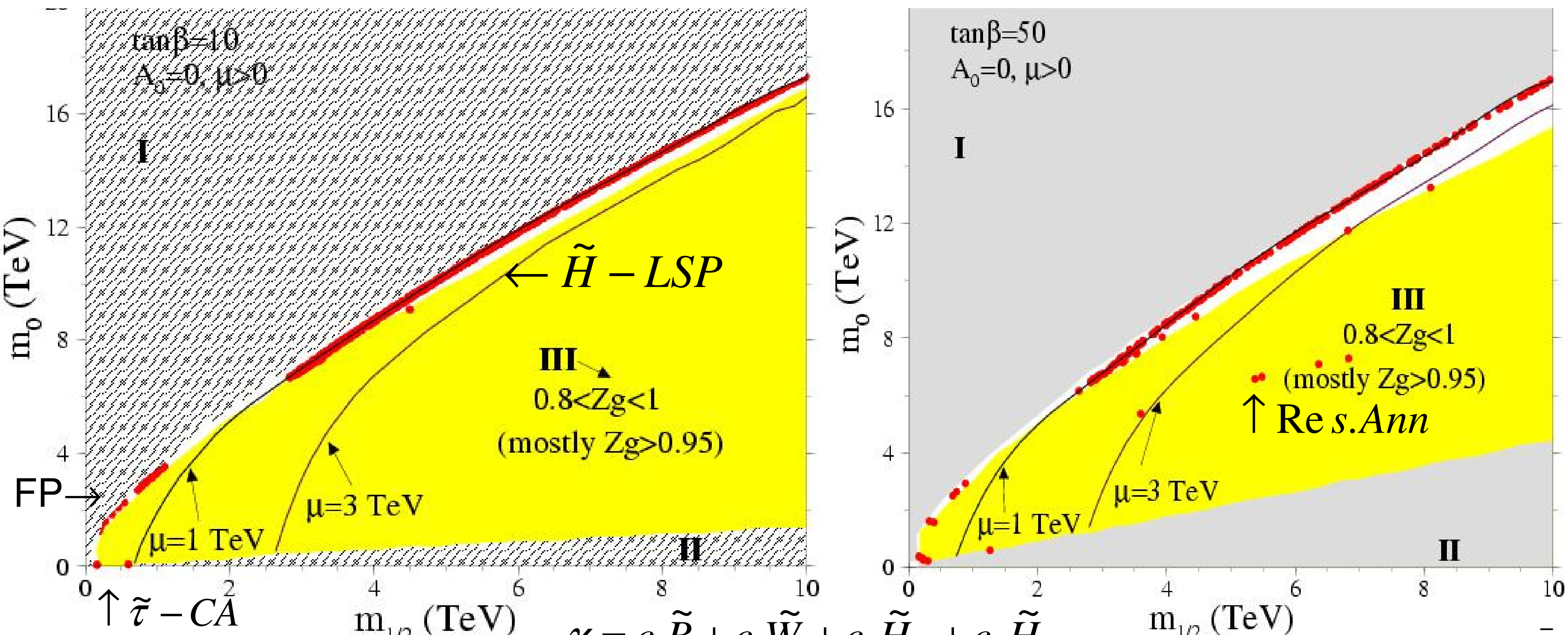
Bino does not carry any gauge charge
$\Rightarrow$ Pair annihilate via sfermion exch



Large sfermion mass $\Rightarrow$ too large Ωh^2
Except for the stau co-ann. region

$m_{\tilde{\tau}} \cong m_{\tilde{B}}$

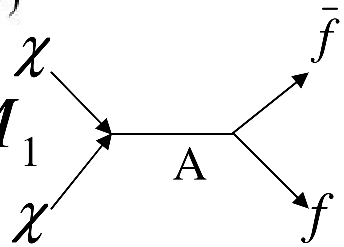




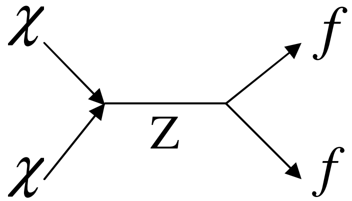
$$\chi = c_1\tilde{B} + c_2\tilde{W} + c_3\tilde{H}_d + c_4\tilde{H}_u$$

$$\tilde{\tau} - CoAnn : m_{\tilde{\tau}} \cong M_1 (within \approx 10\%)$$

$$\mathrm{Re}\, s.Ann : M_A \cong 2M_1$$



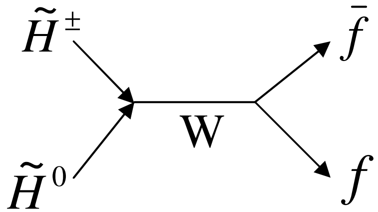
$$Focus - Pt : \mu \cong M_1 (\chi = \tilde{B} - \tilde{H})$$



$$g_{Z\chi\chi} \propto c_3^2 - c_4^2$$

$$\tilde{H} - LSP : M_{\tilde{H}^{\pm,0}} \cong \mu \cong 1 TeV$$

$$(m_\phi \approx m_0 > 7 TeV)$$



$$g_{A\chi\chi}, g_{H\chi\chi} \propto c_{1,2} c_{3,4}$$

Wino LSP (mAMSB model)

SUSY braking in HS in communicated to the OS via the Super-Weyl Anomaly Cont. (Loop)

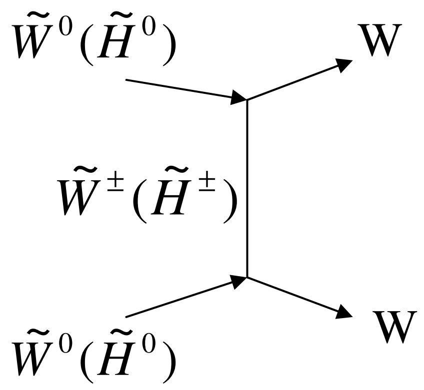
$$M_\lambda = \frac{\beta_g}{g} m_{3/2} \Rightarrow M_1 = \frac{33}{5}\frac{g_1^2}{16\pi^2} m_{3/2}, M_2 = \frac{g_2^2}{16\pi^2} m_{3/2}, M_3 = -3\frac{g_3^2}{16\pi^2} m_{3/2}$$

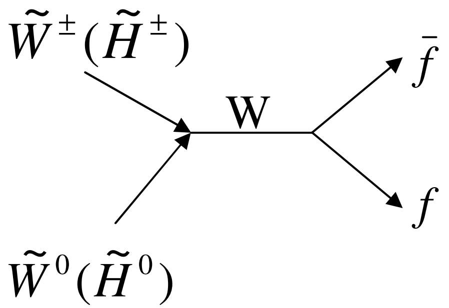
$$A_y = -\frac{\beta_y}{y} m_{3/2} \;\&\; m_\phi^2 = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m_{3/2}^2 + m_0^2$$

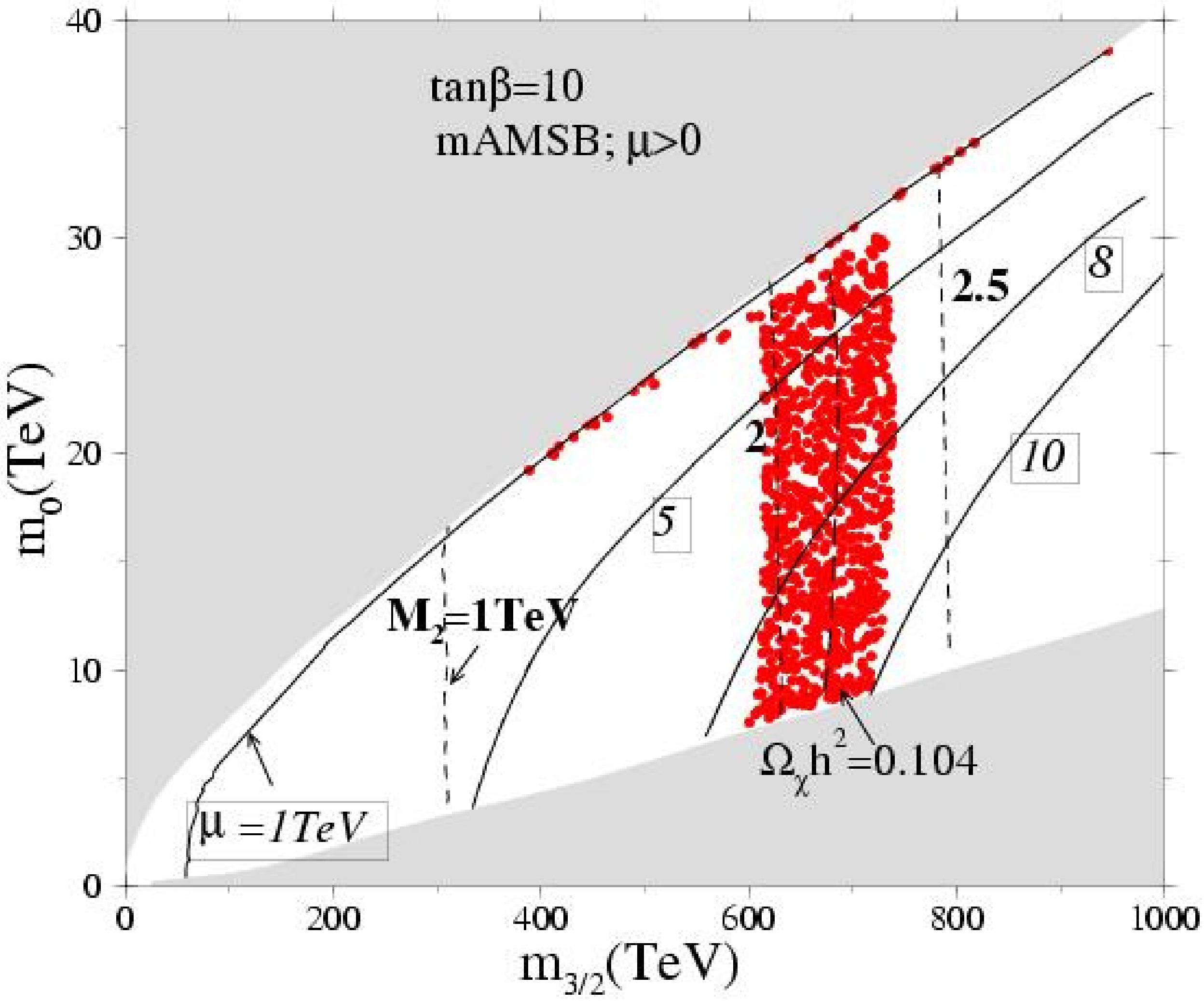
$m_{3/2}$, m_0, tan β, sign (μ)

RGE $\Rightarrow$ *$M_1 : M_2 : |M_3| \approx 2.8 : 1 : 7.1$ including 2-loop conts*

Chattopadhyay et al







$$\tilde{W} - LSP : M_2 = 2.1 \pm 0.2 TeV \ \& \ \tilde{H} - LSP : \mu \cong 1 TeV \, (m_\phi = 10 - 30 TeV)$$

Robust results, independent of other SUSY parameters
(Valid in any SUSY model with Wino(Higgsino) LSP)

Bino LSP Signal at LHC :

$$\tilde{q}\bar{\tilde{q}} \rightarrow q\bar{q}\chi\chi \rightarrow jj\not{E}_T ; \tilde{g}\tilde{g} \rightarrow q\bar{q}q\bar{q}\chi\chi \rightarrow jjjj\not{E}_T$$

Canonical Multijet + Missing-E_T signal with possibly additional jets (leptons) from cascade decay (Valid through out the Bino LSP parameter space, including the **Res.Ann Region**)

Focus Point Region: $M_{Hu}^2 = m_0^2 - (3/2)\underbrace{y_t}_{\approx 2/3} m_0^2 - \underbrace{C_2}_{\approx 2} m_{1/2}^2 = +\varepsilon m_0^2 - 2m_{1/2}^2 = -\mu^2 - M_Z^2/2$

$$m_0 >> m_{1/2} \Rightarrow small|\mu| \approx M_1$$

Inverted Hierarchy

$$m_{\tilde{t}_1}^2 = m_0^2 - \underbrace{y_t}_{2/3} m_0^2 + Cm_{1/2}^2 = (1/3)m_0^2 + Cm_{1/2}^2 ; m_{\tilde{u},\tilde{d}}^2 = m_0^2 + Cm_{1/2}^2$$

$$m_0 = 2TeV, m_{1/2} = 0.5TeV \; \& \tan\beta = 10$$

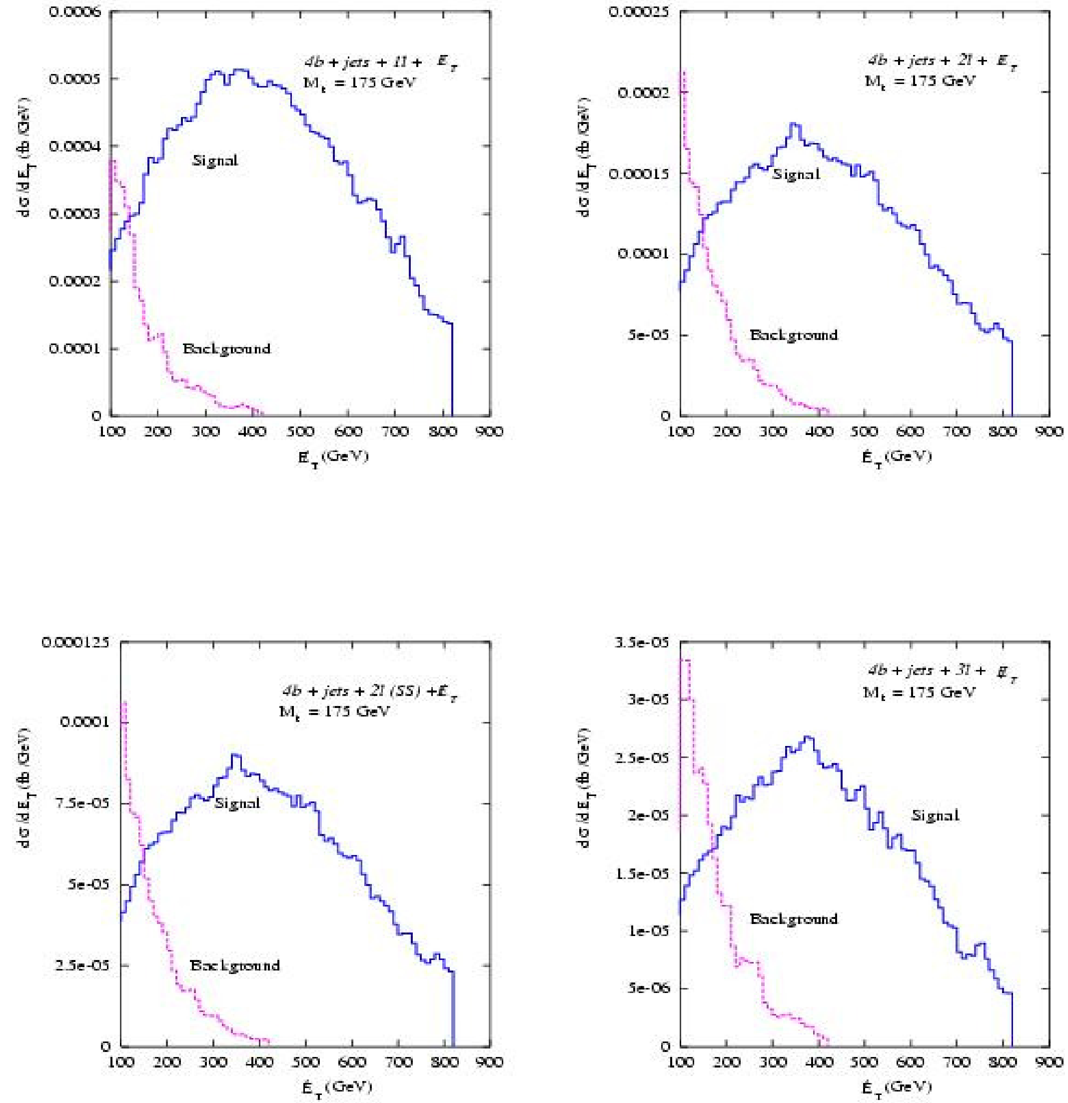
$$\Rightarrow m_{\tilde{g}} = 1.3TeV, m_{\tilde{t}_1} = 1.5TeV, m_{\tilde{u},\tilde{d}} \geq 2.2TeV$$

$$\Rightarrow \tilde{g} \xrightarrow{\tilde{t}_1} \bar{t}t\chi_i^0, \bar{t}b\chi_j^+ \rightarrow 2b2W\chi...$$

$$\Rightarrow \tilde{g}\tilde{g} \rightarrow 4b + 4W(\rightarrow leptons) + \not{E}_T$$

Focus Pt SUSY Signal at LHC

Chattopadhyay et al $4b + jets + \not{E}_T + (1-4)l$



Guchait & Roy

$\tilde{\tau}$ Co-annihilation region

$$m_{\tilde{\tau}_1} \cong m_\chi$$

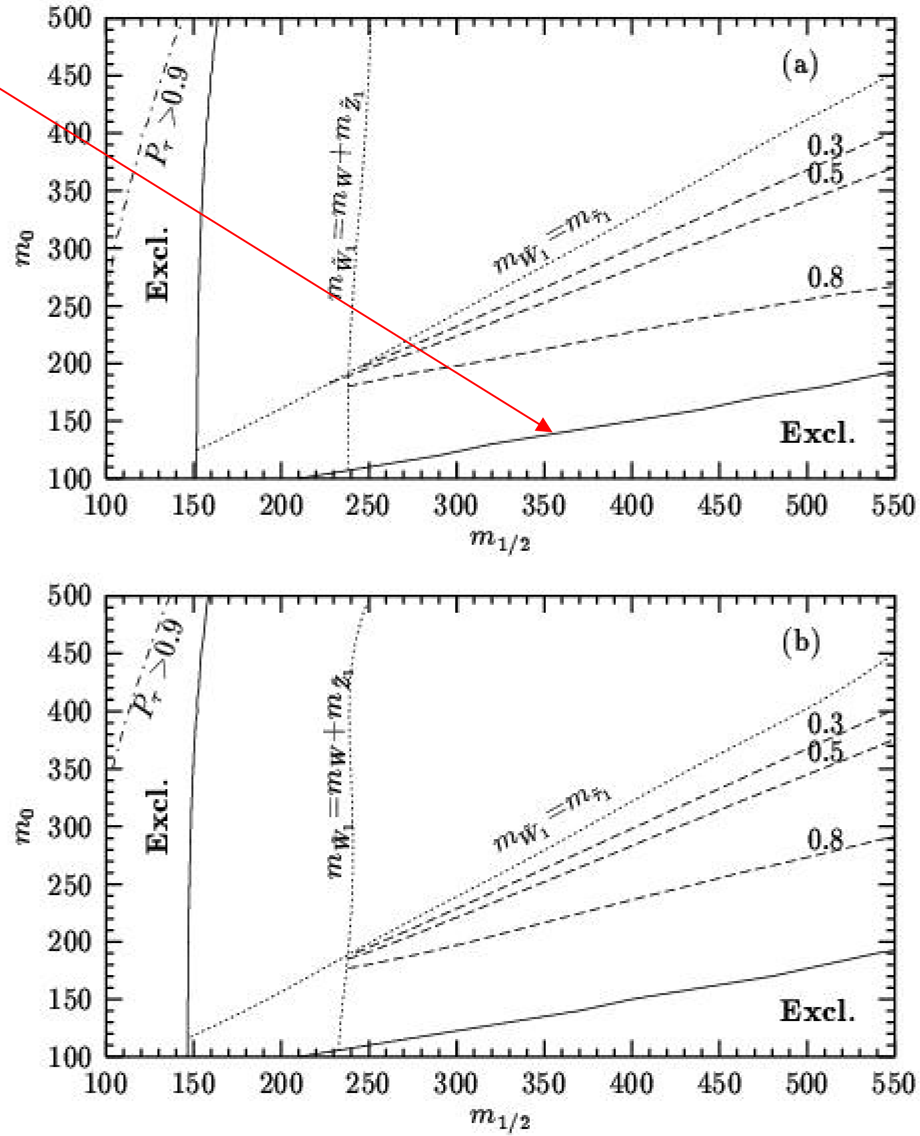
$$\chi_1^\pm \rightarrow \nu\tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \chi\tau$$

BR ≈ 1 BR = 1

τ is soft, but P_τ≈+1

One can use P_τ to detect the Soft τ coming from

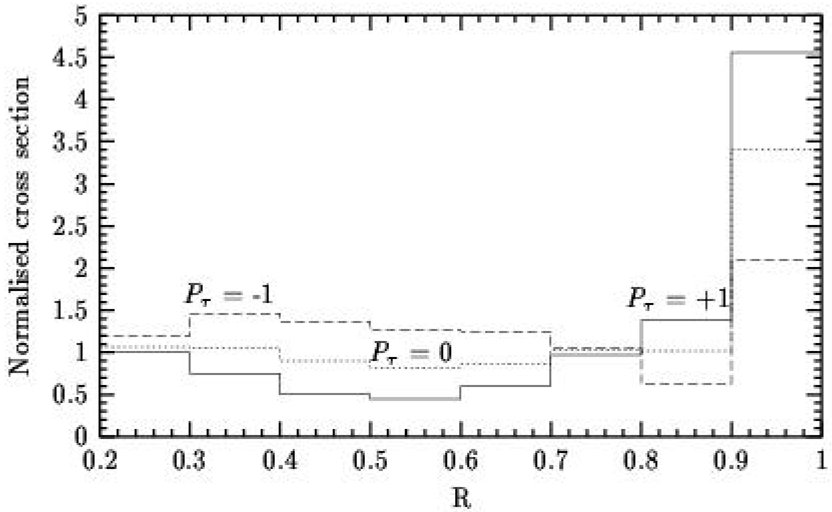
$$\tilde{\tau}_1 \rightarrow \chi\tau.$$



μ >0

μ<0

$$\tilde{W}_1 \equiv \chi_1^\pm, \tilde{Z}_1 \equiv \chi$$



$$R = \frac{p_{\pi^\pm}}{p_{\tau-jet}}$$

$\tau^\pm \to \nu \underbrace{\pi^\pm \pi^0 s}_{\tau-jet}$: 1-prong hadronic τ decay (BR≈0.5)

With $p_T > 20$ GeV cut for the τ-jet the τ misid. Probability from QCD jets goes down from 6% for R > 0.3 ($p_{T\pi\pm}$> 6 GeV) to 0.25% for R > 0.8 ($p_{T\pi\pm}$ > 16 GeV), while retaining most Of the signal.

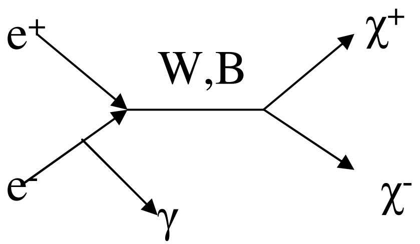
Higgsino & Wino LSP Signals at CLIC:

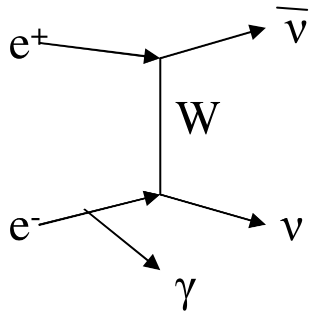
Chottopadhyay et al

$$\bar{q}q \xrightarrow{\gamma,Z} \chi^+\chi^- \rightarrow \pi^+\pi^-\chi\chi; \Delta m \equiv m_{\chi^\pm} - m_{\chi^0} < 10(0.2)GeV \hookleftarrow \tilde{H}(\tilde{W})$$

⇒$\pi^\pm$ are too soft to detect at LHC without any effective tag
⇒Must go to an e^+e^- Collider with reqd. beam energy (CLIC)

Chen, Drees, Gunion





OPAL (LEP) $\Rightarrow m_\chi > 90 GeV (\tilde{H} \,\&\, \tilde{W})$

$$\theta^\gamma > 10^\circ, M_{rec} = \sqrt{s}(1 - 2E^\gamma/\sqrt{s})^{1/2} > 2m_\chi$$

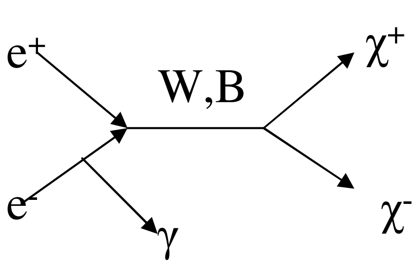
$$e^+e^- \rightarrow \gamma e^+ e^-_\theta : E_T^{\gamma\min} \cong \underbrace{\sqrt{s}}_{3TeV} \sin\theta_{\min} \Rightarrow E_T^\gamma > 50(100)GeV \Rightarrow \theta > 1(2)^\circ$$

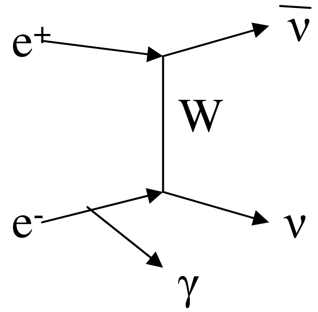
χ± decay tracks :

Δm < 1 GeV ⇒ χ± and /or decay $\pi^\pm$ track with displaced vertex in MVX

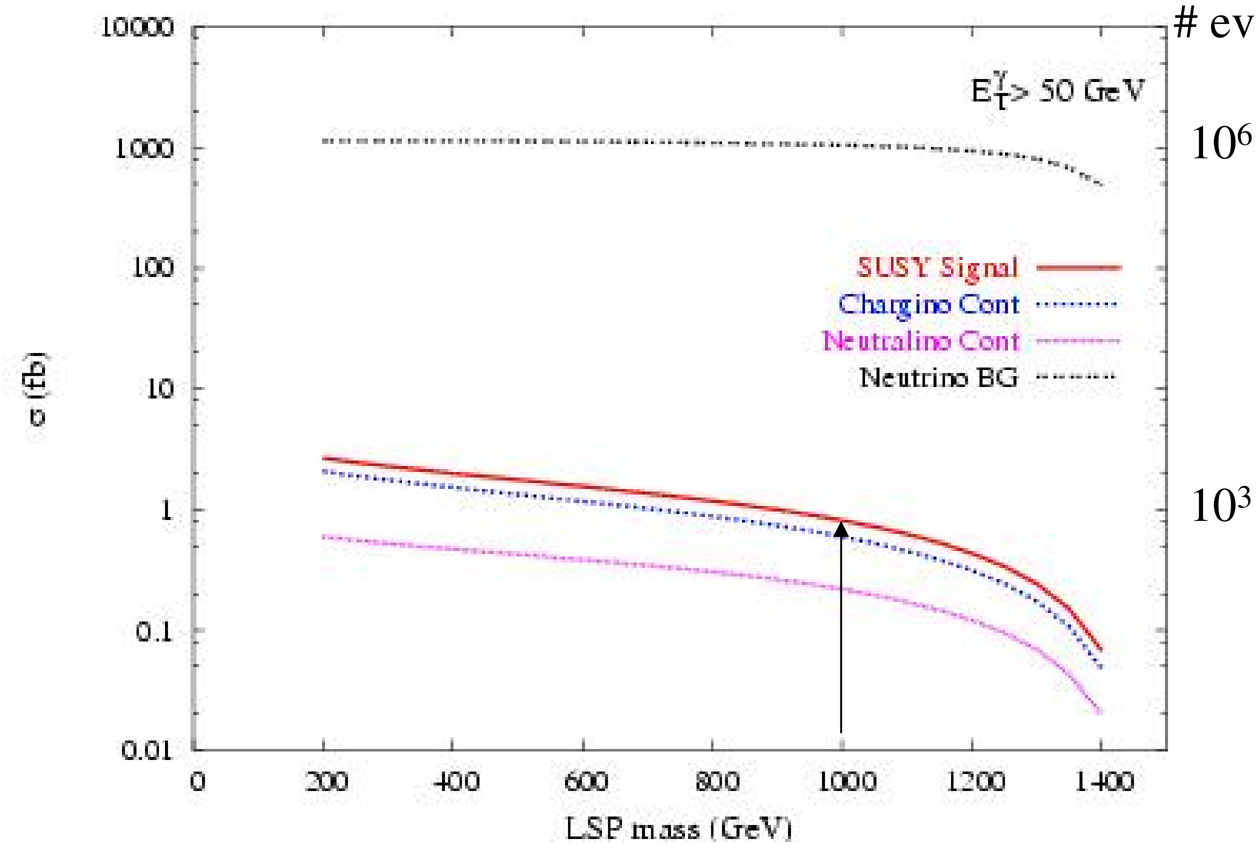
Δm > 1 GeV ⇒ 2 prompt $\pi^\pm$ tracks (Used by OPAL to beat ννγ background)

Higgsino LSP Signal at 3 TeV CLIC : $m_\chi = \mu \approx 1$ TeV





Luminosity = 10^3 ev/fb



$$\frac{S}{B} \approx \frac{1}{1000} \;\&\; \frac{S}{\sqrt{B}} \approx 1$$

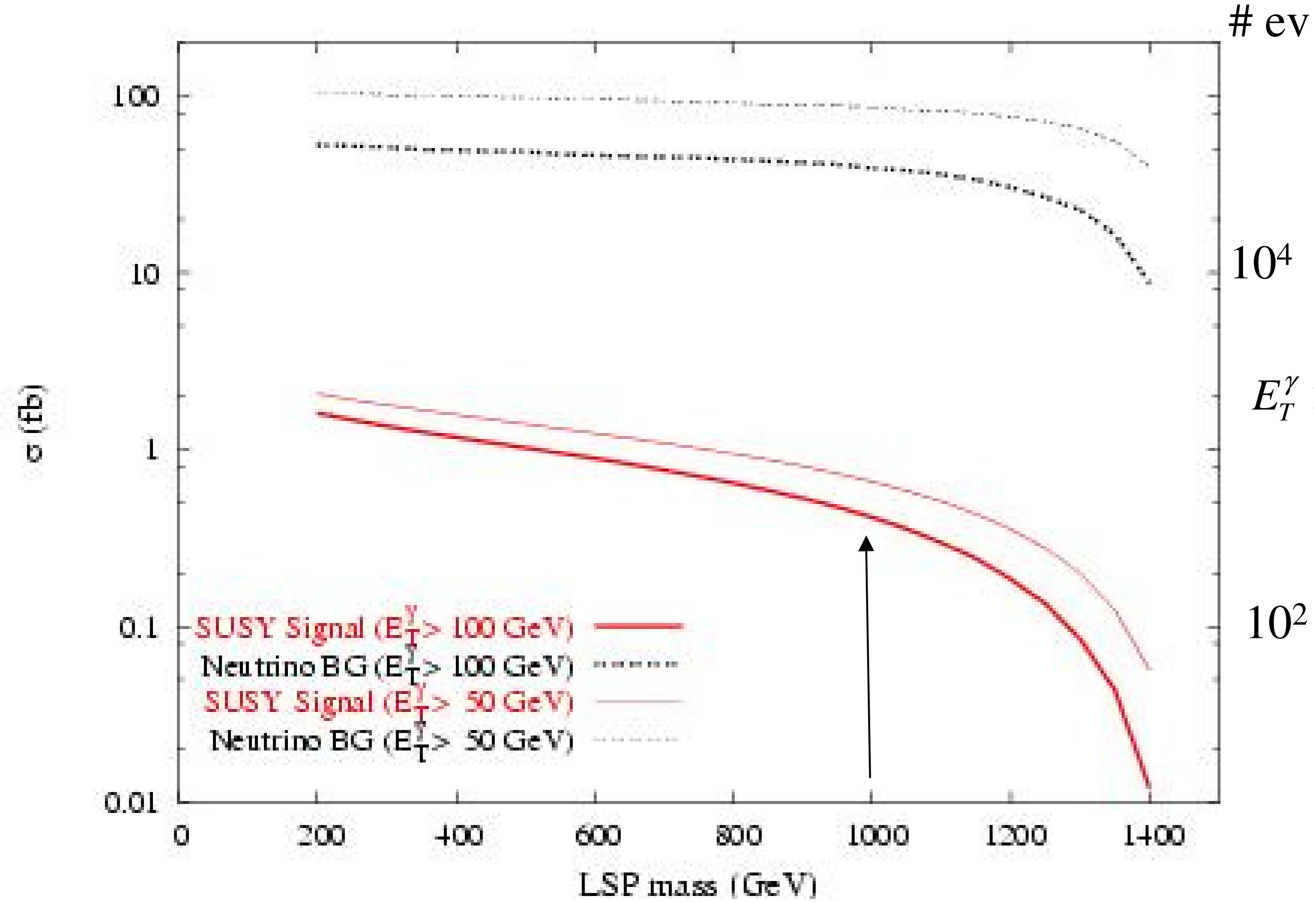
$$\frac{S}{B} \approx \frac{1}{50} \;\&\; \frac{S}{\sqrt{B}} \approx 1 (LEP)$$

($\chi^\pm$ decay $\pi^\pm$ tracks)

Polarized e⁻ (80% R) & e⁺ (60% L) beams :

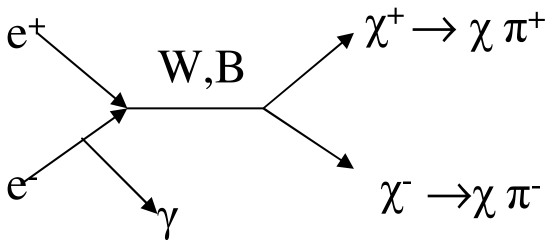
$$e_L^- e_R^+ \Rightarrow 2\% \, Probability (25\% Unpolarized)$$

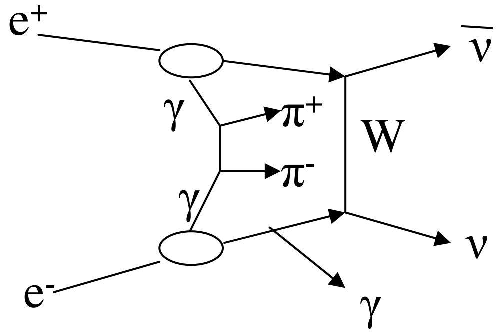
$\Rightarrow$ Suppression of Bg by 0.08 & Sig by 0.8 $\Rightarrow$ Increase of S/B by ~ 10



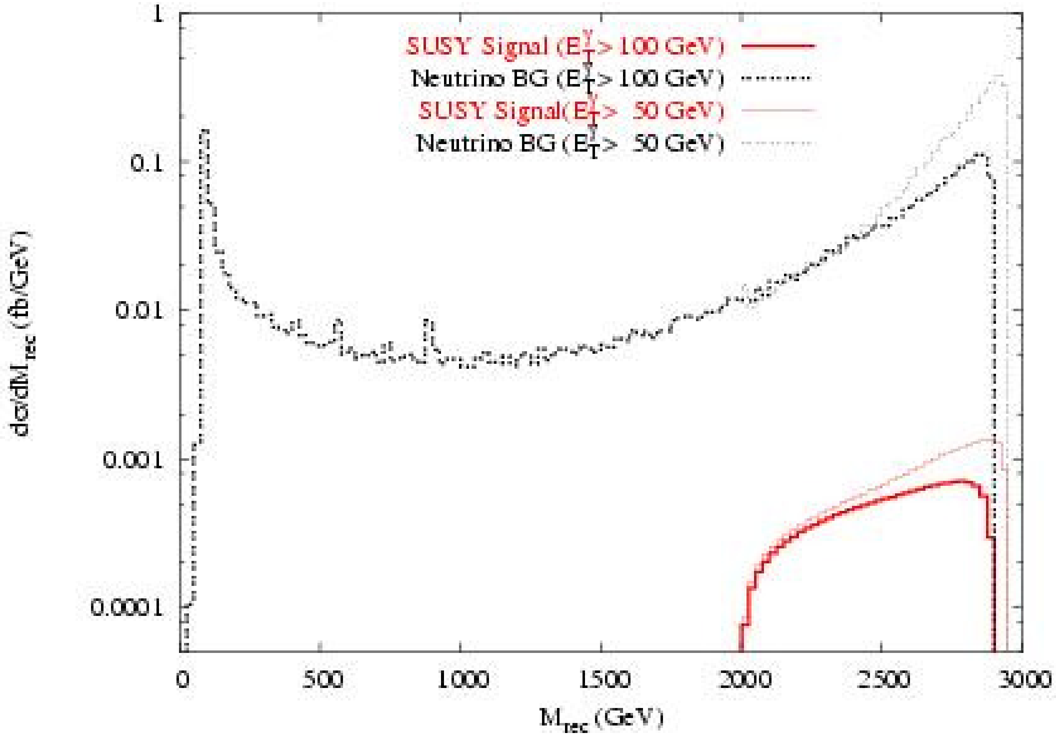
$$E_T^\gamma > 100 GeV \Rightarrow \frac{S}{B} \approx \frac{1}{50} \; \& \; \frac{S}{\sqrt{B}} \approx 3$$

Prompt $\pi^{\pm}$ tracks in the Background from Beamstrahlung





$$\textit{Beamstrahlung Bg } f \approx 0.1: \frac{S}{\sqrt{B}} \approx 3 \Rightarrow \frac{S}{\sqrt{fB}} \approx 10$$



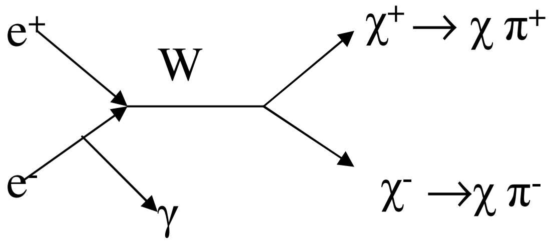
Size of fB present for $M_{rec} < 2$ TeV

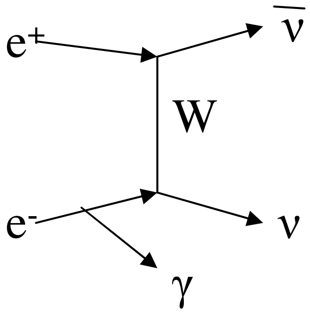
$\Rightarrow$ Estimate of fB for $M_{rec} > 2$ TeV

Any Excess over this Estimate

$\Rightarrow \chi$ signal & χ mass

Wino LSP Signal at 5 TeV CLIC : $m_\chi = M_2 \approx 2$ TeV

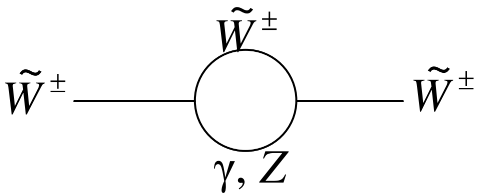




Both Wino Signal and Neutrino Bg couple only to e^-_L & e^+_R.
$\Rightarrow$One can not suppress Bg with polarized beams.
$\Rightarrow$ But one can use polarized beams to increase both Signal and Bg rates.

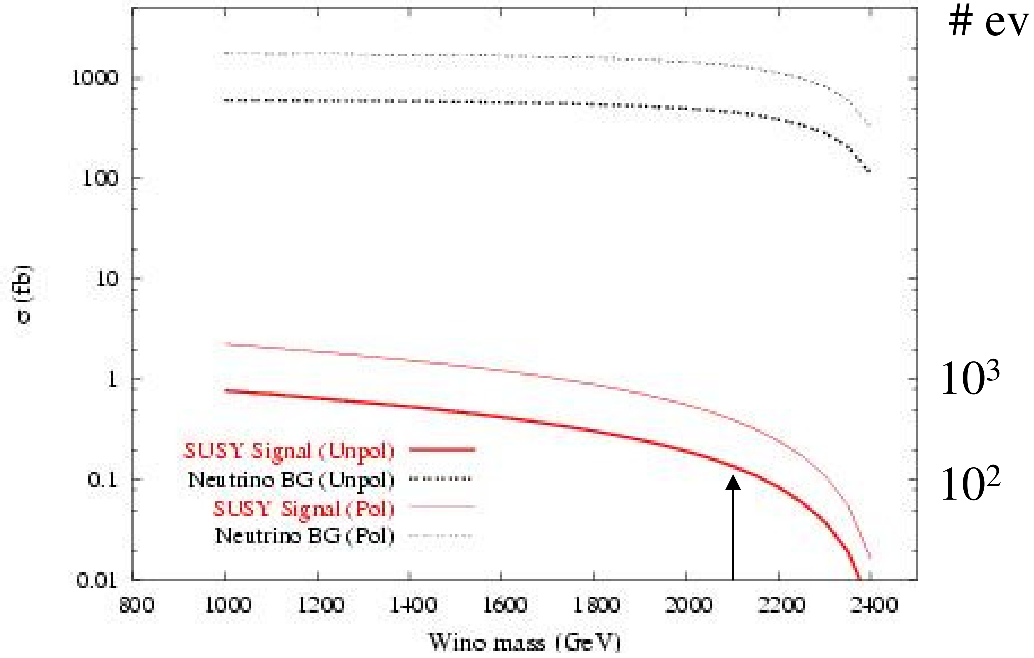
Polarized e^-_L (80%) & e^+_R (60%) $\Rightarrow$ Probability of $e^-_L e^+_R$ = 72% (25% Unpolarized)
$\Rightarrow$ Increase of Signal and Bg rates by factors of 72/25 $\approx$ 3.

Bg effectively suppressed due to a robust prediction of charged and neutral wino mas diff. Δm

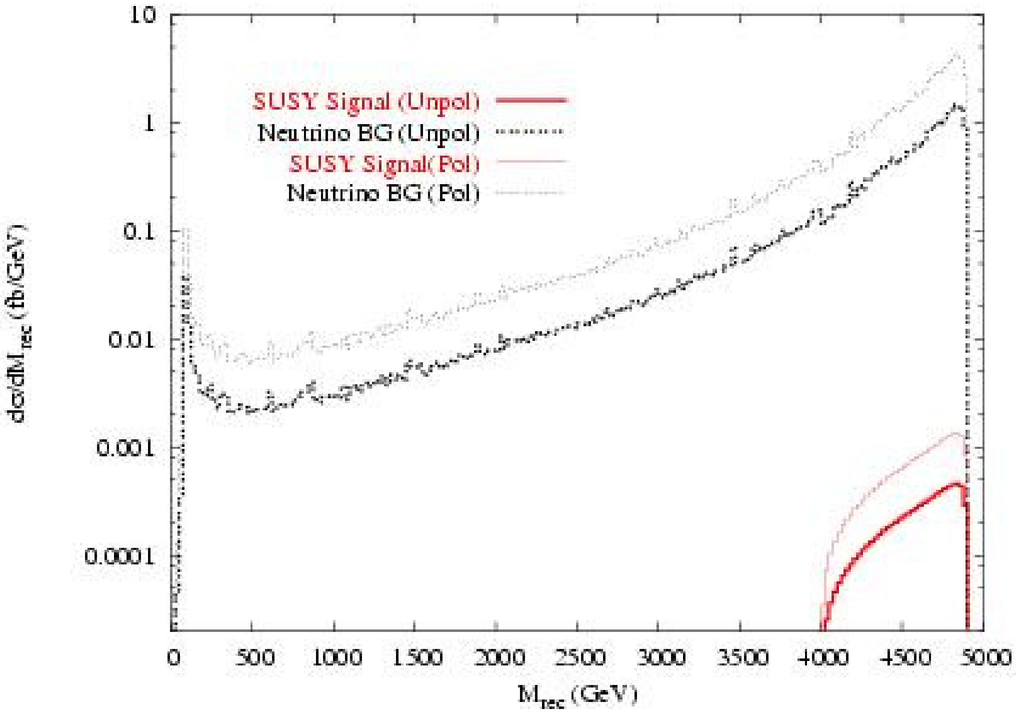


Δm = 165 – 190 MeV for $M_2 \approx 2$ TeV & $\mu > M_2$
$\Rightarrow c\tau$ = 3-7 cm (SLD MVX at 2.5 cm $\rightarrow$ 2 cm at future LC)
$\Rightarrow$Tracks of $\tilde{W}^\pm$ as 2 heavily ionising particles along with their decay $\pi^\pm$ tracks.

Discovery potential is primarily determined by the number of Signal events.



Sig ~ 100 (300) events with Unpolarized (polarized) beams

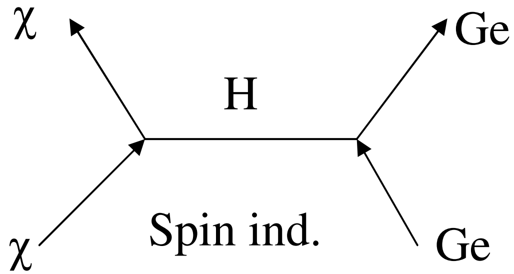


The recoiling mass $M_{rec} > 2m_\chi$ helps to distinguish Sig from Bg & to estimate m_χ.

Bino, Higgsino & Wino LSP Signals in Dark Matter Detection Expts

1. Direct Detection (CDMS, ZEPLIN…)

$$\chi = c_1\tilde{B} + c_2\tilde{W} + c_3\tilde{H}_d + c_4\tilde{H}_u$$



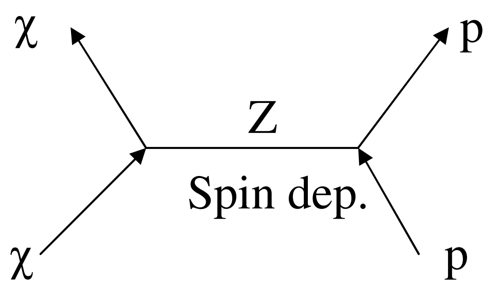
$$g_{Z\chi\chi} \propto c_3^2 - c_4^2 \;\&\; g_{H\chi\chi} \propto c_{1,2}c_{3,4}$$

Best suited for Focus pt. region $\Rightarrow \chi = \tilde{B} - \tilde{H}$

Less for $\tilde{\tau}$ *co-ann & res.ann regions* $\chi \cong \tilde{B}$

Unsuited for $\chi \cong \tilde{H} \,\&\, \tilde{W}$ *(Suppressed both by Hχχ coupling and large χ mass)*

2. Indirect Detection via HE ν from χχ annihilation in the Sun (Ice Cube,Antares)



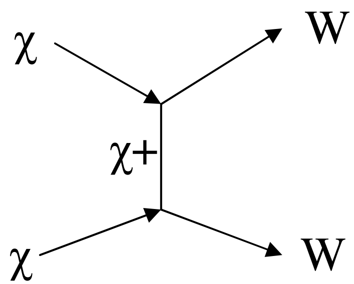
$$R^{ann.}_{\chi\chi} = R^{trap}_{\chi} \propto \sigma_{\chi p} \propto g^2_{Z\chi\chi} \propto (c_3^2 - c_4^2)^2$$

$$\Rightarrow OK for\ \chi = mixed\ (\tilde{B} - \tilde{H})\, Foc.Pt$$

$$\Rightarrow 0\ for\ \chi \cong \tilde{B}, \tilde{W}\ \&\ \tilde{H} \equiv \tilde{H}_d \pm \tilde{H}_u$$

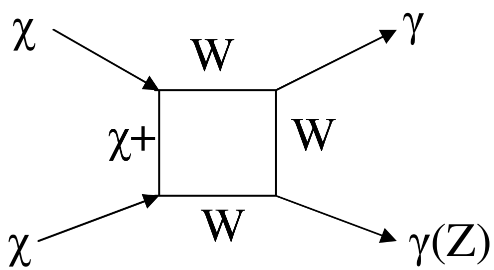
3. Detection of HE γ Rays from Galactic Centre in ACT (HESS,CANGAROO,MAGIC,VERITAS)

$$\chi \cong \tilde{H} \, \& \, \tilde{W}$$



$W \to \pi^0 s \to \gamma s$

$v\sigma_{WW} \sim 10^{-26}$ cm^3/s
⇒Cont. γ Ray Signal
(But too large $\pi^0 \to \gamma$ from Cosmic Rays)



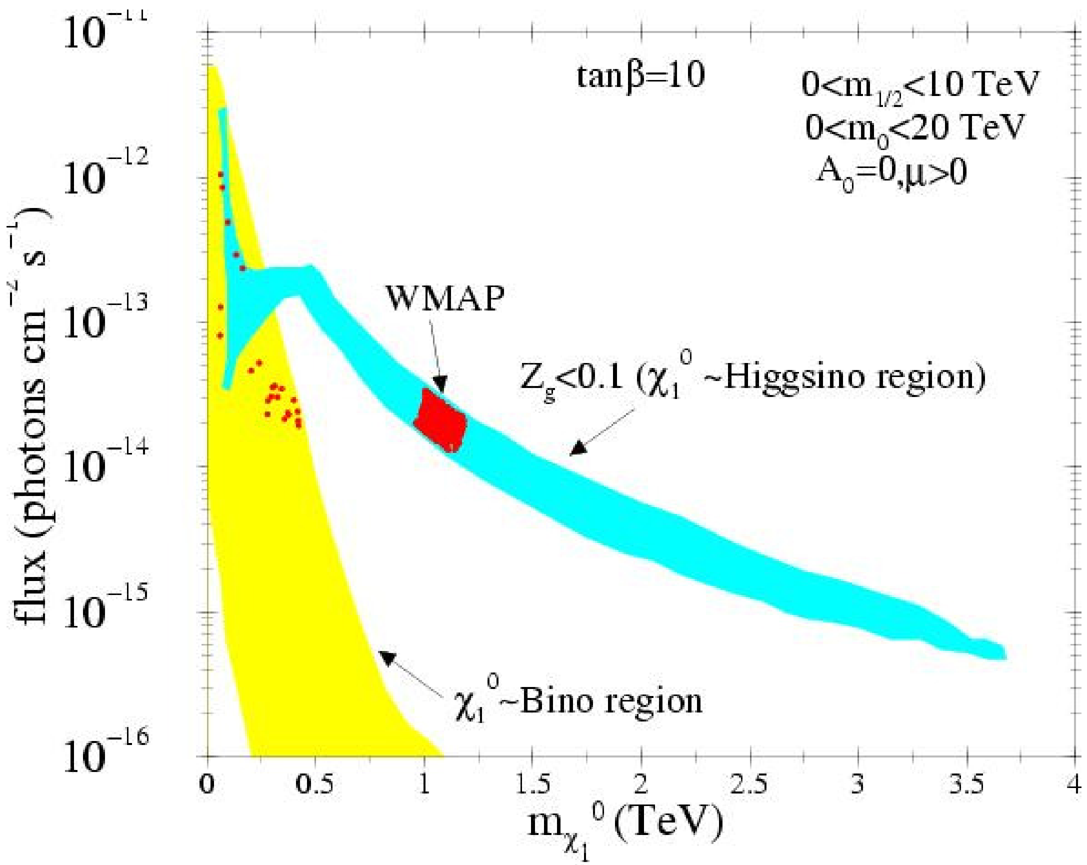
$v\sigma_{\gamma\gamma} \sim v\sigma_{\gamma Z} \sim 10^{-27}$-$10^{-28}$ cm^3/s
⇒Discrete γ Ray Line Signal ($E_\gamma \approx m_\chi$)
(Small but Clean)

γ flux coming from an angle ψ wrt Galactic Centre

$$\phi_\gamma(\psi) = \frac{N_\gamma v\sigma}{4\pi m_\chi^2}\int_{LS}\underbrace{\rho(l)^2}_{DMenergy-density} dl(\psi); N_\gamma = 2(\gamma\gamma),1(\gamma Z)$$

$$\phi_\gamma(\psi) = 1.87\times10^{-14}(N_\gamma v\sigma/10^{-28}cm^3s^{-1})(1TeV/m_\chi)^2 J(\psi)cm^{-2}s^{-1}sr^{-1}$$

$$J(\psi) = \int_{LS}\rho(l)^2 dl/[(0.3GeV/cm^3)^2\times 8.5kpc]$$



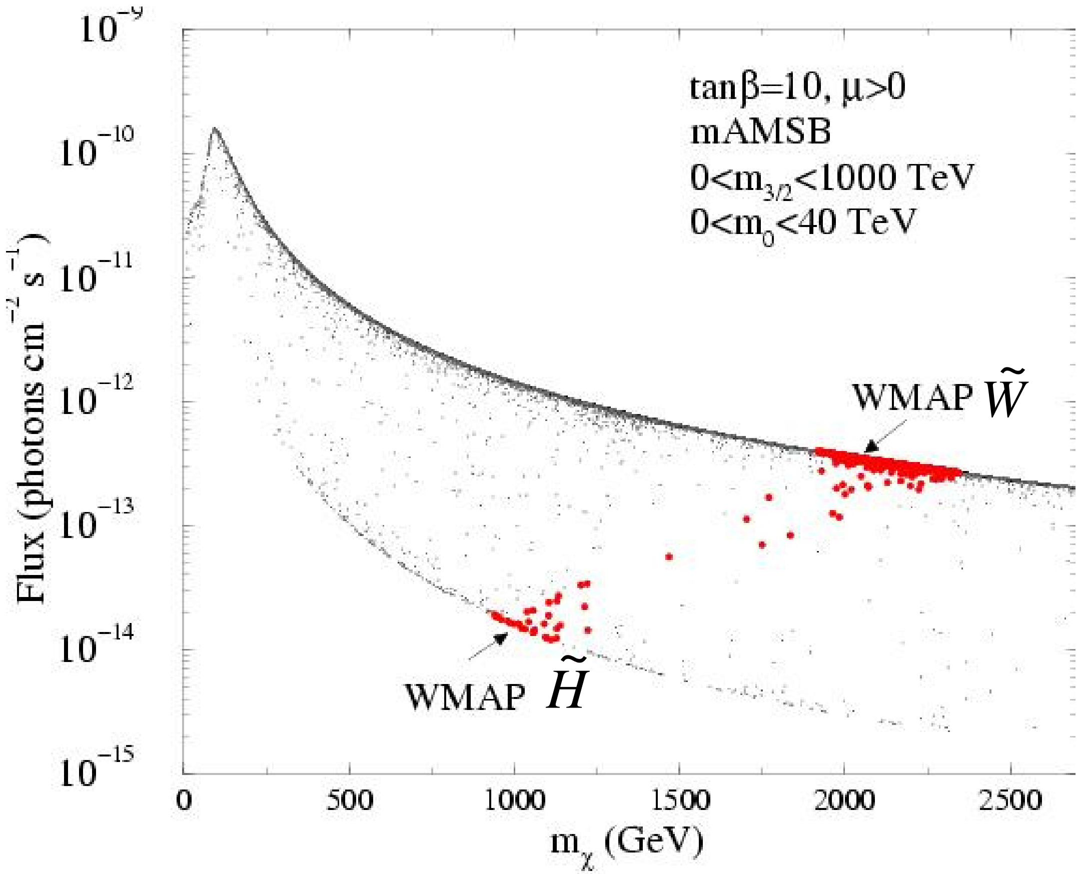
$\int_{\Delta\Omega=0.001sr} J(0)d\Omega \approx 1$ sr (Cuspy:NFW), 10^3 (Spiked), 10^{-3} (Core)

mSUGRA

$\int_{\Delta\Omega=0.001sr}\phi_\gamma\, d\Omega$ (NFW)

←Discovery limit of ACT

Chattopadhyay et al



mAMSB

$$\int_{\Delta\Omega=0.001} \phi_\gamma(\psi)\, d\Omega(NFW)$$

←**Discovery limit of ACT**

Chattopadhyay et al

HESS has reported TeV range γ rays from GC.
But with power law energy spec ⇒ SNR ⇒ Formidable Bg to DM Signal.
The source could be GC (Sgr A*) or the nearby SNR (Sgr A east) within its ang. res.
⇒Better energy & angular resolution to extract DM Signal from this Bg.

Higgsino, Wino & Bino LSP in nonminimal SUSY models

$\tilde{H}$ **LSP in SUGRA models with nonuniversal 1)scalar & 2)gaugino masses**

1)

$$m^2_{Hu} = m^2_{0Hu} - \frac{3}{2}\underbrace{y_t}_{\cong 2/3} m^2_{0\tilde{t}} - \underbrace{C_2}_{\cong 2} m^2_{1/2} = -\mu^2 - M_Z^2/2$$

$$m^2_{0Hu} = m^2_{0\tilde{t}} = m^2_0 \Rightarrow \varepsilon m^2_0 - 2m^2_{1/2} \cong -\mu^2 - M_Z^2/2 \Rightarrow |\mu| > M_1 \;@\; m_0 \approx m_{1/2}$$

$$But: m^2_{0Hu} = 3m^2_0 \Rightarrow 2m^2_0 - 2m^2_{1/2} \cong -\mu^2 - M_Z^2/2 \Rightarrow |\mu| < M_1 \;@\; m_0 \approx m_{1/2}$$

$$\Rightarrow \tilde{H} - LSP$$

J.Ellis et al,….

2)

$$M_i^G \equiv M_{\lambda i} \in \frac{\langle F_S \rangle_{ij}}{M_{Pl}} \lambda_i \lambda_j ; i \;\&\; j = 1,2,3$$

$$SU(5): F_S \supset 24 \otimes 24 = 1 + 24 + 75 + 200$$

$$F_S = 1 \Rightarrow M^G_{1,2,3} = m_{1/2} (Universal) \Rightarrow C_2 \cong 2 \Rightarrow |\mu| > M_1 \;@\; m_0 \approx m_{1/2}$$

$$F_S = 200 \Rightarrow M^G_{1,2,3} = (10,2,1) \times m_{1/2} \Rightarrow C_2 \cong 1.4 \Rightarrow |\mu| < M_1$$

$$\Rightarrow \tilde{H} - LSP$$

Chattopadhyay & Roy,….

Wino LSP in 1)Nonminimal AMSB & 2)String models

1) Tree level SUSY breaking contributions to gaugino and scalar masses

$$M_\lambda \in \frac{\langle F_S \rangle}{M_{Pl}} \lambda\lambda; m_\phi^2 \in \frac{\langle F_S^\dagger \rangle \langle F_S \rangle}{M_{Pl}^2} \phi^* \phi$$

$$F_S \neq 1 (or\, 24 \otimes 24 \not\subset F_S) \Rightarrow M_\lambda = 0 \,@\, tree-level$$

$$But : m_\phi \neq 0 \,@\, tree-level (Symm. Consideration)$$

$m_\phi(tree) \sim 100\, M_\lambda\, (AMSB)$ Giudice et al, Wells

2) String Th: Tree level SUSY breaking masses come only from Dilaton field, while they receive only one-loop contributions from Modulii fields.

Assuming SUSY breaking by a Modulus field $\Rightarrow M_\lambda$ & m_ϕ^2 *at one-loop level*
$\Rightarrow M_2 < M_1 < M_3$ *similar to the AMSB* ($\Rightarrow$ *Wino LSP*) & $m_\phi \sim 10\, M_\lambda$

Brignole, Ibanez & Munoz '94

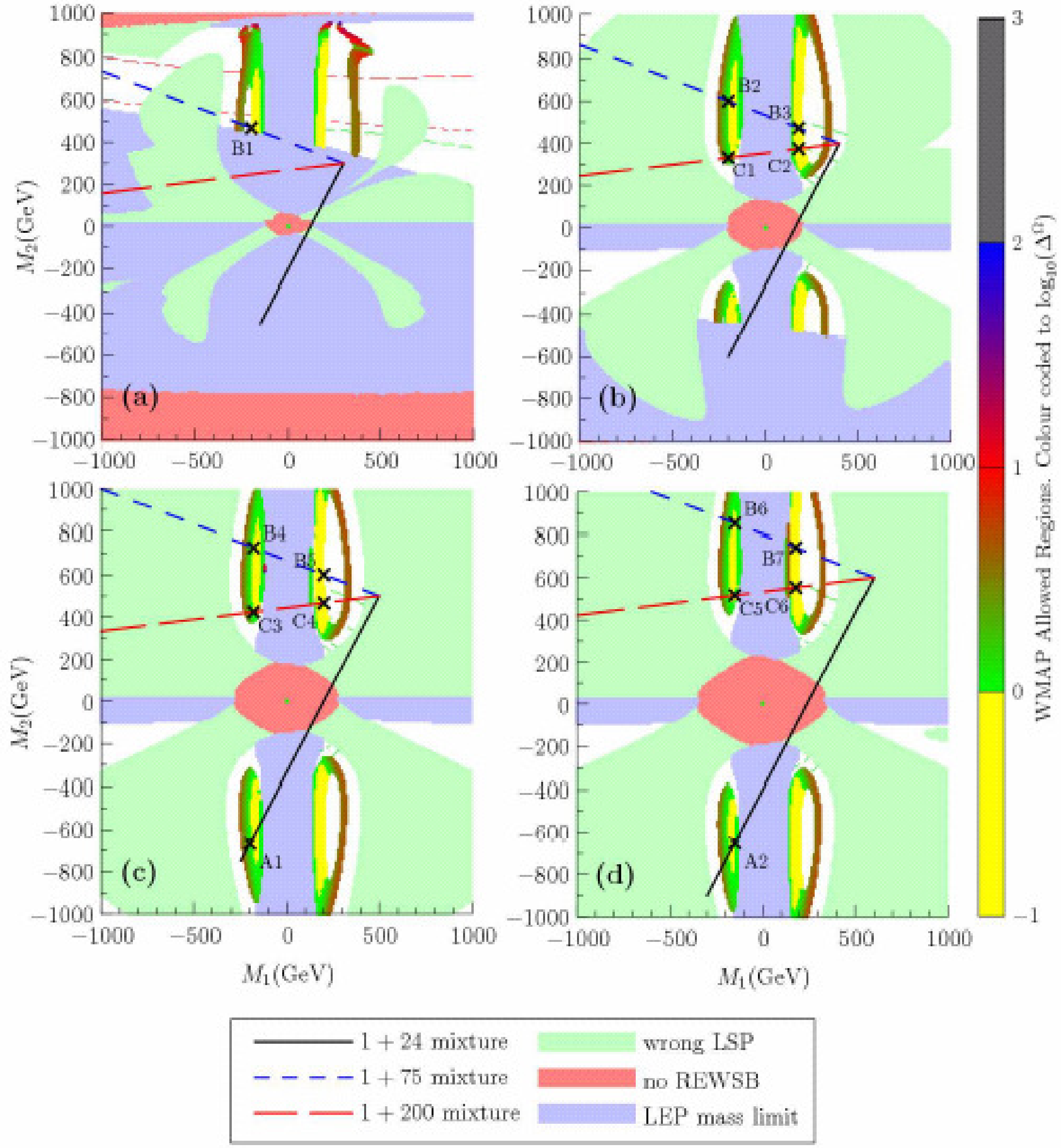
In these models: $M_{\tilde{W}} \approx 2 TeV \Rightarrow m_\phi \approx 10^{1-2} TeV$

Bino LSP in Non-universal Gaugino Mass Model

King, Roberts & Roy 07

Bulk annihilation region of Bino DM (yellow) allowed in Non-universal gaugino mass models

M3 = 300, 400, 500 & 600 GeV



Light right sleptons
Even left sleptons lighter than Wino
=>Large leptonic BR of SUSY
Cascade deacy via Wino

Particle	Mass (GeV)
$\tilde{\chi}_1^0$ (bino)	78.1
$\tilde{\chi}_2^0$ (wino)	457
$\tilde{\chi}_3^0$ (higgsino)	614
$\tilde{\chi}_4^0$ (higgsino)	636
$\tilde{\chi}_1^+$ (wino)	461
$\tilde{\chi}_2^+$ (higgsino)	635
M_1	81
M_2	470
μ	611
$\tilde{g}$	1150
$\tilde{\tau}_1$	104
$\tilde{\tau}_2$	399
$\tilde{e}_R, \tilde{\mu}_R$	115
$\tilde{e}_L, \tilde{\mu}_L$	399
$\tilde{t}_1$	793
$\tilde{t}_2$	1025
$\tilde{b}_1$	980
$\tilde{b}_2$	1000
$\tilde{q}_{1,2,R}$	$\sim$ 1005
$\tilde{q}_{1,2,L}$	$\sim$ 1070