Neutralinos and Charginos in the Light of the Higgs Boson

Tao Han
PITT PACC &
TsingHua Center for HEP

Work to appear, in collaboration with
Sanjay Padhi, Shufang Su

Outline

- Introduction/Motivation
- Current exp search limits on MSSM EW sector
- MSSM EW-ino sector
- Neutralinos/Charginos: production and decay
- Collider analyses:
    - Wh, Zh, hh final states
    - Comparison with conventional Neutralino/Chargino search channels
- Conclusion

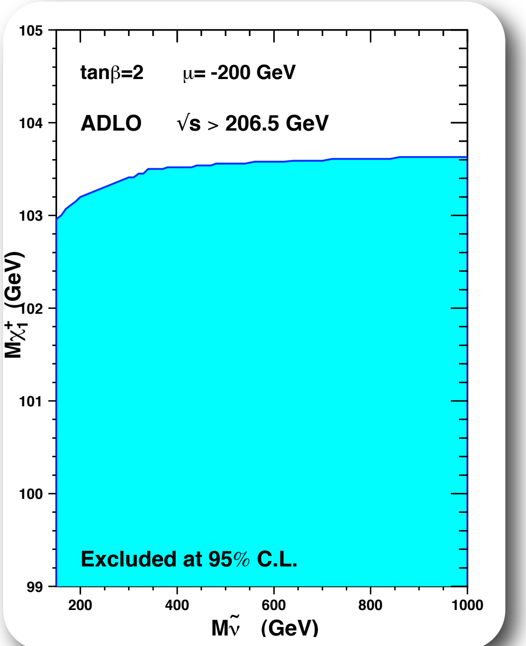
Motivation

- Higgs connection
  - natural SUSY: light gauginos and Higgsinos
- DM connection
  - neutralinos: DM candidate
- Colored superparticle might be very heavy
  - no indication from current LHC search: m_{sq}, m_{gluino} > 1 TeV
  - EW sector (+stop/sbottoms) might be the only particles accessible at the LHC
- Neutralinos and Charginos
  - suffer from small electroweak production
  - current search mostly focused on slepton assisted channels
  - current reach of neutralino/chargino w/o slepton: limited
- Connection to Lepton Collider

Exploring LHC reach for the electroweak sector of MSSM
gauginos, Higgsinos with the help of the Higgs boson

Current limits: neutralino/chargino

canonical case

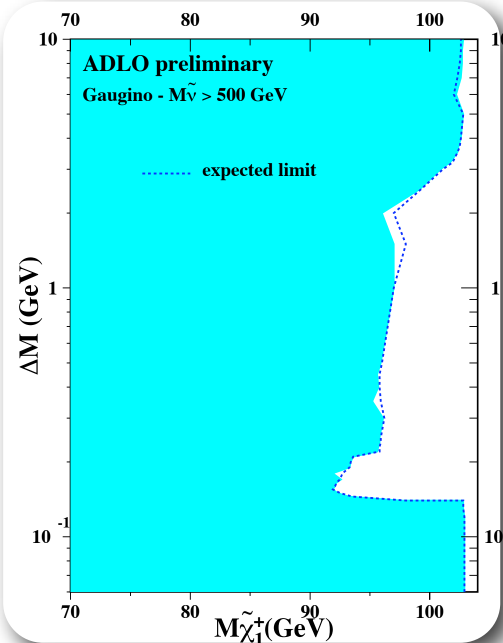


$m\chi_1^\pm$ > 103.5 GeV
for m_{snue} > 300 GeV

LEPSUSYWG/01-03.1

T. Han

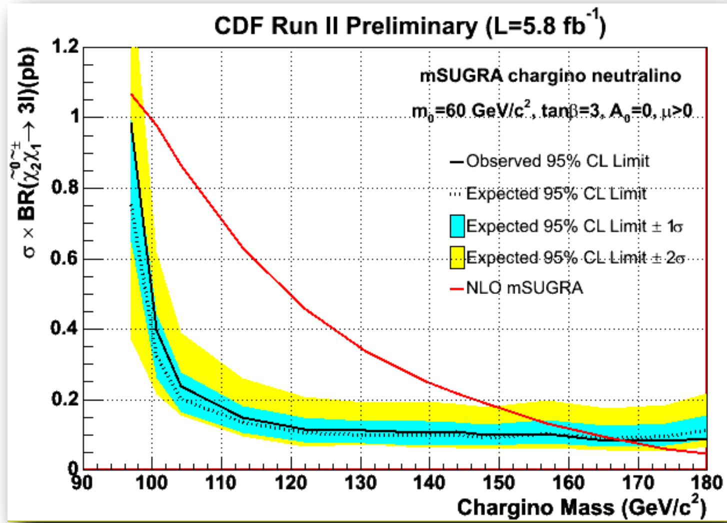
degenerate case



$m\chi_1^\pm$ > 91.9 /92.4 GeV

LEPSUSYWG/02-04.1

trilepton+MET from $\chi_1^\pm$ χ_2^0



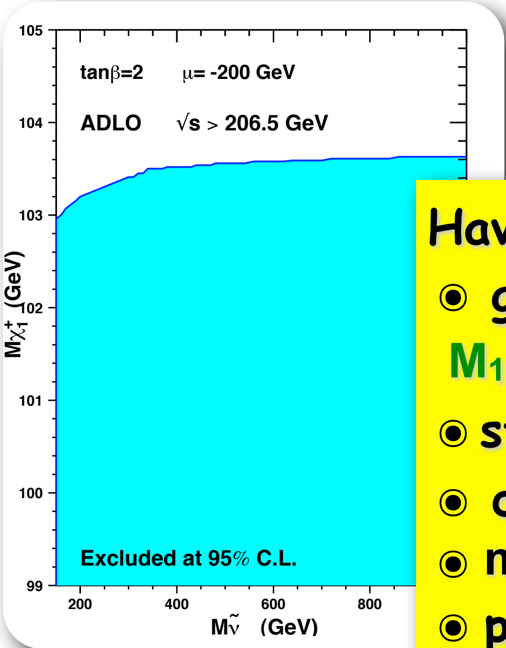
$m\chi_1^\pm$ > 167 GeV
(mSUGRA tanβ=3, A_0=0)

CDF Note 10636
D0: arXiv:0901.0646

$m\chi_1^0$ > 47/50 GeV
(CMSSM, mSUGRA)
No mass limit in general

Current limits: neutralino/chargino

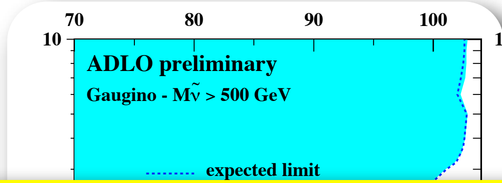
canonical case



$m\chi_1^\pm > 103.5$ GeV
for $m_{snue} > 300$ GeV

LEPSUSYWG/01-03.1

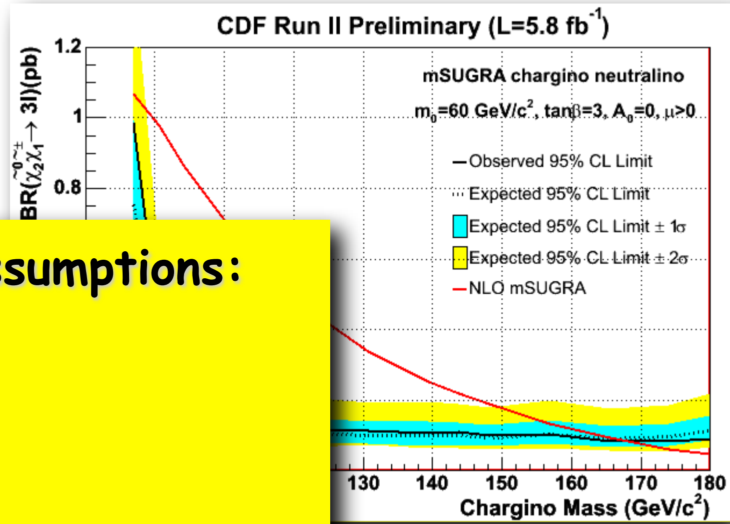
degenerate case



$m\chi_1^\pm > 91.9\ /92.4$ GeV

LEPSUSYWG/02-04.1

trilepton+MET from $\chi_1^\pm\ \chi_2^0$



GeV
tanβ=3, A_0=0)

36

D0: arXiv:0901.0646

$m\chi_1^0 > 47/50$ GeV
(CMSSM, mSUGRA)
No mass limit in general

Have at least one of these assumptions:

- gaugino mass unification:
  $M_1 = (5/3)\tan^2\theta_W M_2 = 1/2\ M_2$
- sfermion mass unification
- decouple sfermions
- mSUGRA
- particular benchmark point
- ...

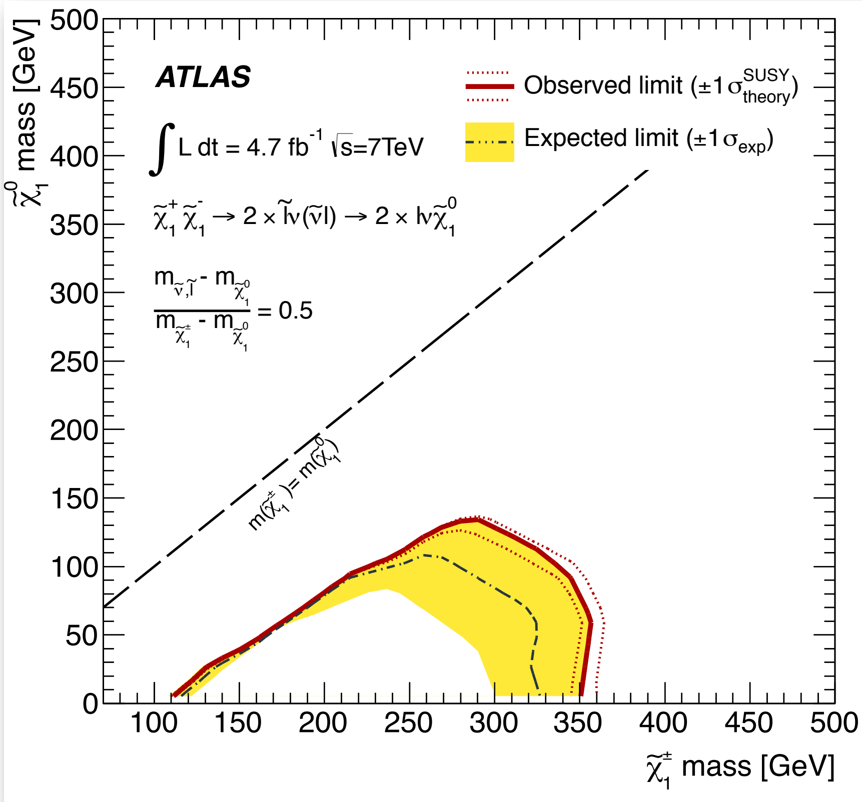
T. Han

Monday, November 12, 2012

ATLAS Limits: LHC 7 TeV with 4.7 fb^{-1}

dilepton + MET, with or w/o jets

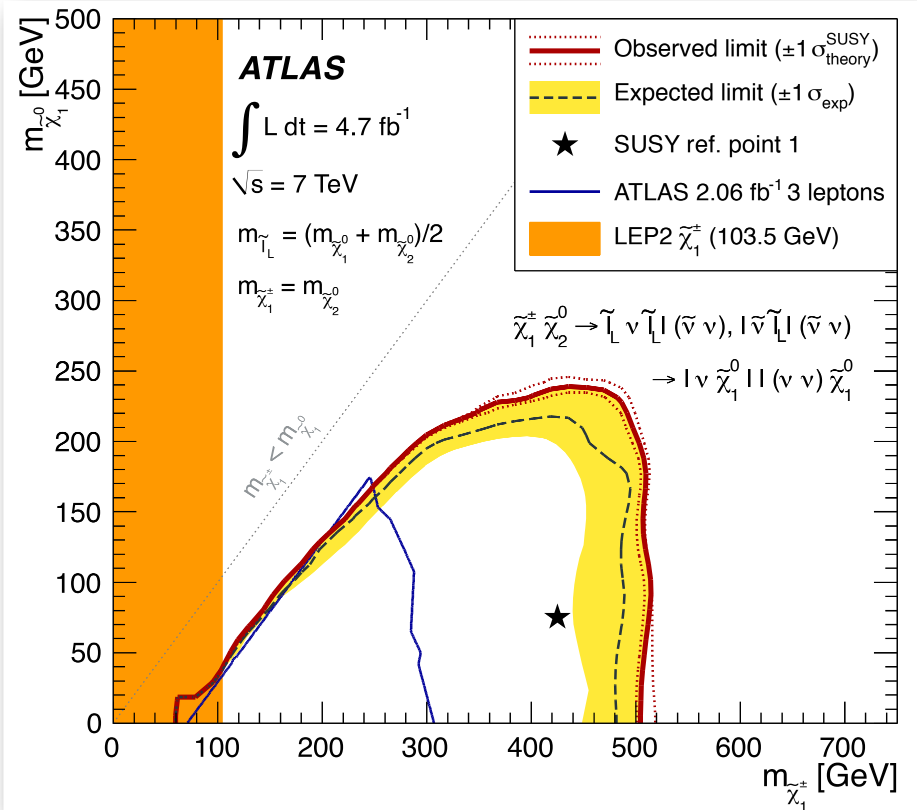
ATLAS 1208.2884



110 GeV < $m_{\chi 1\pm}$ < 340 GeV

trilepton + MET

ATLAS 1208.3144



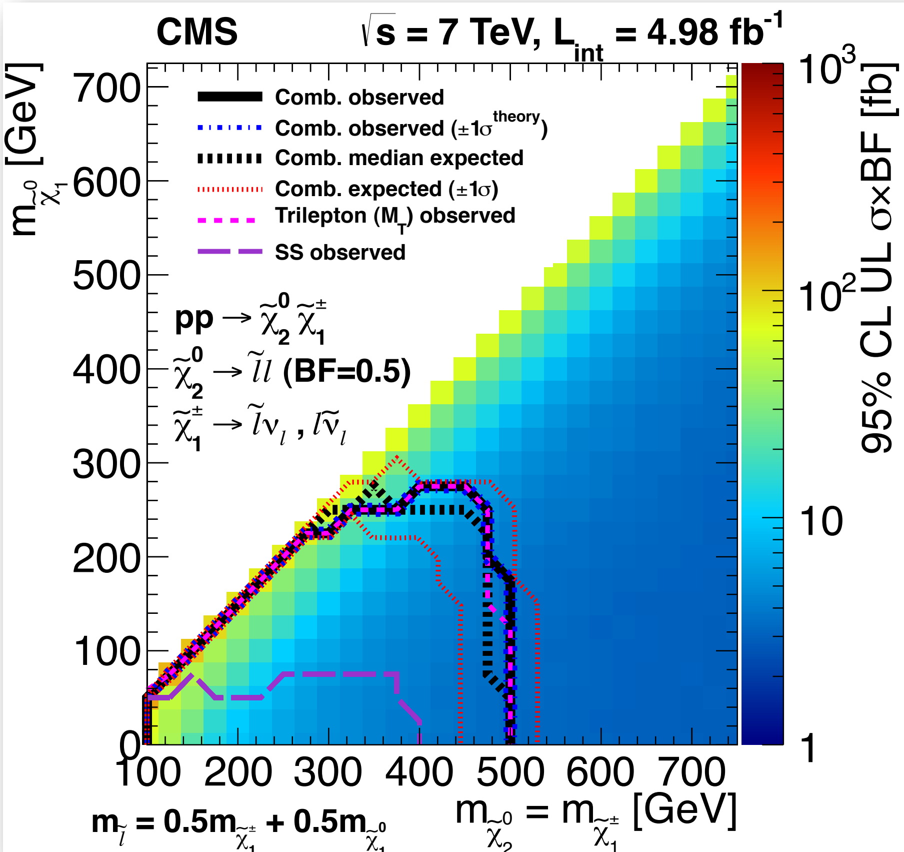
60 GeV < $m_{\chi 1\pm}$ < 500 GeV

Monday, November 12, 2012

ATLAS Limits: LHC 7 TeV with 4.7 fb^{-1}

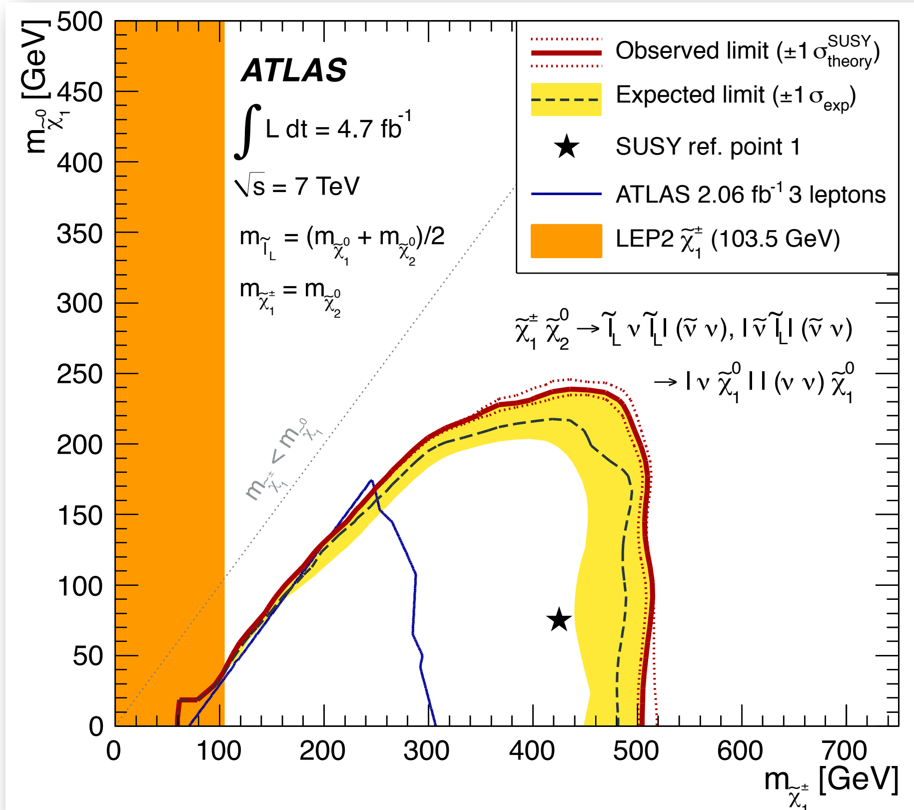
dilepton or trilepton + MET

CMS 1209.6620



trilepton + MET

ATLAS 1208.3144



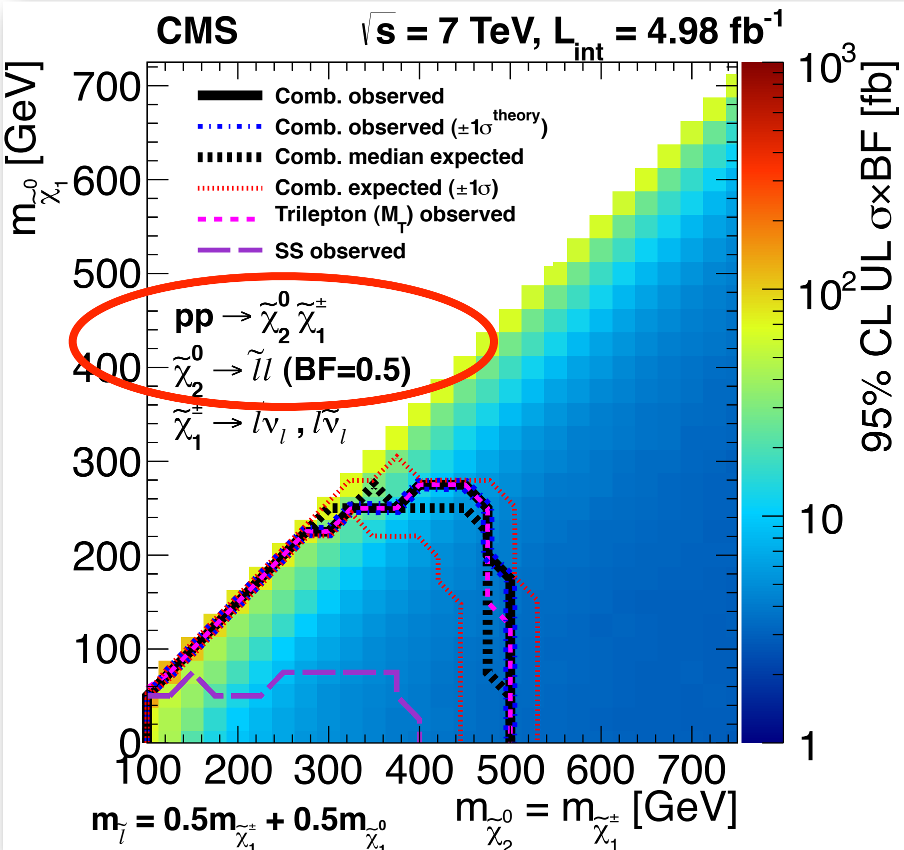
T. Han

60 GeV < $m_{\chi 1\pm}$ < 500 GeV

ATLAS Limits: LHC 7 TeV with 4.7 fb^{-1}

dilepton or trilepton + MET

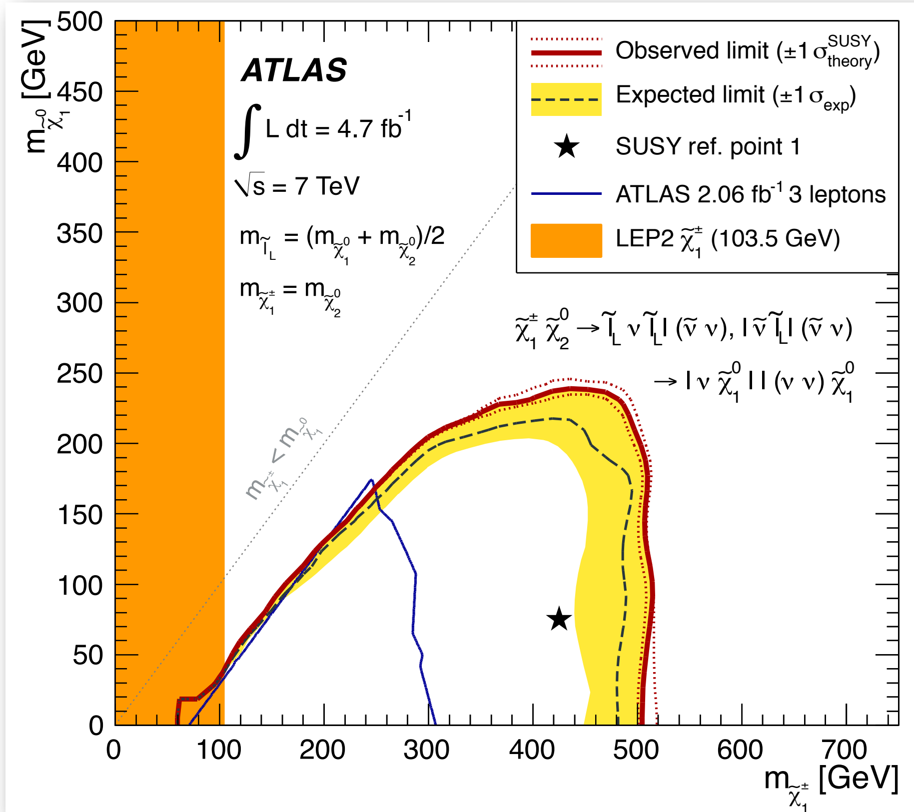
CMS 1209.6620



T. Han

trilepton + MET

ATLAS 1208.3144

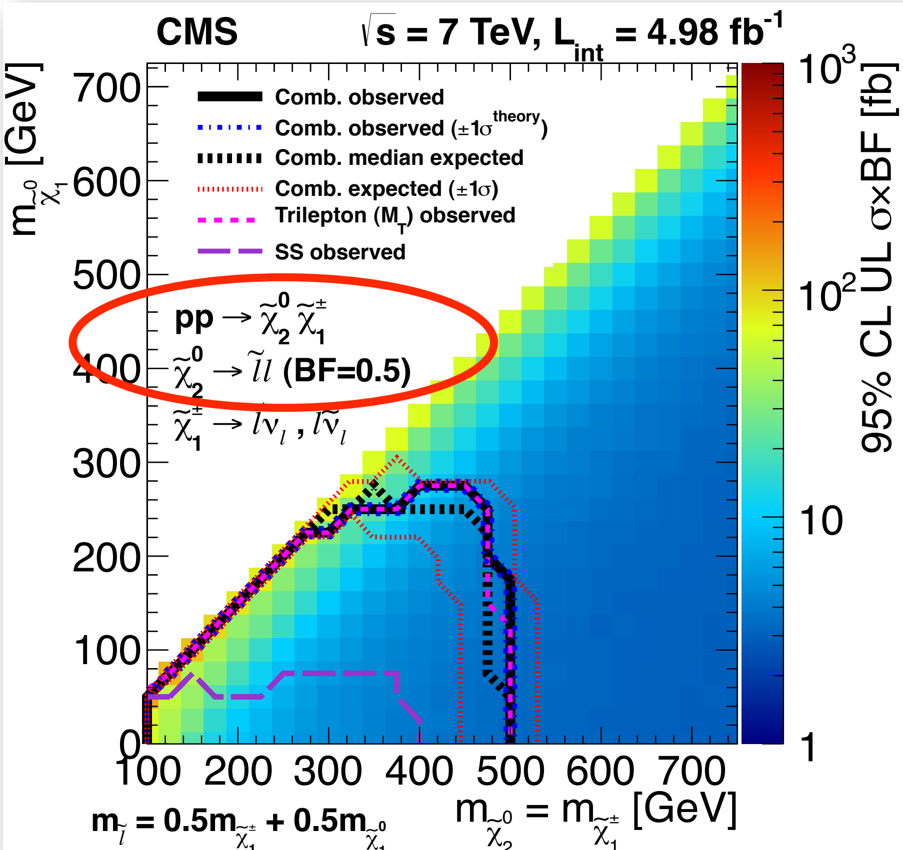


60 GeV < $m_{\chi 1\pm}$ < 500 GeV

ATLAS Limits: LHC 7 TeV with 4.7 fb^{-1}

dilepton or trilepton + MET

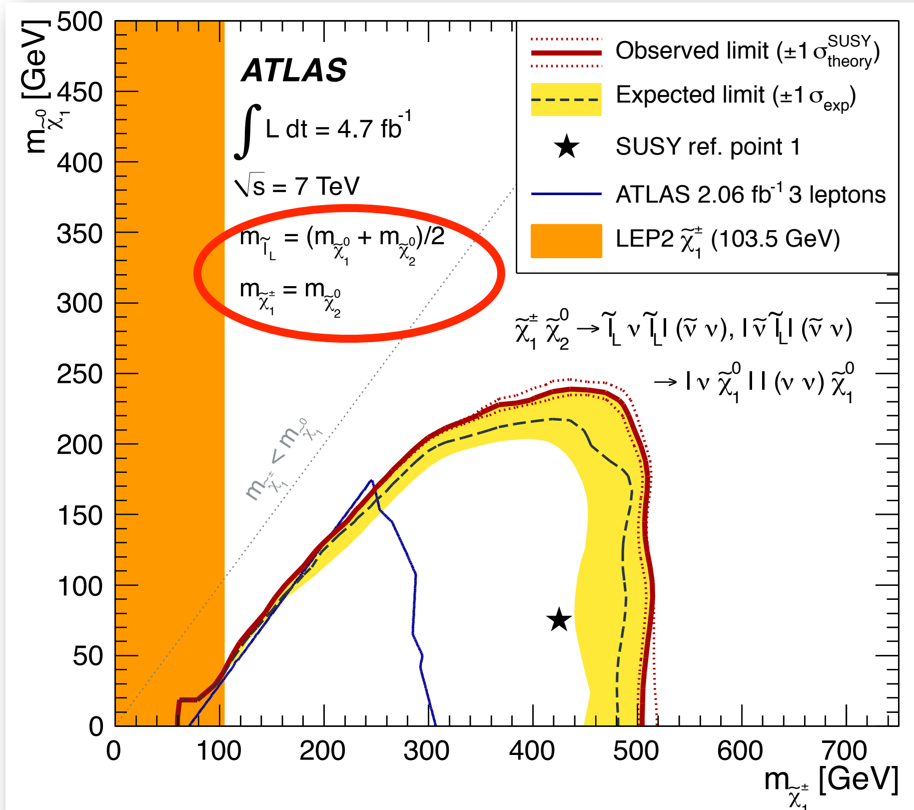
CMS 1209.6620



T. Han

trilepton + MET

ATLAS 1208.3144

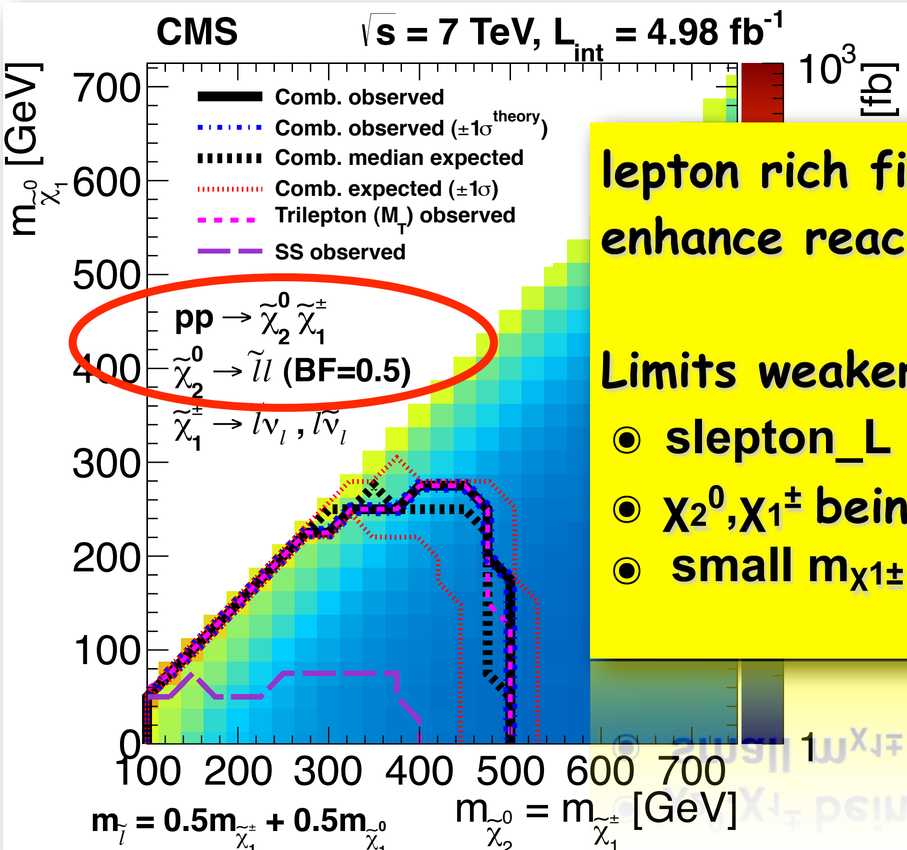


60 GeV < $m_{\chi 1\pm}$ < 500 GeV

ATLAS Limits: LHC 7 TeV with 4.7 fb^{-1}

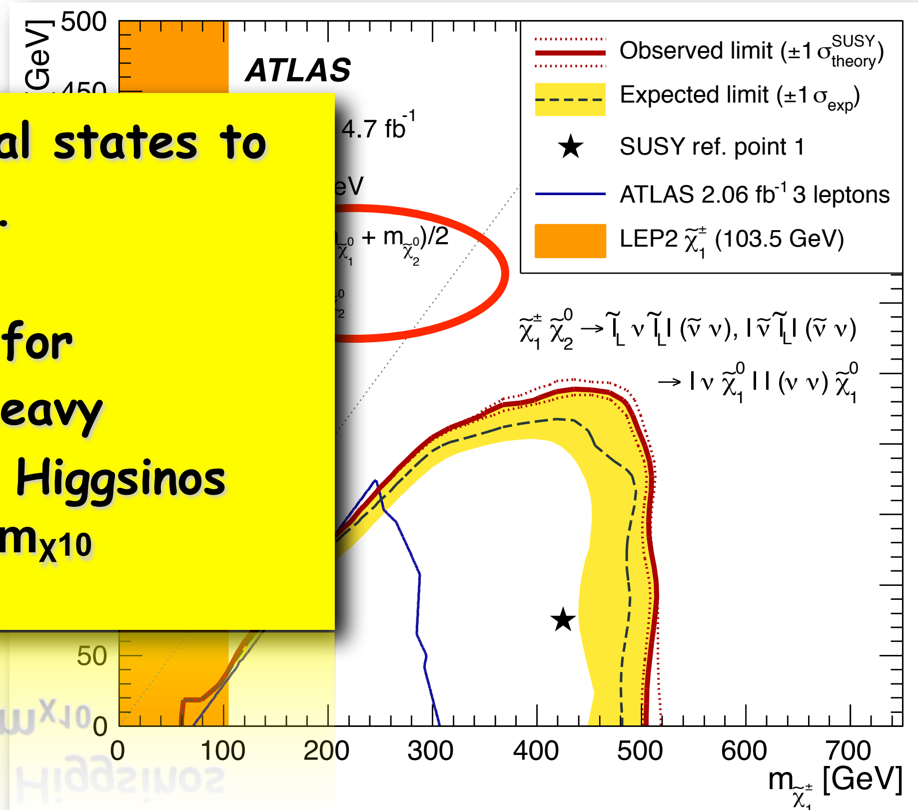
dilepton or trilepton + MET

CMS 1209.6620



trilepton + MET

ATLAS 1208.3144



lepton rich final states to enhance reach.

Limits weaker for

- **slepton_L heavy**
- **$\chi_2^0, \chi_1^\pm$ being Higgsinos**
- **small $m_{\chi 1\pm} - m_{\chi 10}$**

60 GeV < $m_{\chi 1\pm}$ < 500 GeV

T. Han

MSSM EW-ino sector 101

- Gauginos and Higgsinos
  - Neutral ones: Bino, Wino, $\tilde{H}_u^0$, $\tilde{H}_d^0$
  - charged ones: Winos, $\tilde{H}_u^+$, $\tilde{H}_d^-$
- Parameters: M_1, M_2, μ, $\tan\beta$

→

- Neutralinos and charginos

Neutralinos

- **Neutralinos** $\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

M_1 Bino
M_2 Wino
$|\mu|$ Higgsino
$|\mu|$ Higgsino

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & 1 & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

Neutralinos

- **Neutralinos** $\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

M_1	**Bino**
M_2	**Wino**
$\lvert\mu\rvert$	**Higgsino**
$\lvert\mu\rvert$	**Higgsino**

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & 1 & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

Neutralinos

- **Neutralinos** $\psi^0 = (\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

M_1	Bino
M_2	Wino
$\lvert\mu\rvert$	Higgsino
$\lvert\mu\rvert$	Higgsino

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}\frac{m_Z}{M'}) & 1 & \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \mathcal{O}(\frac{m_Z}{M}) & \mathcal{O}(\frac{m_Z}{M}) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

Charginos

- **Charginos** $\psi^{\pm} = (\tilde{W}^{+}, \tilde{H}_u^{+}, \tilde{W}^{-}, \tilde{H}_d^{-})$

$$M_{\tilde{C}} = \begin{pmatrix} 0_{2\times 2} & X_{2\times 2}^T \\ X_{2\times 2} & 0_{2\times 2} \end{pmatrix}, \quad \text{with} \quad X_{2\times 2} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

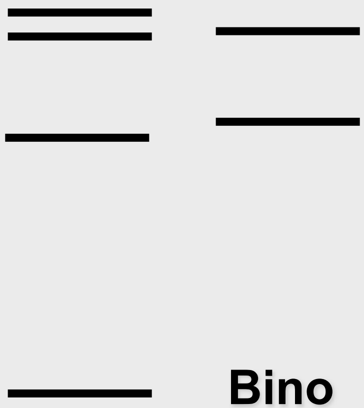
M_2 **Wino**
$|\mu|$ **Higgsino**

$$\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & 1 \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

$$\begin{pmatrix} \chi_1^- \\ \chi_2^- \end{pmatrix} = \begin{pmatrix} 1 & \mathcal{O}(\frac{m_Z}{M}) \\ \mathcal{O}(\frac{m_Z}{M}) & 1 \end{pmatrix} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix}$$

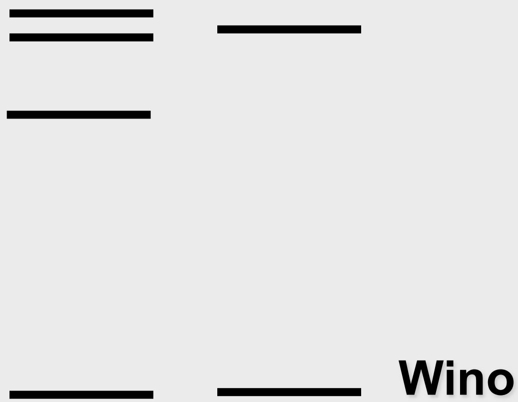
Order of M_1, M_2 and μ

Bino LSP
$M_1 < M_2, \mu$



e.g.:
sugra, CMSSM,
gaugino mass
unification, ...
canonical case

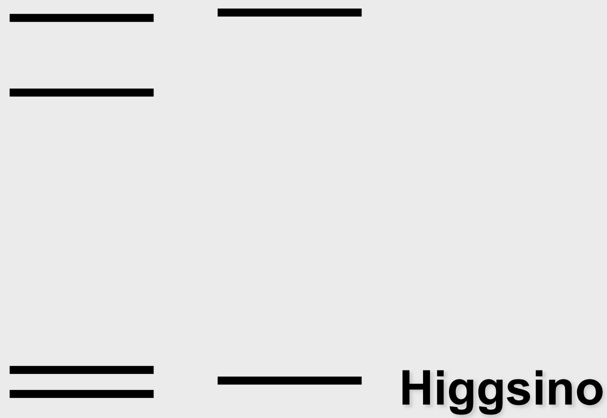
Wino LSP
$M_2 < M_1, \mu$



e.g.: AMSB,...

Chen et. al., hep-ph/9512230
Moroi et. al., hep-ph/9904250
Gherghetta et. al., hep-ph/9904378
Bear et. al., hep-ph/0007073
Moroi et. al., ArXiv: 0802.3725

Higgsino LSP
$\mu < M_1, M_2$



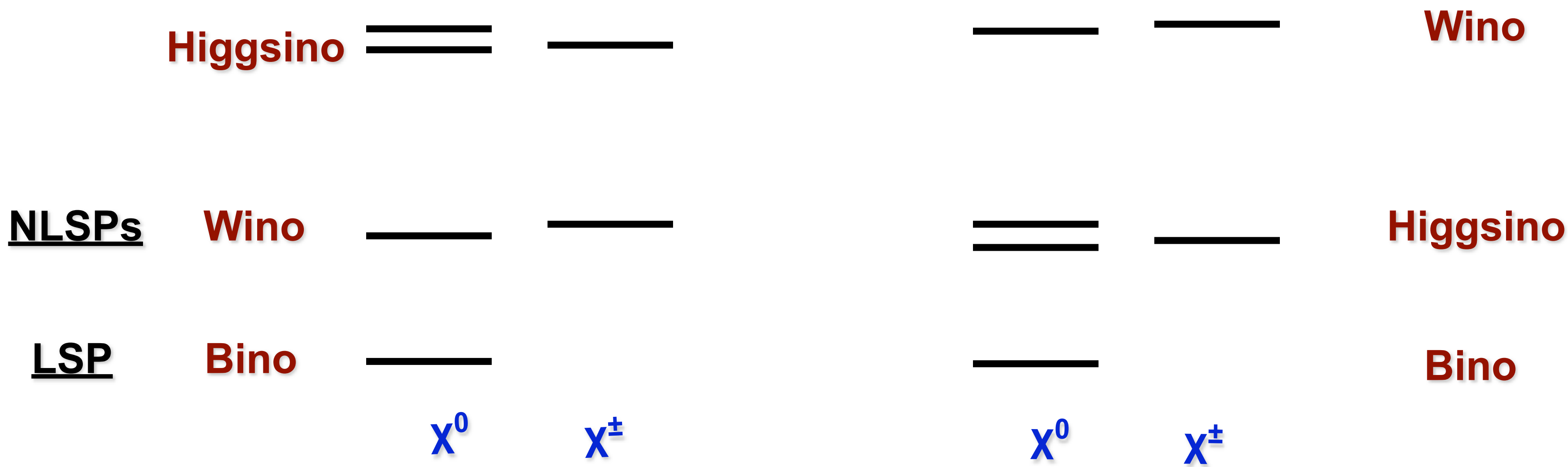
e.g.:"Higgsino-world",...

Baer, Barger and Huang,
ArXiv: 1107.5581

Bino LSP case

Case AI
Wino NLSP $M_1 < M_2 < \mu$

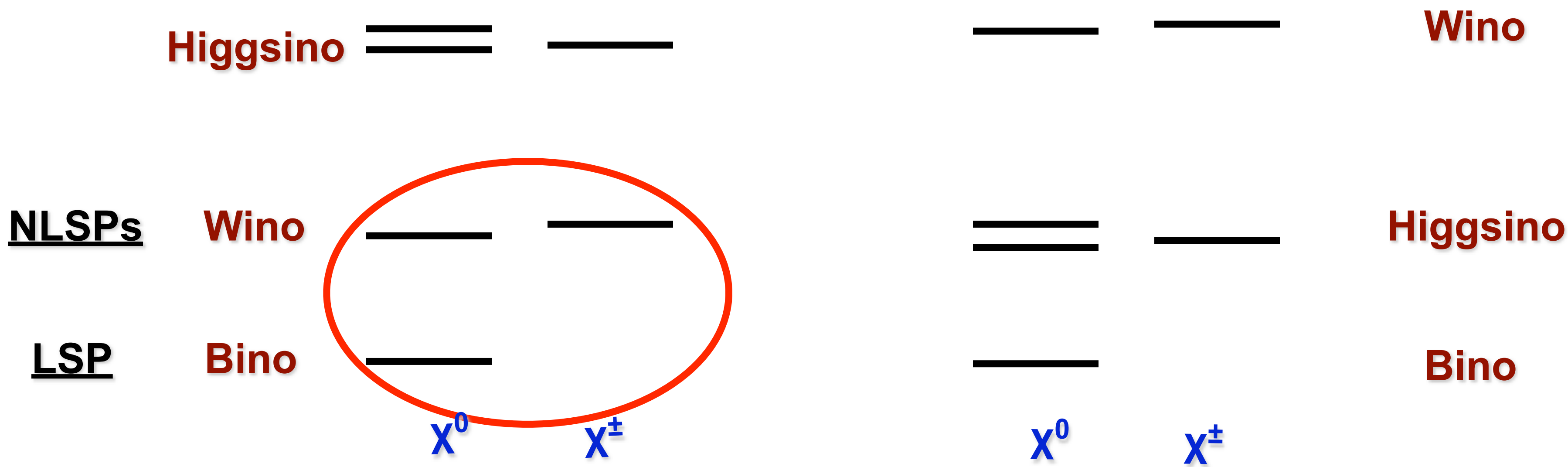
Case AII
Higgsino NLSP $M_1 < \mu < M_2$



Bino LSP case

Case AI
Wino NLSP $M_1 < M_2 < \mu$

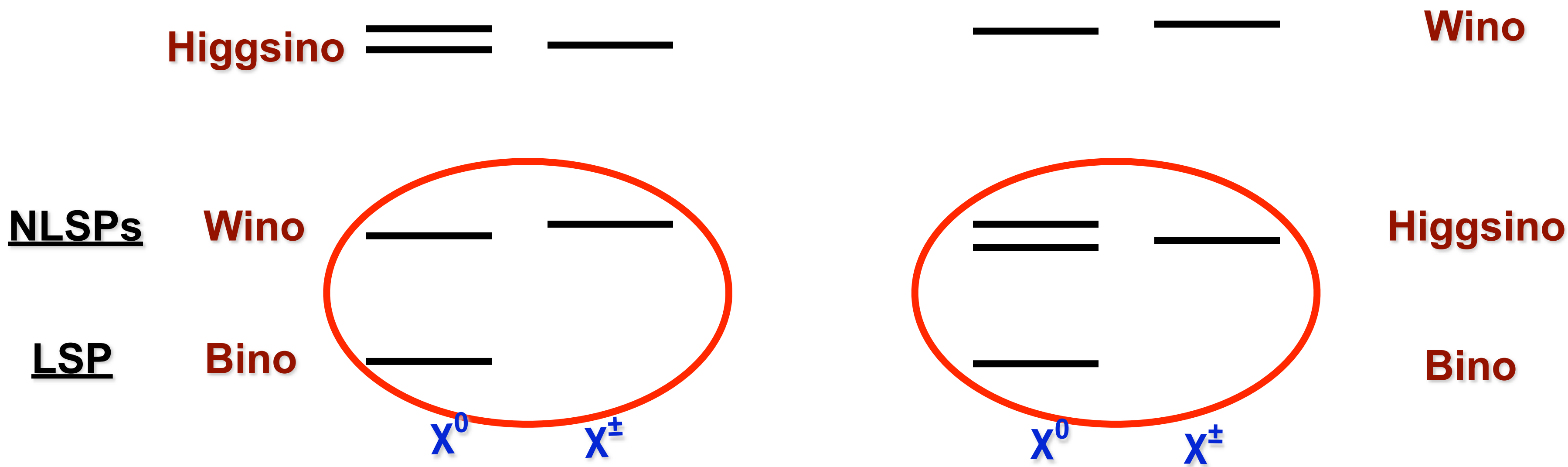
Case AII
Higgsino NLSP $M_1 < \mu < M_2$



Bino LSP case

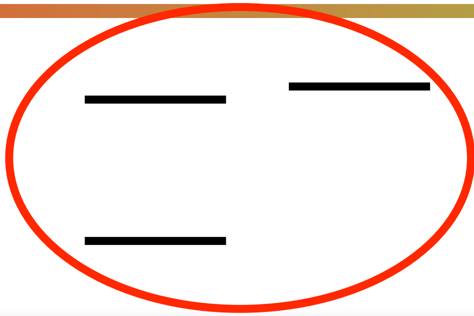
Case AI
Wino NLSP $M_1 < M_2 < \mu$

Case AII
Higgsino NLSP $M_1 < \mu < M_2$

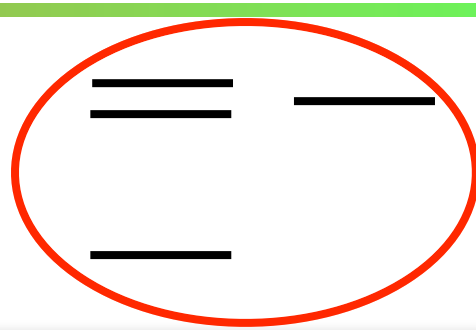


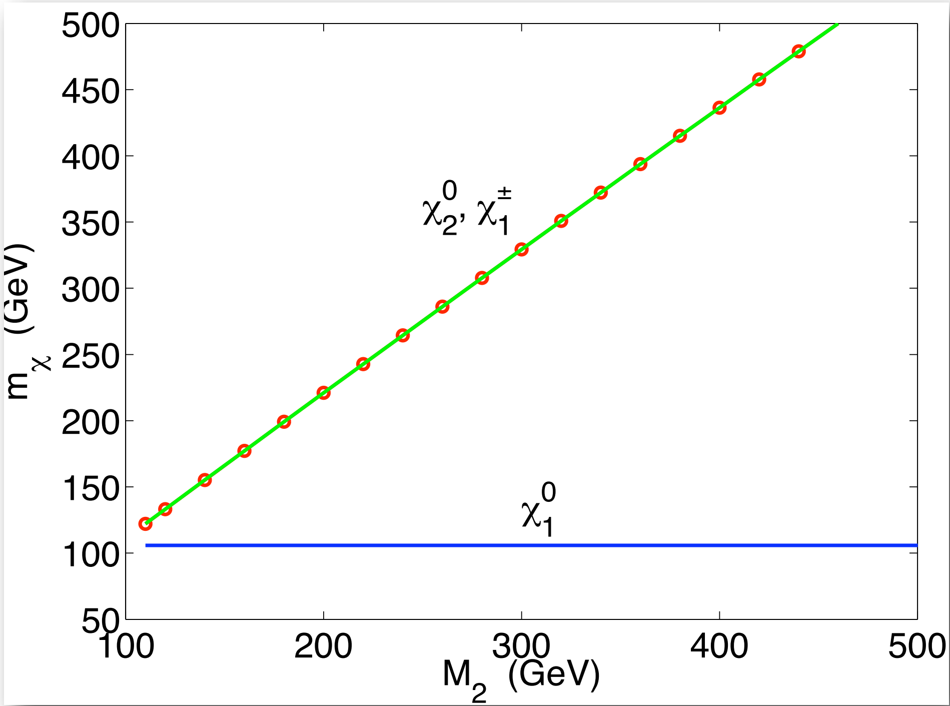
Masses: Bino LSP

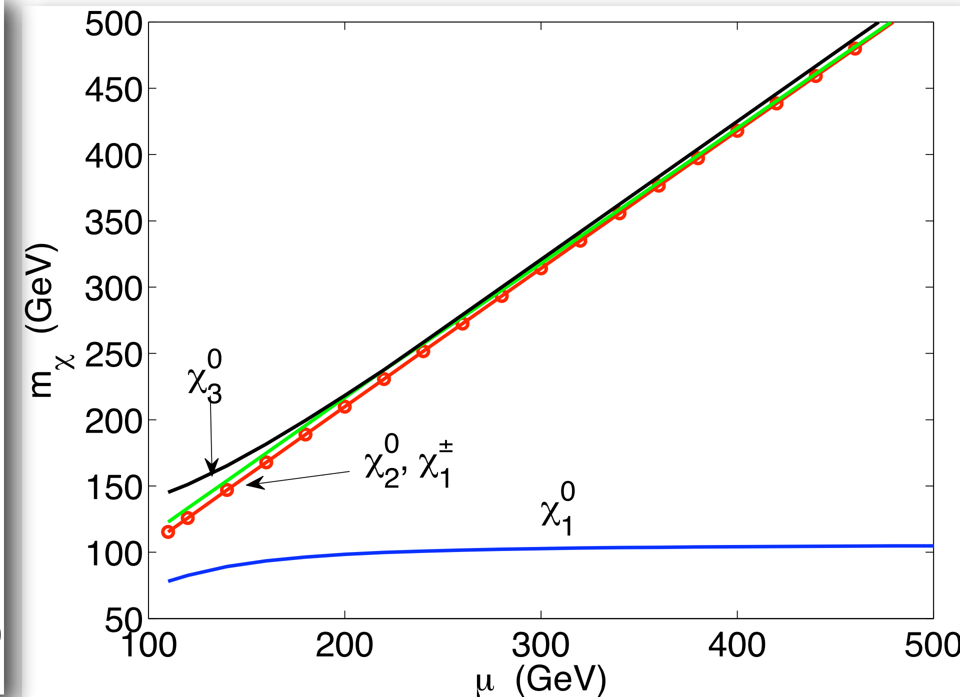
Case AI:
$M_1 < M_2 < \mu$



Case AII:
$M_1 < \mu < M_2$

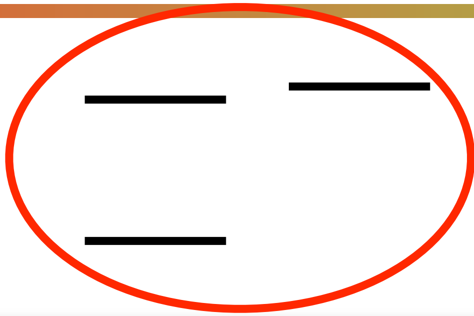




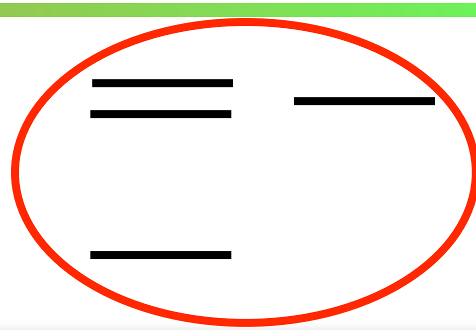


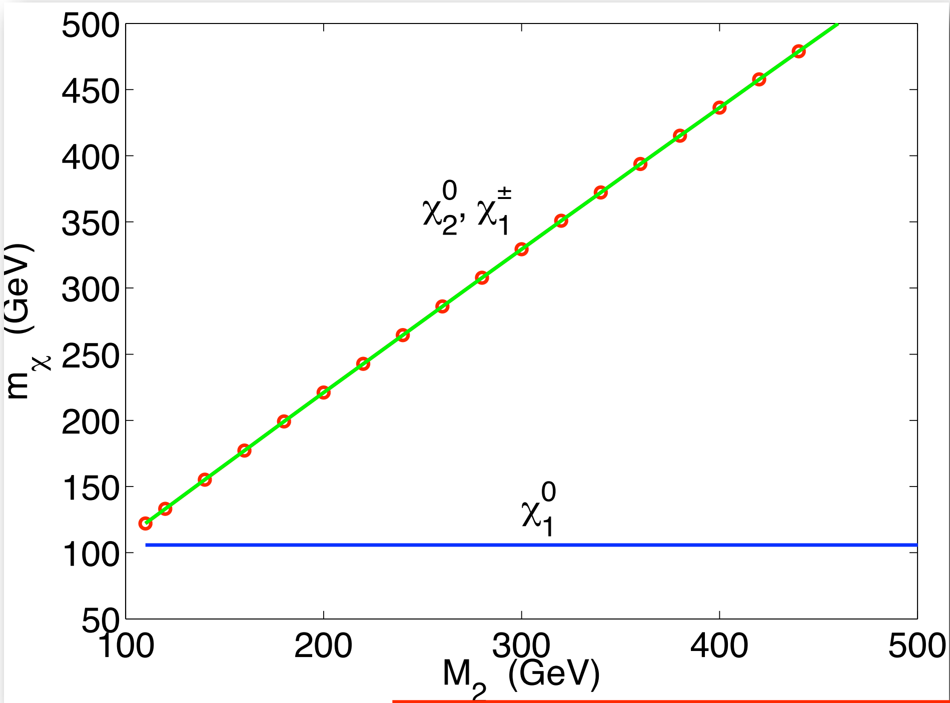
Masses: Bino LSP

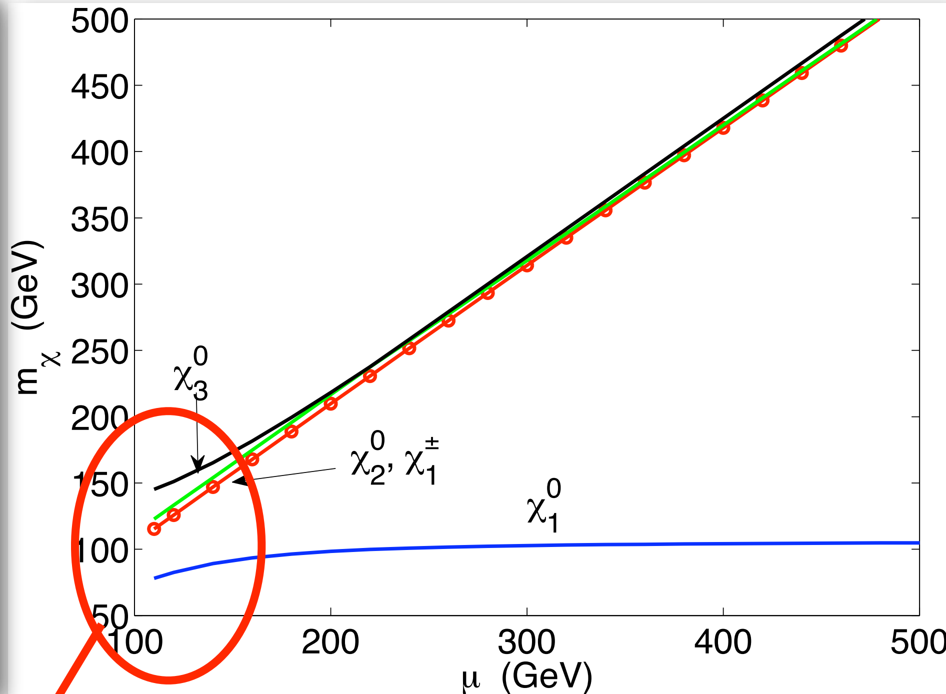
Case AI:
$M_1 < M_2 < \mu$



Case AII:
$M_1 < \mu < M_2$



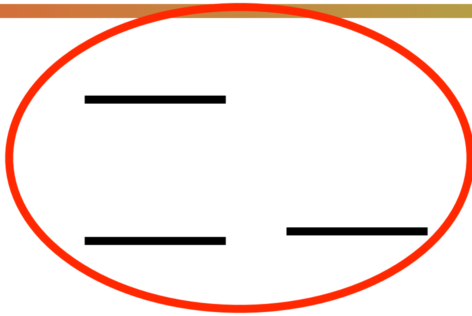




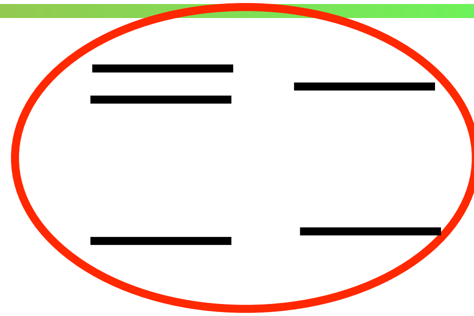
large mixing, natural compressed spectrum

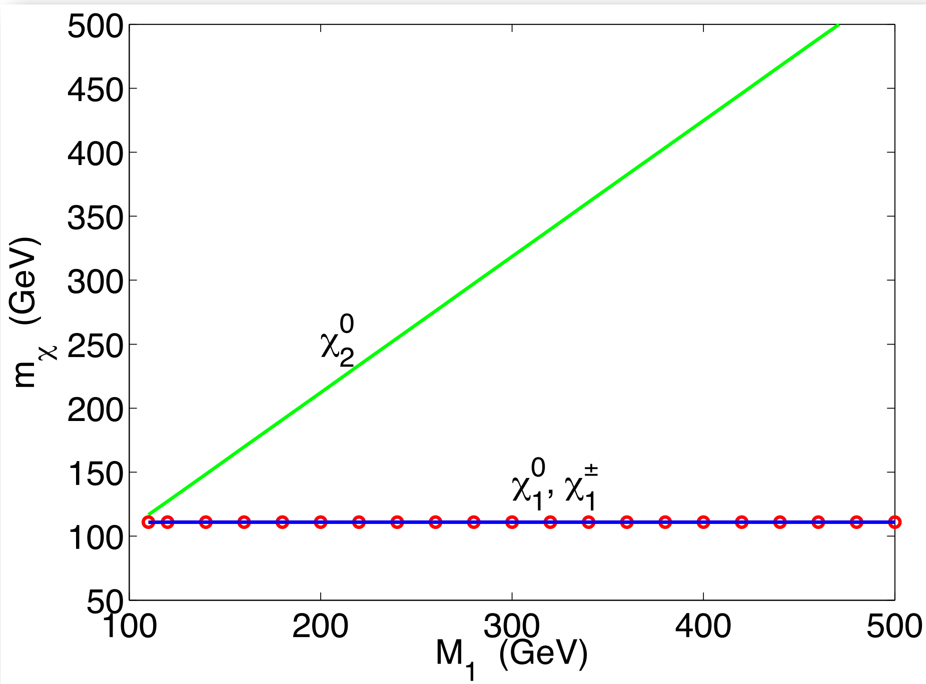
Masses: Wino LSP

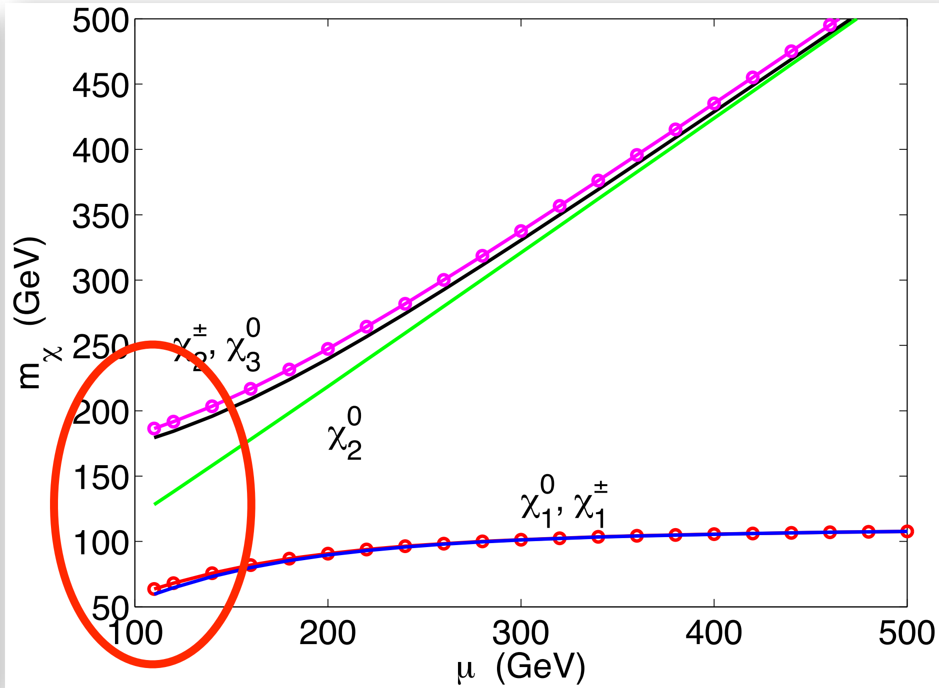
Case BI:
$M_2 < M_1 < \mu$



Case BII:
$M_2 < \mu < M_1$

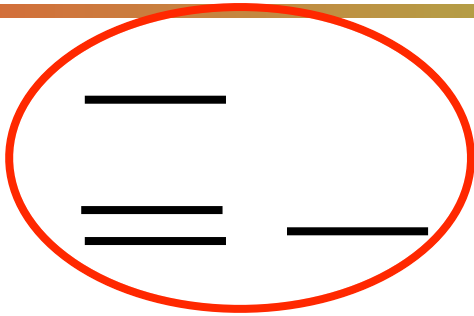




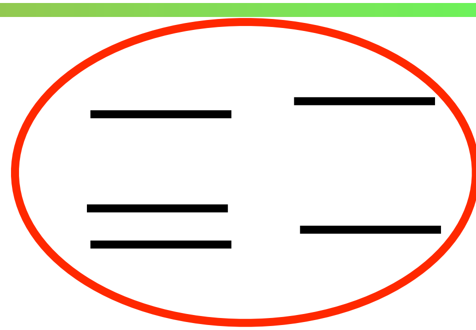


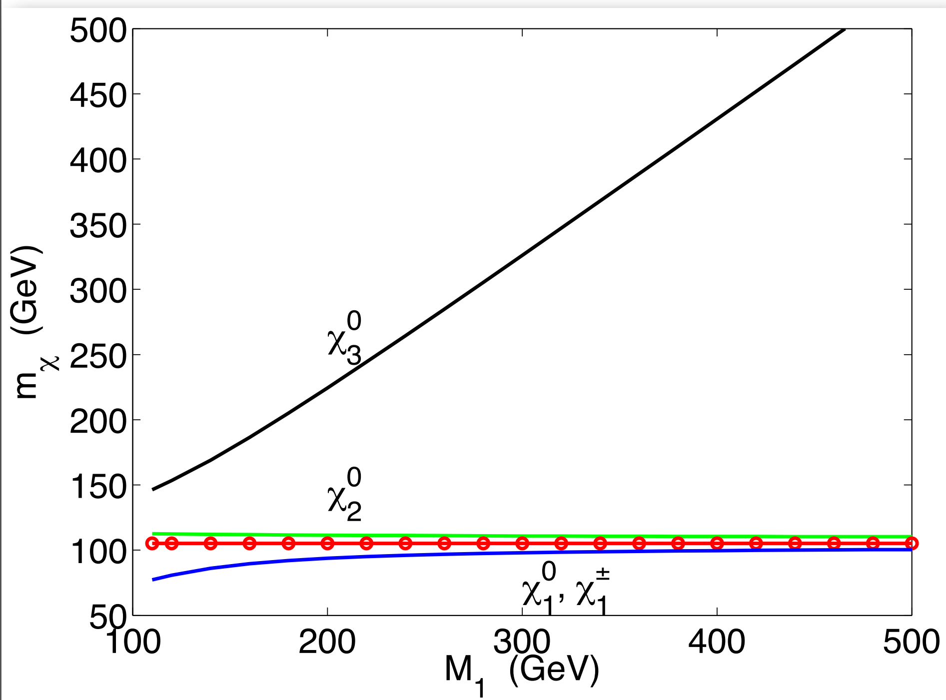
Masses: Higgsino LSP

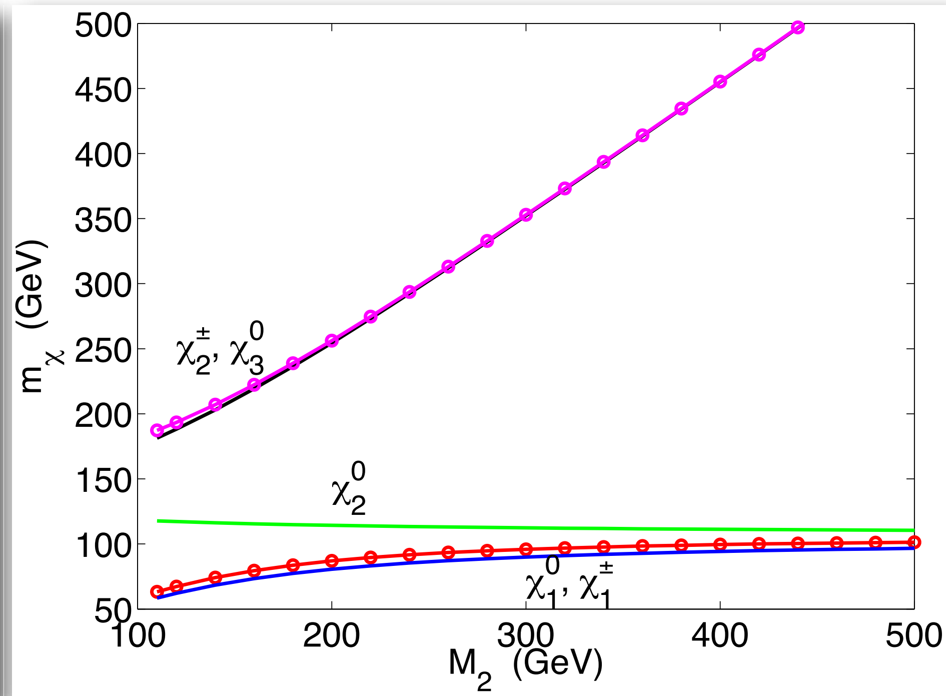
Case CI:
$\mu < M_1 < M_2$



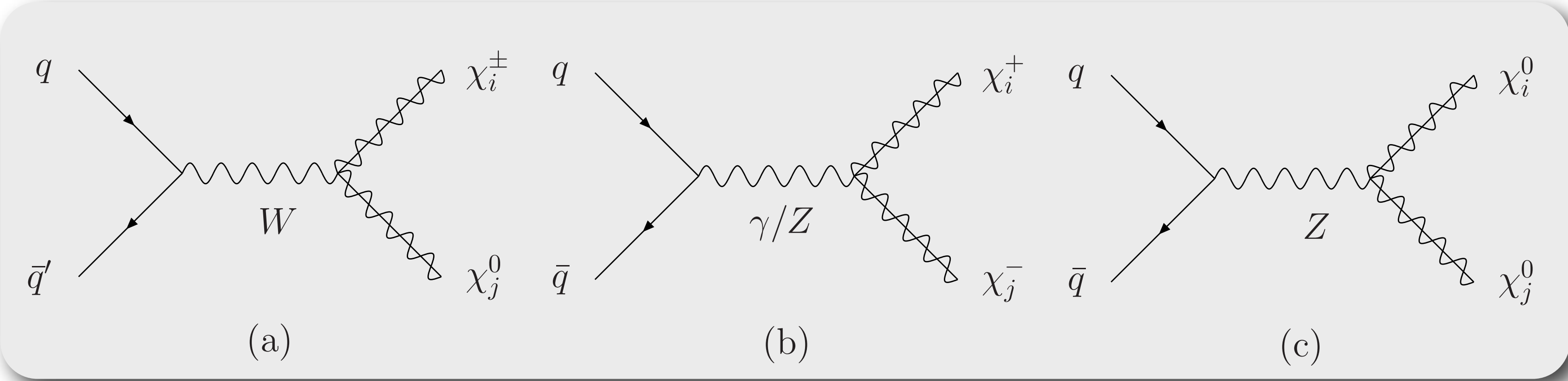
Case CII:
$\mu < M_2 < M_1$







Production

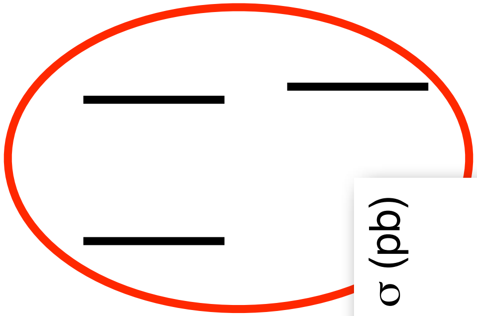


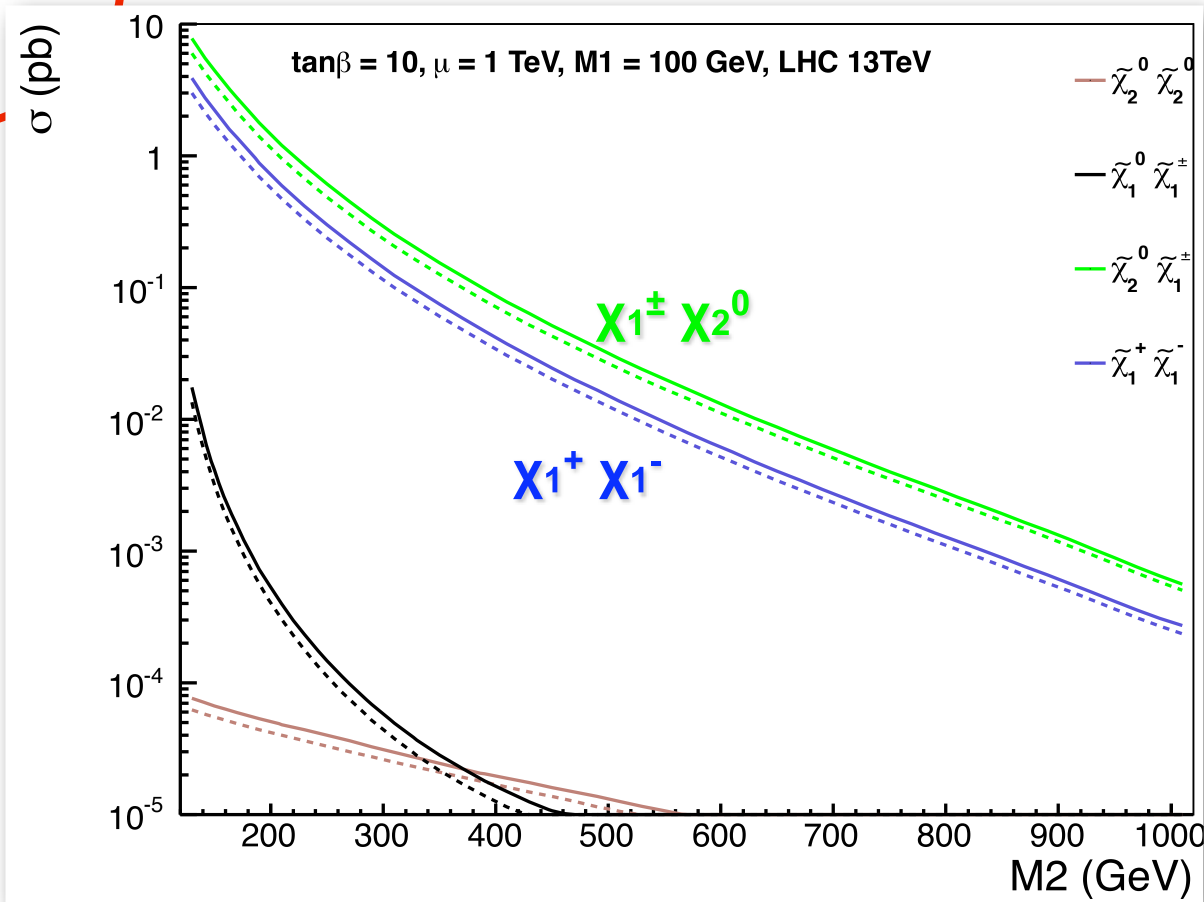
Dominant production:

- **Wino pair production: cha-cha, cha-neu**
- **Higgsino pair production: cha-cha, cha-neu, neu-neu**

Production: Bino LSP - Wino NLSP

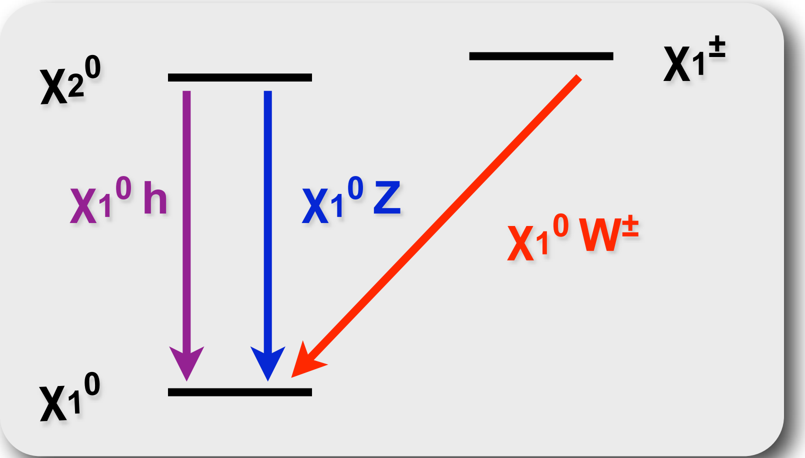
Case AI: $M_1 < M_2 < \mu$

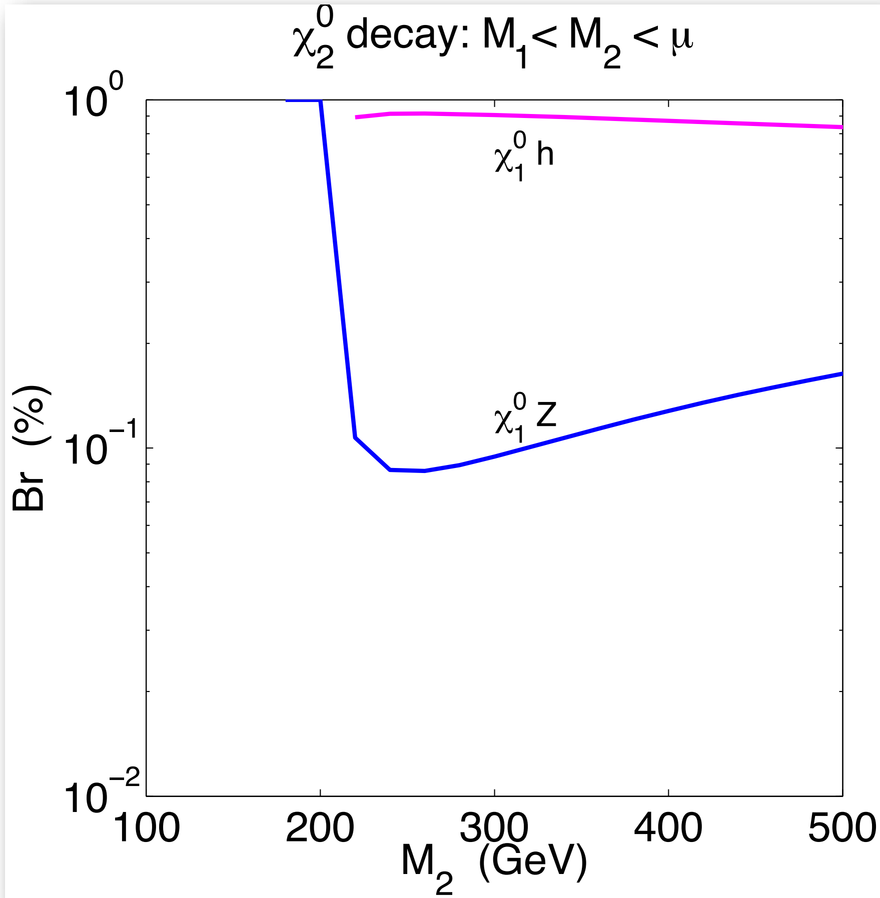




T. Han

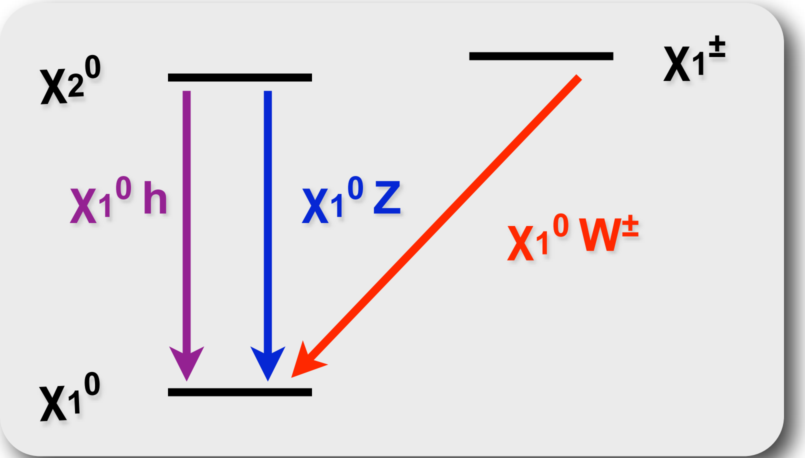
Case AI: Bino LSP - Wino NLSP



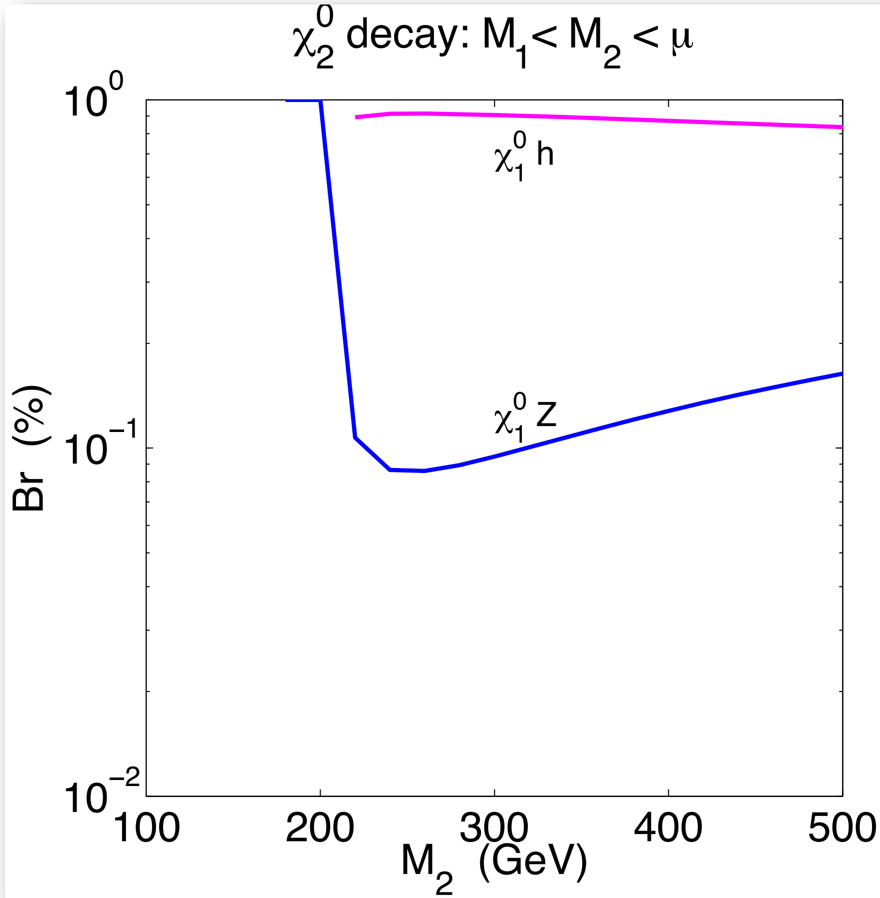


T. Han

Case AI: Bino LSP - Wino NLSP

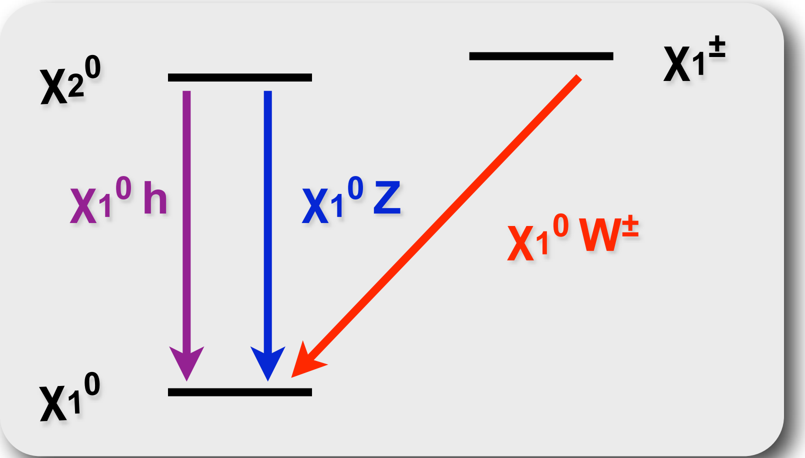


$\chi_1^\pm$ decay 100% via on/off-shell W

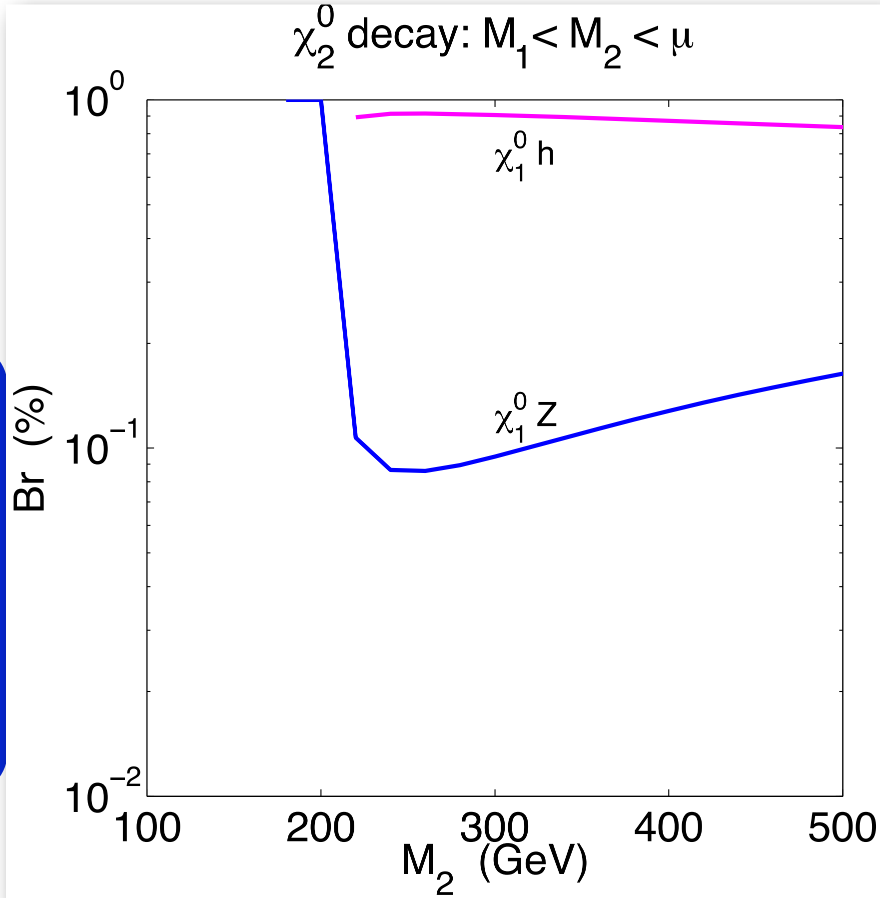


T. Han

Case AI: Bino LSP - Wino NLSP



$\chi_1^\pm$ decay 100% via on/off-shell W



- below h threshold, decay via on/off-shell Z
- χ_2^0 on-shell decay to h dominate over on-shell Z for $\mu > 0$
- χ_2^0 decay to h and Z flipped for $\mu < 0$

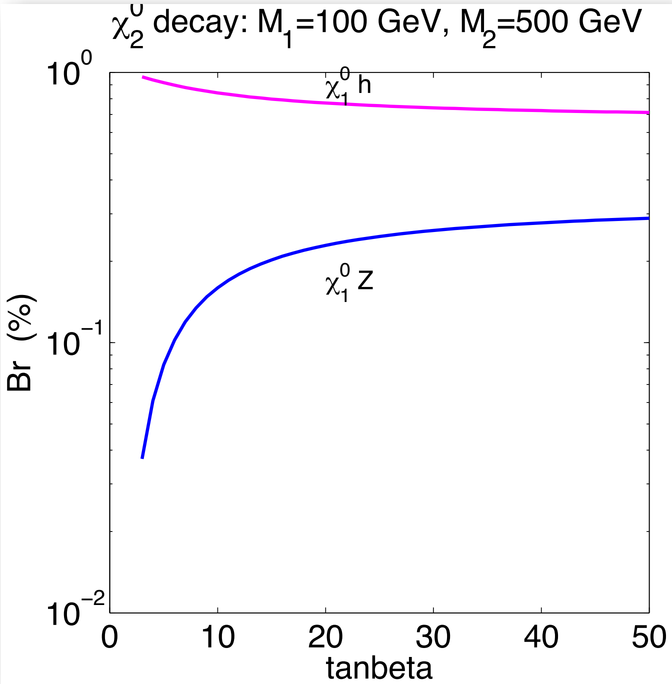
T. Han

Neutralino and Chargino mixing

	Neutralinos	Charginos
case AI	$\chi_1^0 \sim \tilde{B} + \mathcal{O}(\frac{m_Z}{\mu})(\frac{m_Z}{M_2})\tilde{W}^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_d^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_u^0$ $\chi_2^0 \sim \mathcal{O}(\frac{m_Z}{\mu})(\frac{m_Z}{M_2})\tilde{B} + \tilde{W}^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_d^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_u^0$	$\chi_1^+ \sim \tilde{W}^+ + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_u^+$ $\chi_1^- \sim \tilde{W}^- + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_d^-$
case AII	$\chi_1^0 \sim \tilde{B} + \mathcal{O}(\frac{m_Z}{M_2})(\frac{m_Z}{\mu})\tilde{W}^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_d^0 + \mathcal{O}(\frac{m_Z}{\mu})\tilde{H}_u^0$ $\chi_2^0 \sim \mathcal{O}(\frac{m_Z}{\mu})\tilde{B} + \mathcal{O}(\frac{m_Z}{M_2})\tilde{W}^0 + \frac{1}{\sqrt{2}}\tilde{H}_d^0 - \frac{1}{\sqrt{2}}\tilde{H}_u^0$ $\chi_3^0 \sim \mathcal{O}(\frac{m_Z}{\mu})\tilde{B} + \mathcal{O}(\frac{m_Z}{M_2})\tilde{W}^0 + \frac{1}{\sqrt{2}}\tilde{H}_d^0 + \frac{1}{\sqrt{2}}\tilde{H}_u^0$	$\chi_1^+ \sim \mathcal{O}(\frac{m_Z}{M_2})\tilde{W}^+ + \tilde{H}_u^+$ $\chi_1^- \sim \mathcal{O}(\frac{m_Z}{M_2})\tilde{W}^- + \tilde{H}_d^-$

Case AI: Bino LSP - Wino NLSP

- decay occur via mixing through Higgsino
- $M_2 >> M_1$, $\chi_2^0 \rightarrow \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0



$$\Gamma(\chi_2^0 \to \chi_1^0 h) \propto \left(2s_{2\beta} + \frac{M_2}{\mu}\right)^2 \left[(M_2 + M_1)^2 - m_h^2\right],$$

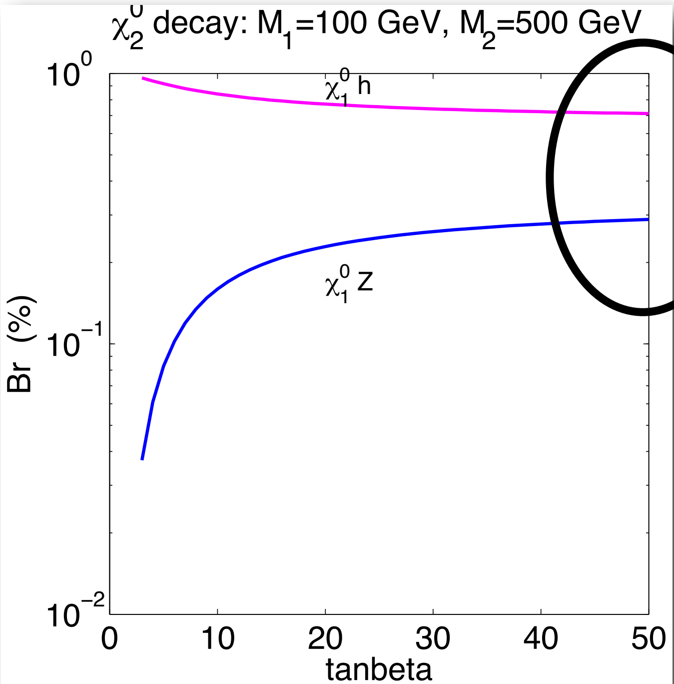
$$\Gamma(\chi_2^0 \to \chi_1^0 Z) \propto \left(c_{2\beta}\frac{M_2}{\mu}\right)^2 \left[(M_2 - M_1)^2 - m_Z^2\right].$$

Case AI: Bino LSP - Wino NLSP

- decay occur via mixing through Higgsino
- $M_2 >> M_1$, $\chi_2^0 \to \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0

$$\Gamma(\chi_2^0 \to \chi_1^0 h) \propto \left(2s_{2\beta} + \frac{M_2}{\mu}\right)^2 \left[(M_2 + M_1)^2 - m_h^2\right],$$

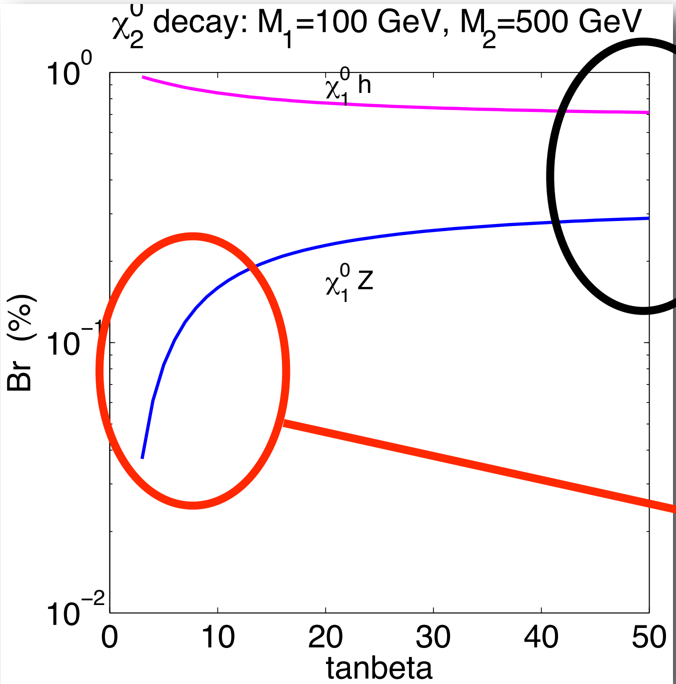
$$\Gamma(\chi_2^0 \to \chi_1^0 Z) \propto \left(c_{2\beta}\frac{M_2}{\mu}\right)^2 \left[(M_2 - M_1)^2 - m_Z^2\right].$$



large tanβ ; $[(M_2 + M_1)^2 - m_h^2] \,/\, [(M_2 - M_1)^2 - m_h^2]$

Case AI: Bino LSP - Wino NLSP

- decay occur via mixing through Higgsino
- $M_2 >> M_1$, $\chi_2^0 \to \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0



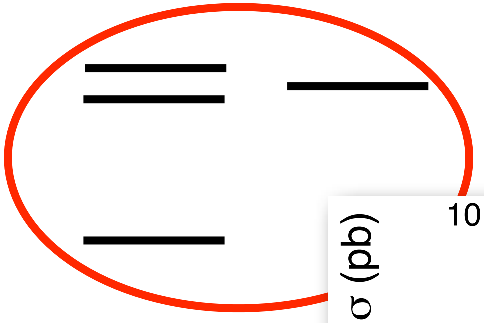
$$\Gamma(\chi_2^0 \to \chi_1^0 h) \propto \left(2s_{2\beta} + \frac{M_2}{\mu}\right)^2 \left[(M_2+M_1)^2 - m_h^2\right],$$

$$\Gamma(\chi_2^0 \to \chi_1^0 Z) \propto \left(c_{2\beta}\frac{M_2}{\mu}\right)^2 \left[(M_2-M_1)^2 - m_Z^2\right].$$

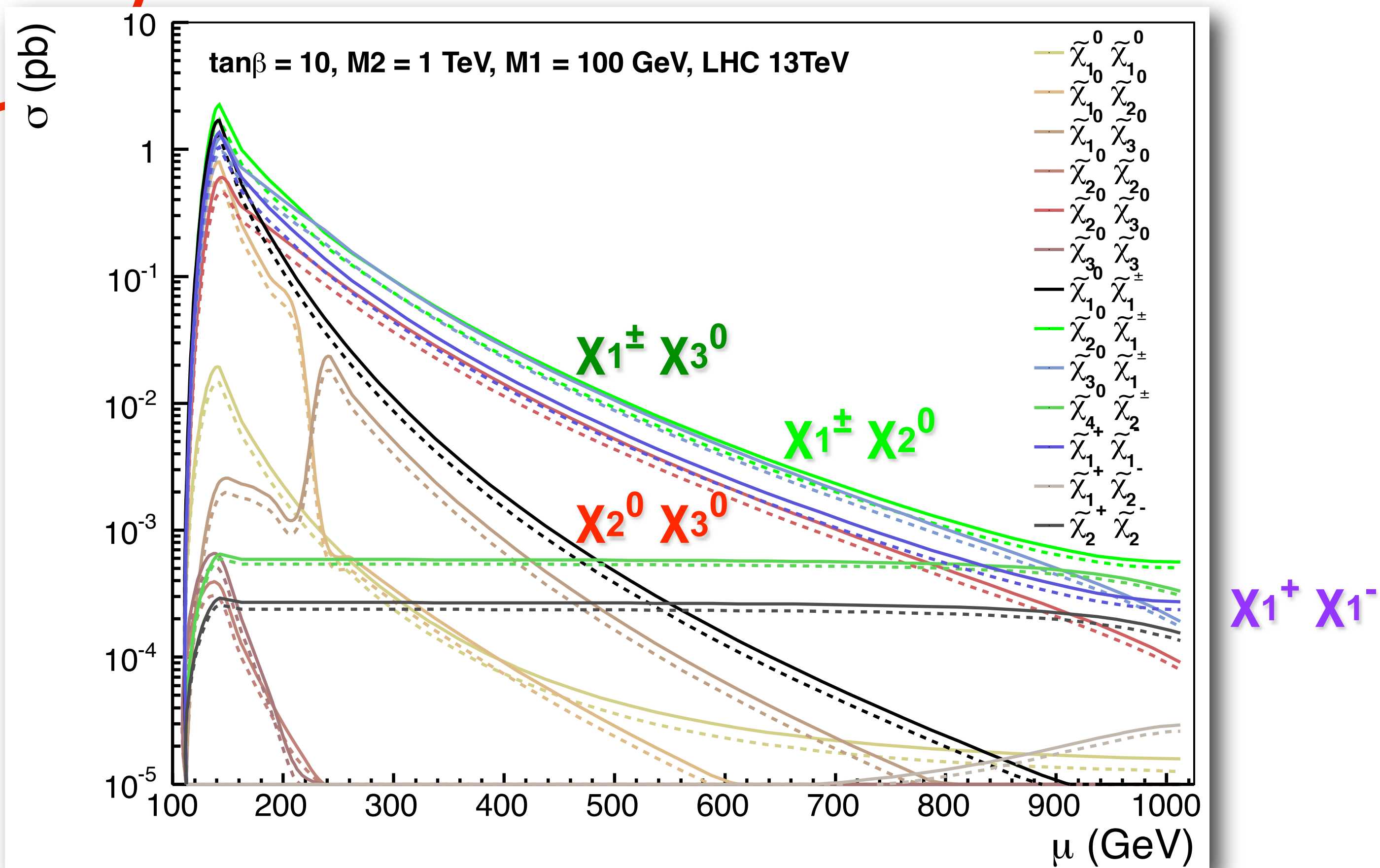
large tanβ ; $[(M_2+M_1)^2 - m_h^2] / [(M_2-M_1)^2 - m_h^2]$

small tanβ , Z channel relatively suppressed

Production: Bino LSP - Higgsino NLSP

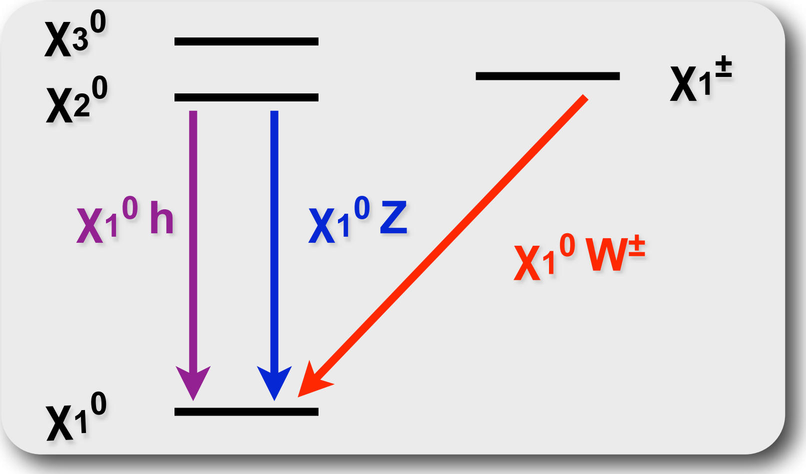


Case All: $M_1 < \mu < M_2$



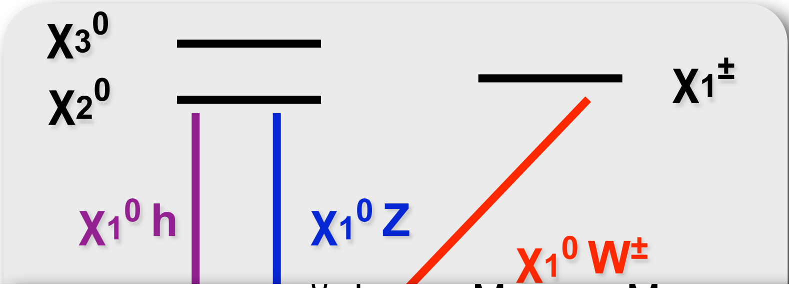
T. Han

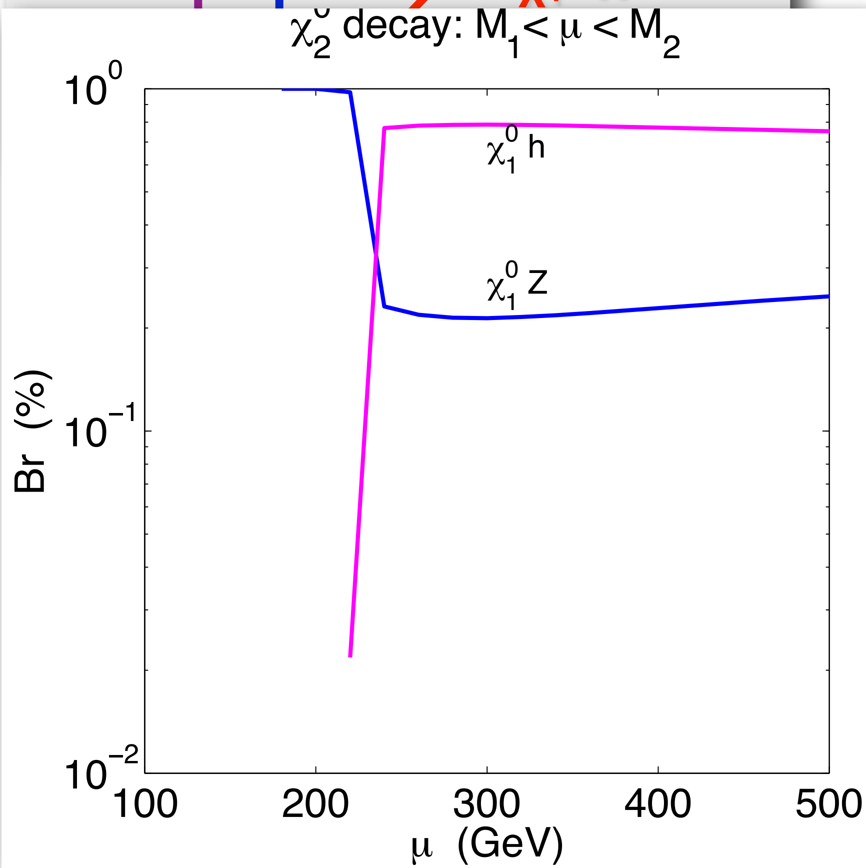
Case AII: Bino LSP-Higgsino NLSP



$\chi_1^\pm$ decay 100% via on/off-shell W

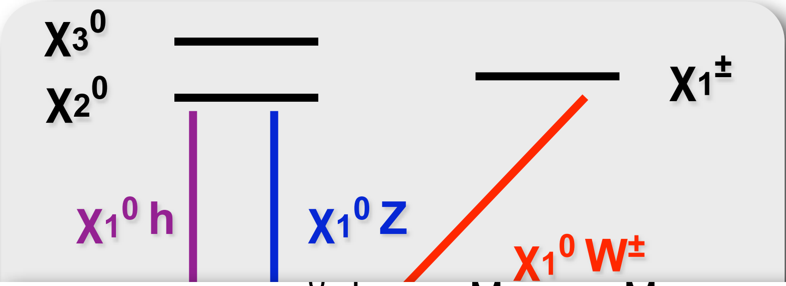
Case AII: Bino LSP-Higgsino NLSP



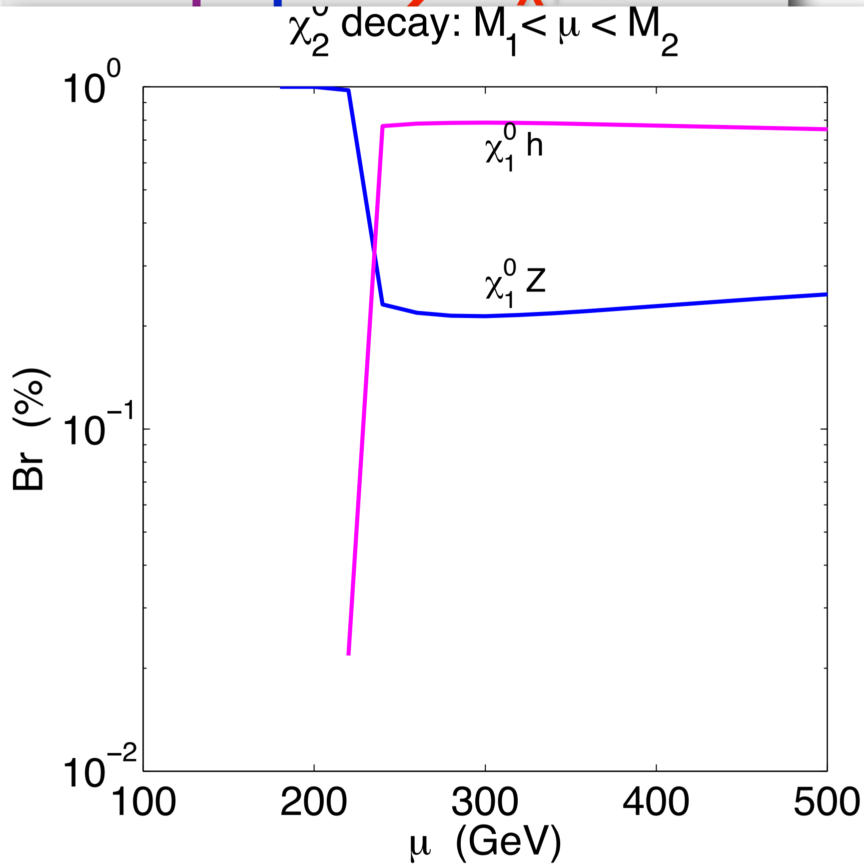


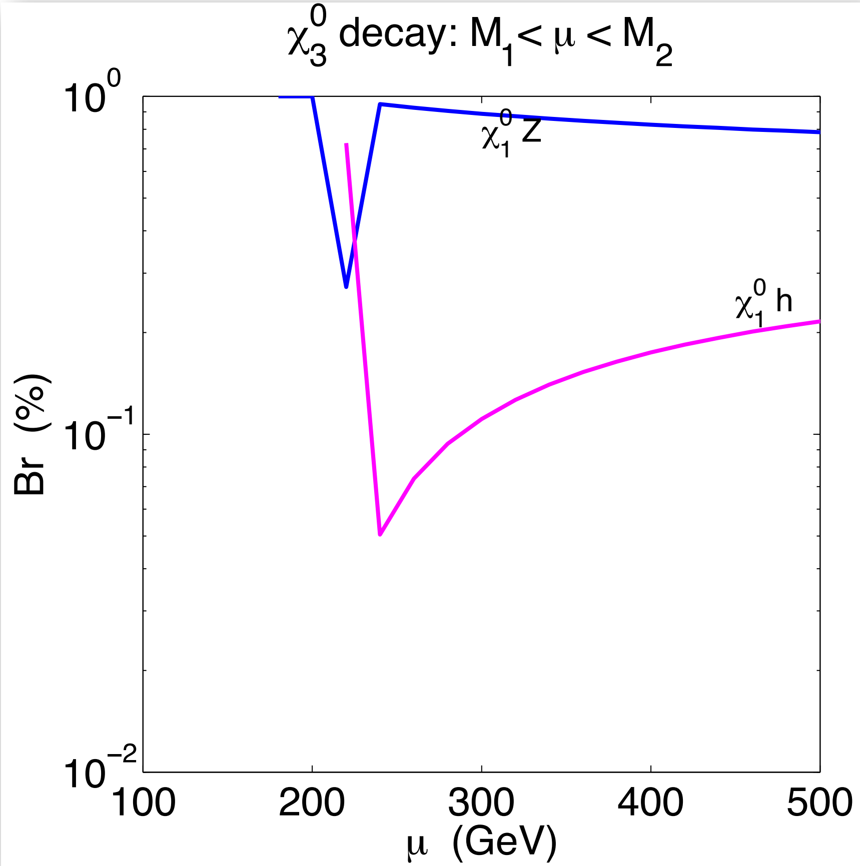
$\chi_1^\pm$ decay 100% via on/off-shell W

Case AII: Bino LSP-Higgsino NLSP

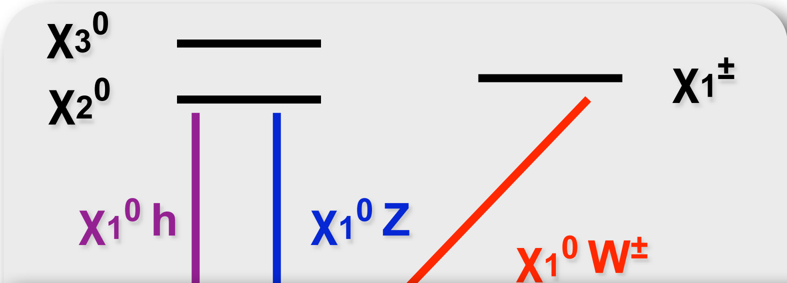


$\chi_1^\pm$ decay 100% via on/off-shell W

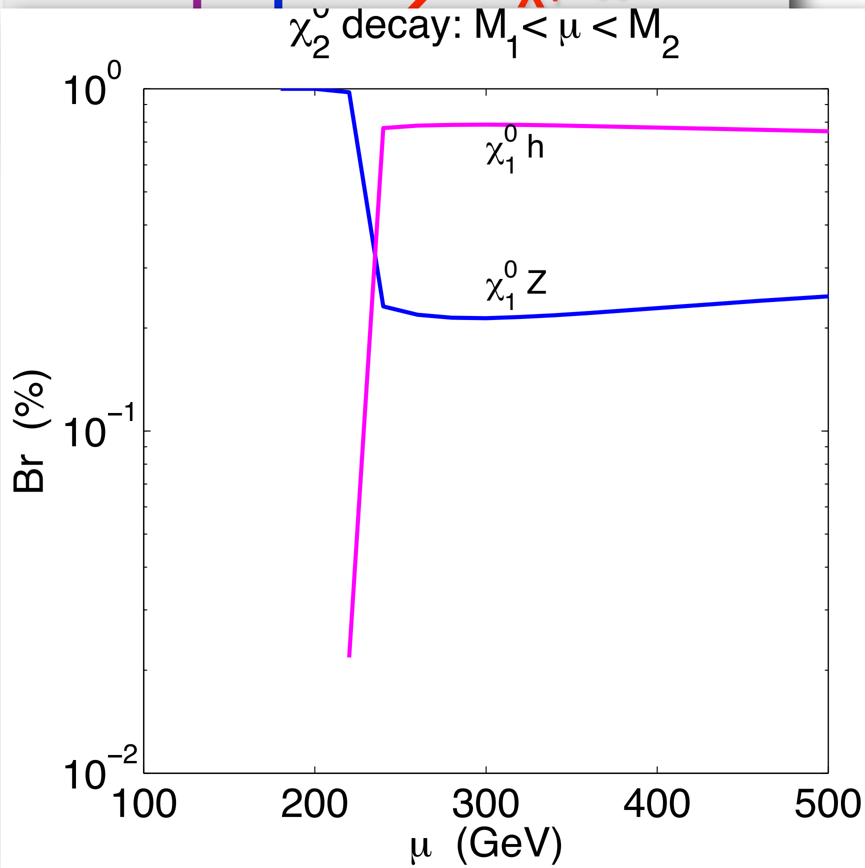


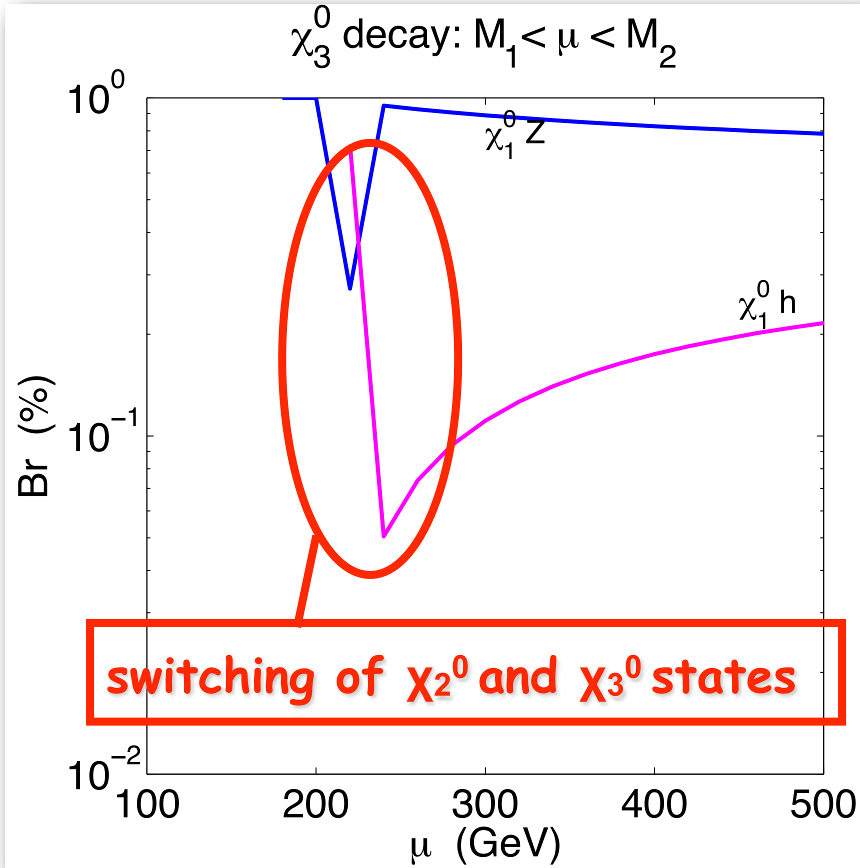


Case AII: Bino LSP-Higgsino NLSP



$\chi_1^{\pm}$ decay 100% via on/off-shell W





Case AII: Bino LSP - Higgsino NLSP

- $M_2 >> M_1$, $\chi_2^0 \to \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0

$$h = -\sqrt{2} \quad (s_\beta \,\mathrm{Re}(H_u^0) + c_\beta \,\mathrm{Re}(H_d^0)),$$
$$G^0 = \sqrt{2} \quad (s_\beta \,\mathrm{Im}(H_u^0) - c_\beta \,\mathrm{Im}(H_d^0)).$$

$$\chi_2^0 \approx \frac{1}{\sqrt{2}}(\tilde{H}_d^0 - \tilde{H}_u^0)$$

$$\chi_3^0 \approx \frac{1}{\sqrt{2}}(\tilde{H}_d^0 + \tilde{H}_u^0)$$

$$\Gamma(\chi_2^0 \to \chi_1^0 h) \propto (s_\beta + c_\beta)^2 \left[(\mu + M_1)^2 - m_h^2\right],$$
$$\Gamma(\chi_2^0 \to \chi_1^0 Z) \propto (s_\beta - c_\beta)^2 \left[(\mu - M_1)^2 - m_Z^2\right].$$

$$\Gamma(\chi_3^0 \to \chi_1^0 h) \propto (s_\beta - c_\beta)^2 \left[(\mu - M_1)^2 - m_h^2\right],$$
$$\Gamma(\chi_3^0 \to \chi_1^0 Z) \propto (s_\beta + c_\beta)^2 \left[(\mu + M_1)^2 - m_Z^2\right].$$

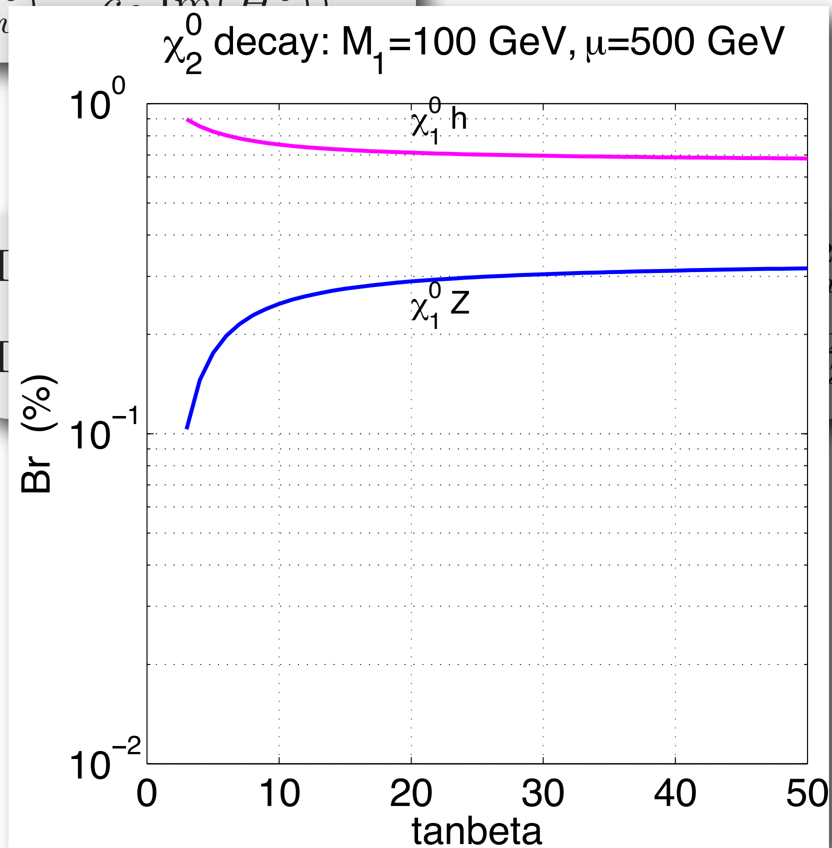
Case AII: Bino LSP - Higgsino NLSP

- $M_2 >> M_1$, $\chi_2^0 \rightarrow \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0

$$h = -\sqrt{2} \quad (s_\beta \,\mathrm{Re}(H_u^0) + c_\beta \,\mathrm{Re}(H_d^0)),$$
$$G^0 = \sqrt{2} \quad (s_\beta \,\mathrm{Im}(H_u^0) - c_\beta \,\mathrm{Im}(H_d^0))$$

$$\chi_2^0 \approx \frac{1}{\sqrt{2}}(\tilde{H}_d^0 - \tilde{H}_u^0)$$

$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 h) \propto (s_\beta + c_\beta)^2 \left[(\mu + M_1)^2 - m_h^2\right],$$
$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 Z) \propto (s_\beta - c_\beta)^2 \left[(\mu - M_1)^2 - m_Z^2\right].$$



T. Han

Case AII: Bino LSP - Higgsino NLSP

- $M_2 >> M_1$, $\chi_2^0 \rightarrow \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0

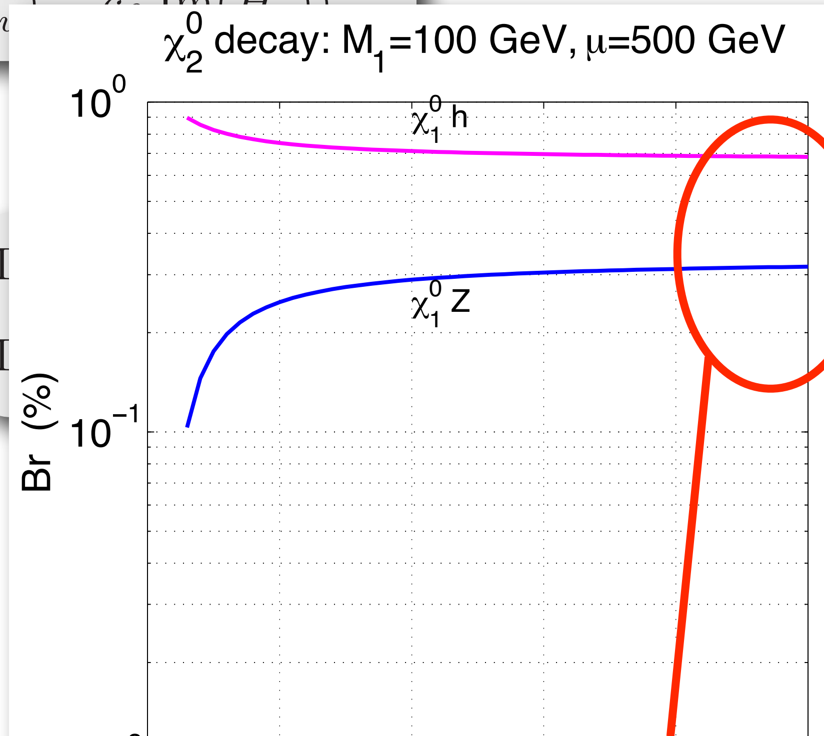
$$h = -\sqrt{2} \quad (s_\beta \,\mathrm{Re}(H_u^0) + c_\beta \,\mathrm{Re}(H_d^0)),$$

$$G^0 = \sqrt{2} \quad (s_\beta \,\mathrm{Im}(H_u^0) - c_\beta \,\mathrm{Im}(H_d^0))$$

$$\chi_2^0 \approx \frac{1}{\sqrt{2}}(\tilde{H}_d^0 - \tilde{H}_u^0)$$

$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 h) \propto (s_\beta + c_\beta)^2 \left[(\mu + M_1)^2 - m_h^2\right],$$

$$\Gamma(\chi_2^0 \rightarrow \chi_1^0 Z) \propto (s_\beta - c_\beta)^2 \left[(\mu - M_1)^2 - m_Z^2\right].$$



large $\tan\beta$, large μ, Br(h) ~ Br(Z) = 50%

T. Han

Case AII: Bino LSP - Higgsino NLSP

- $M_2 >> M_1$, $\chi_2^0 \to \chi_1^0 Z$ dominated by the decay via Z_L (goldstone mode G^0)
- h, G^0 as mixture of H_u^0 and H_d^0

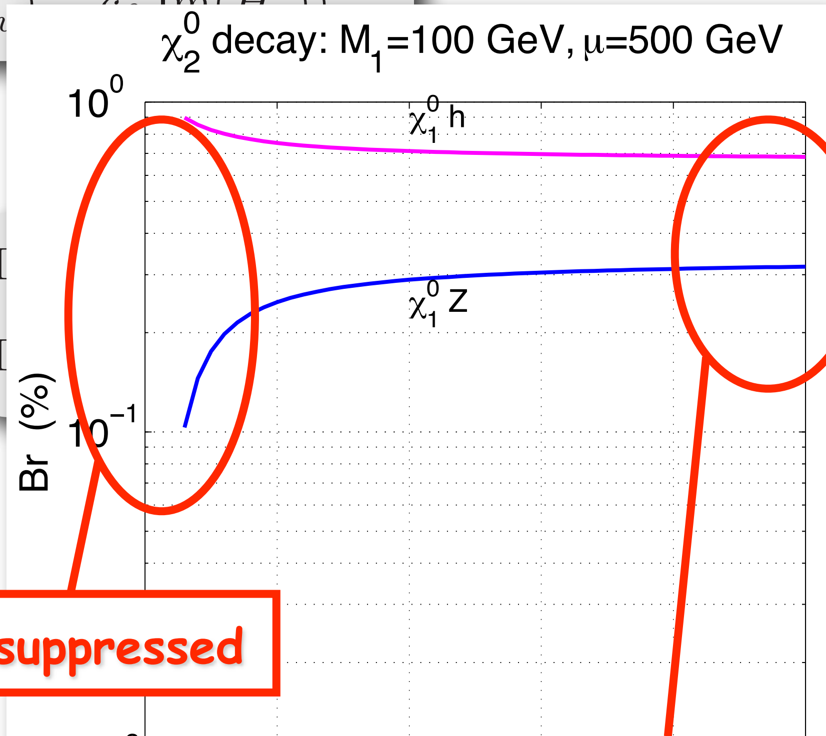
$$h = -\sqrt{2} \quad (s_\beta \,\mathrm{Re}(H_u^0) + c_\beta \,\mathrm{Re}(H_d^0)),$$

$$G^0 = \sqrt{2} \quad (s_\beta \,\mathrm{Im}(H_u^0) - c_\beta \,\mathrm{Im}(H_d^0)),$$

$$\chi_2^0 \approx \frac{1}{\sqrt{2}}(\tilde{H}_d^0 - \tilde{H}_u^0)$$

$$\Gamma(\chi_2^0 \to \chi_1^0 h) \propto (s_\beta + c_\beta)^2 \left[(\mu + M_1)^2 - m_h^2\right],$$

$$\Gamma(\chi_2^0 \to \chi_1^0 Z) \propto (s_\beta - c_\beta)^2 \left[(\mu - M_1)^2 - m_Z^2\right].$$



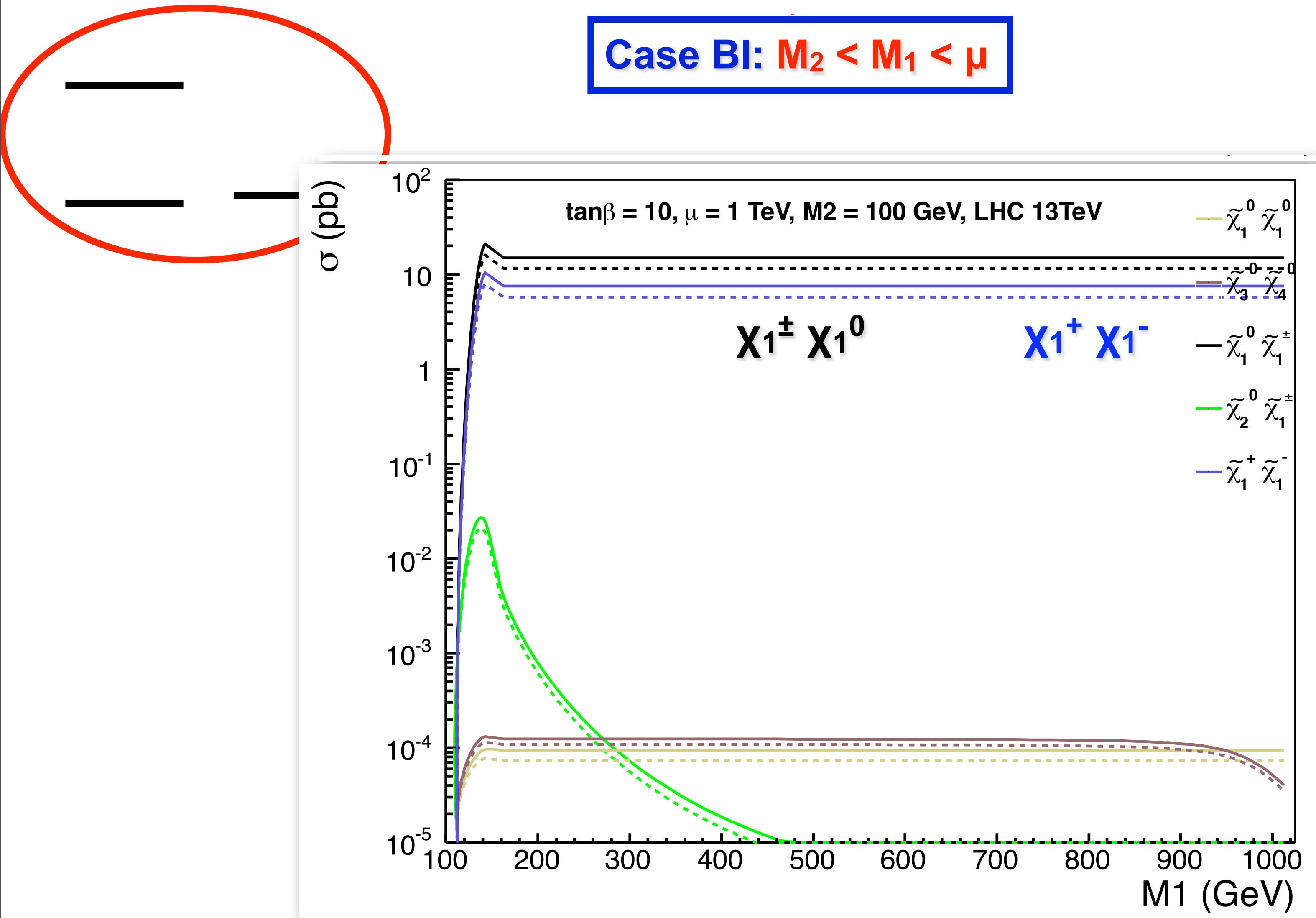
small tanβ , Z channel highly suppressed

large tanβ , large μ, Br(h) ~ Br(Z) = 50%

T. Han

Production: Wino LSP - Bino NLSP

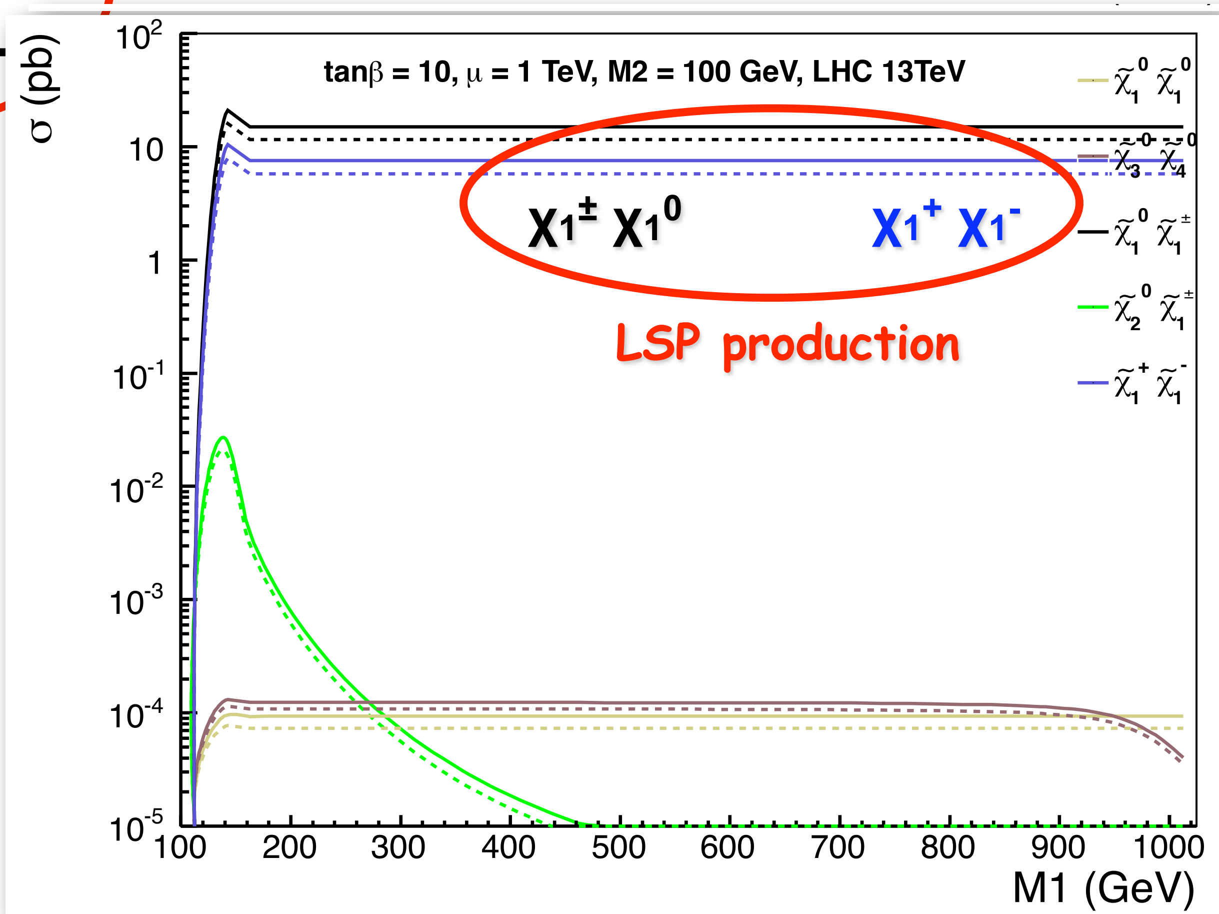
Case BI: $M_2 < M_1 < \mu$



T. Han

Production: Wino LSP - Bino NLSP

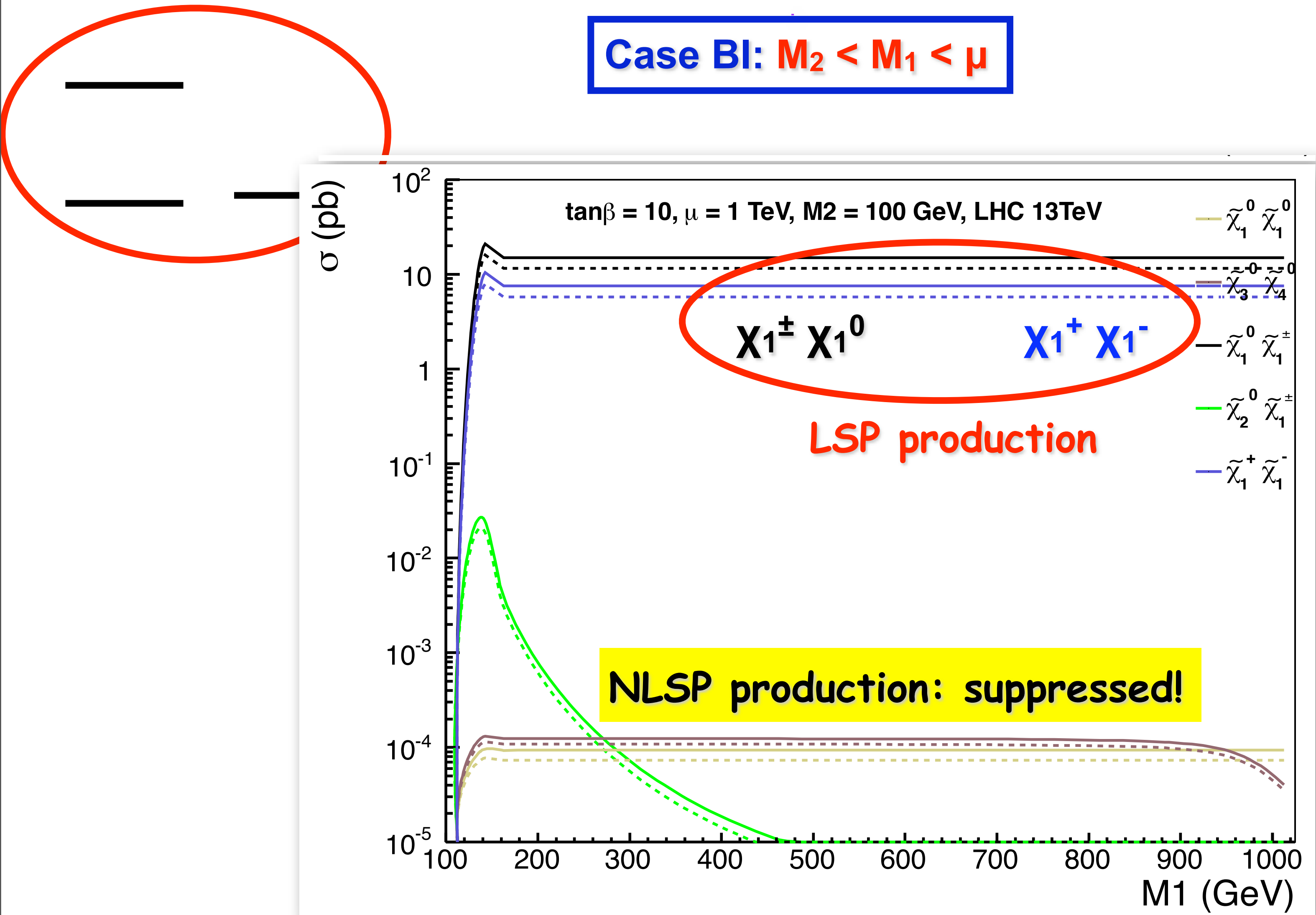
Case BI: $M_2 < M_1 < \mu$



T. Han

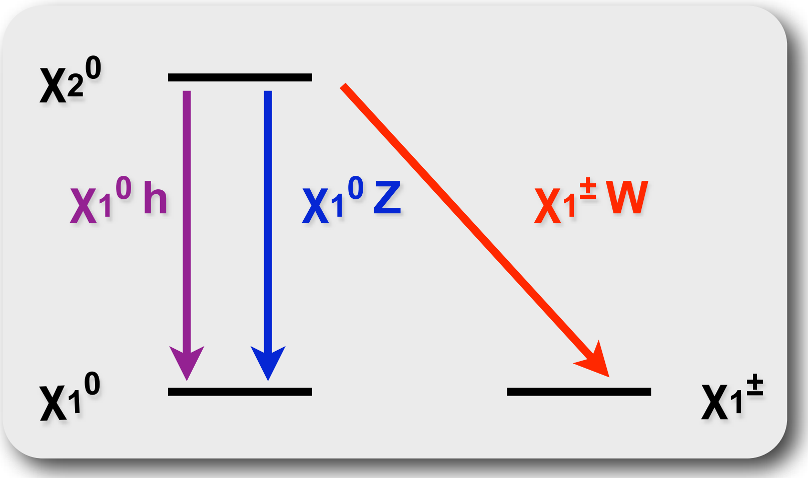
Production: Wino LSP - Bino NLSP

Case BI: $M_2 < M_1 < \mu$



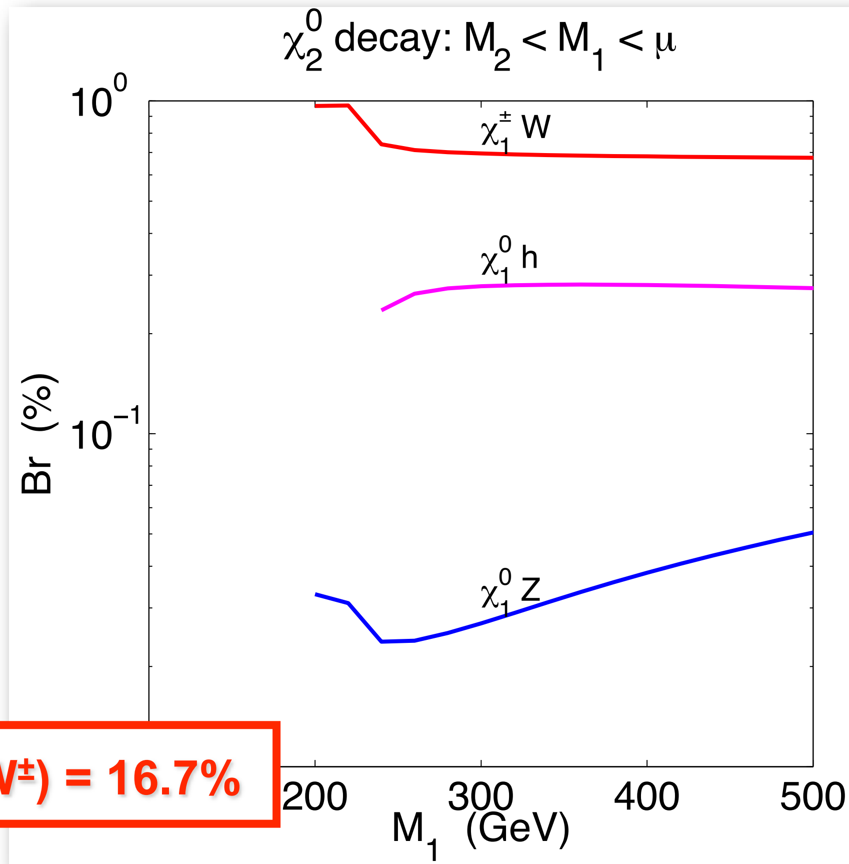
T. Han

Case BI: Wino LSP- Bino NLSP



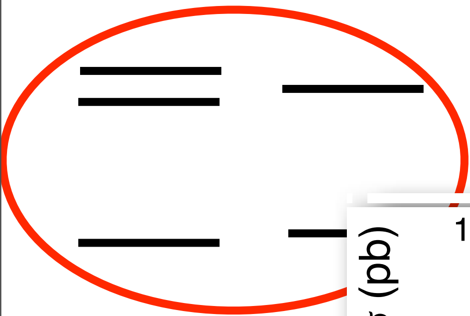
- decay occur via mixing through Higgsino state

$$\boxed{\Gamma_{\chi_1^+ W^-} = \Gamma_{\chi_1^- W^+} \approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_1^0 h}.}$$

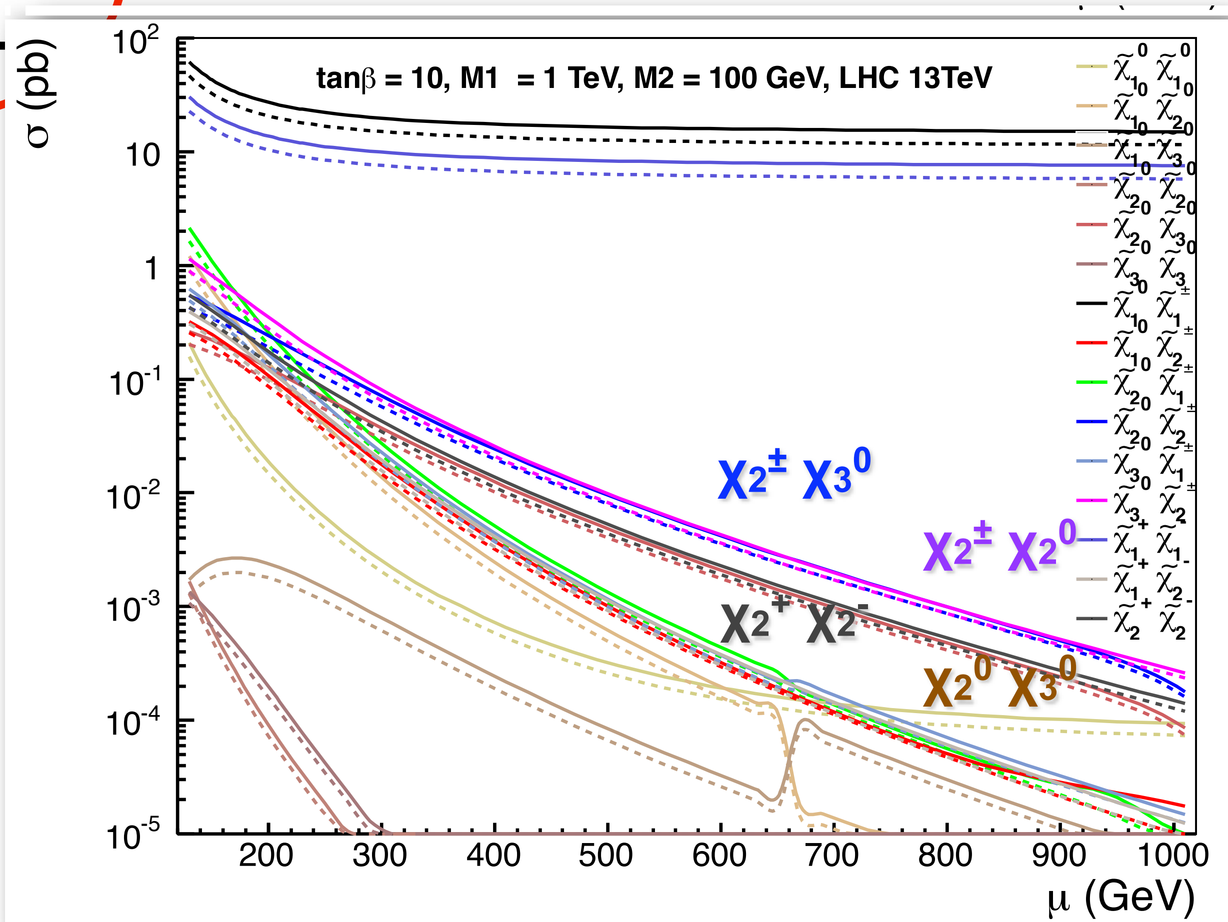


tanβ , large M_1, Br(h) ~ Br(Z) ~ 1/4 Br($W^\pm$) = 16.7%

Production: Wino LSP - Higgsino NLSP



Case BII: $M_2 < \mu < M_1$

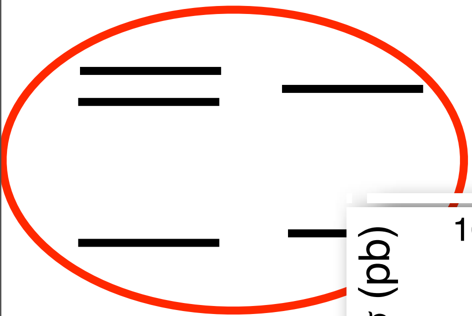


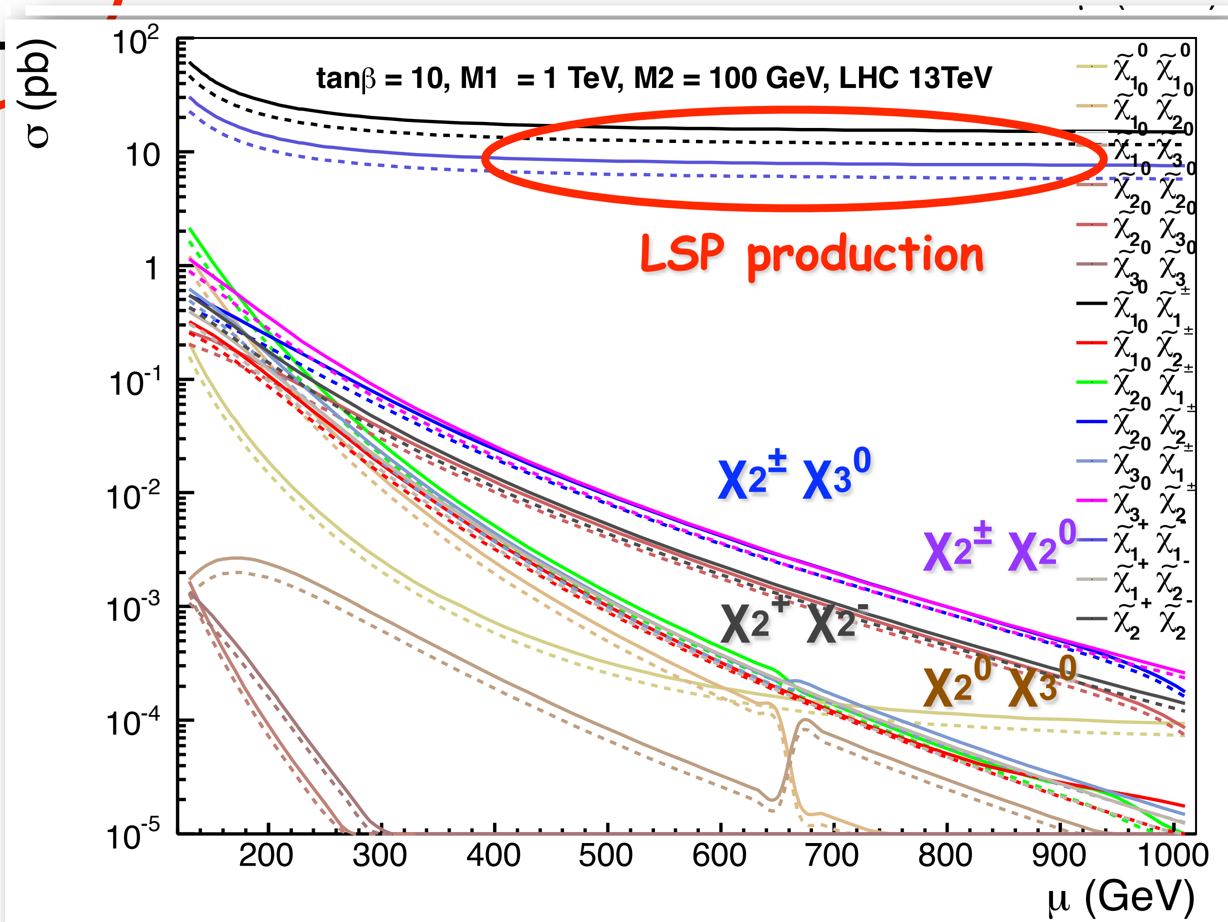
T. Han

Monday, November 12, 2012

Production: Wino LSP - Higgsino NLSP

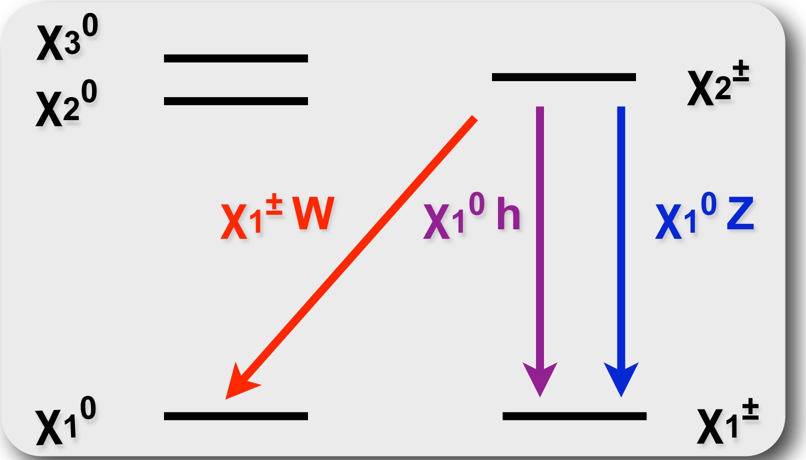
Case BII: $M_2 < \mu < M_1$

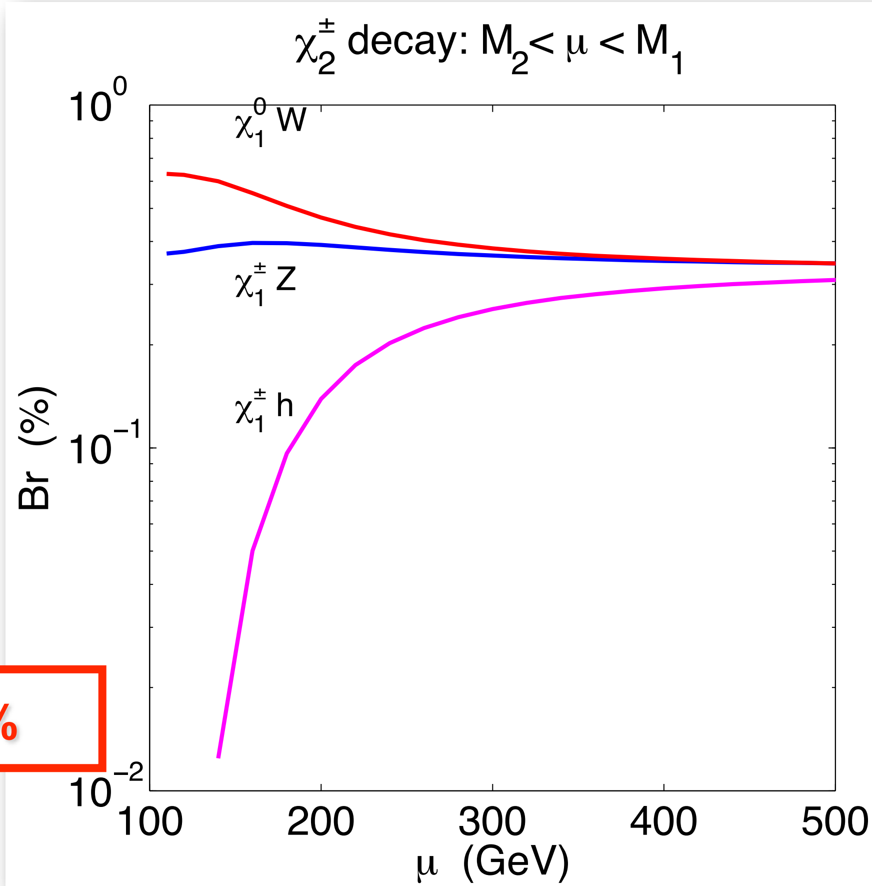




T. Han

Case BII: Wino LSP- Higgsino NLSP



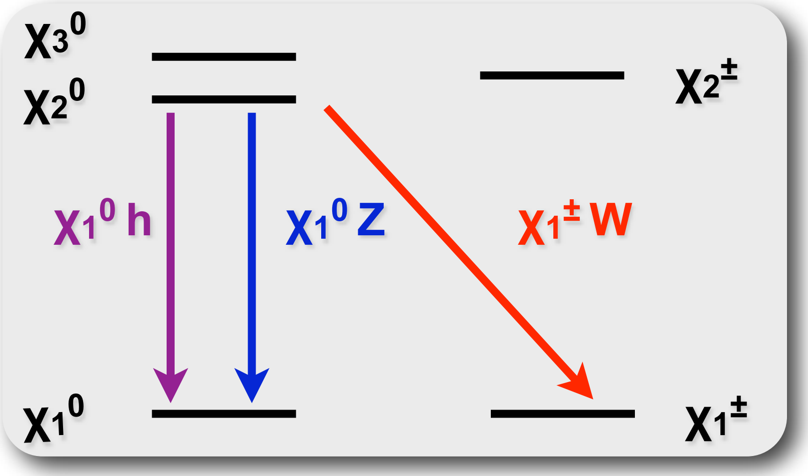


$$\boxed{\Gamma_{\chi_1^0 W} : \Gamma_{\chi_1^\pm Z} : \Gamma_{\chi_1^\pm h} \approx 1 : 1 : 1}$$

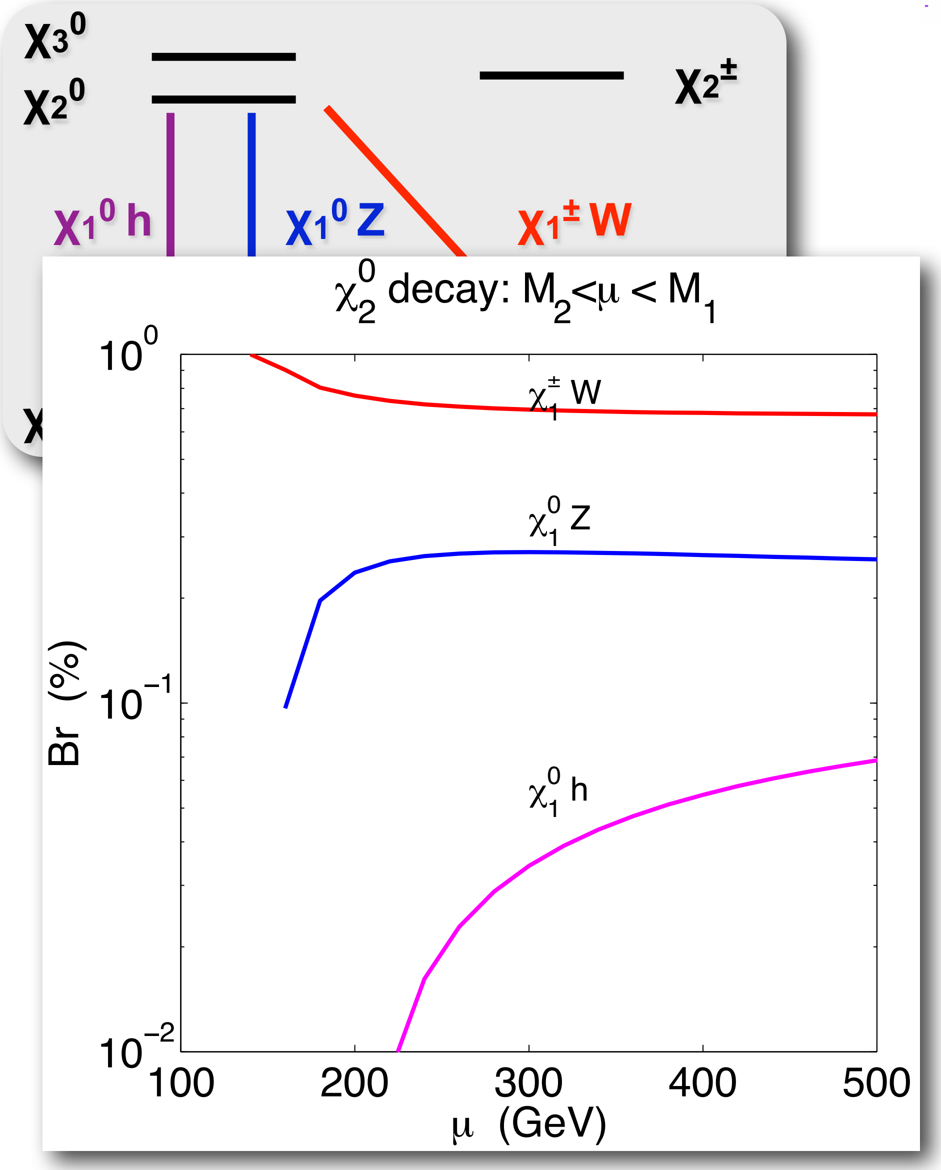
large μ, Br(h) ~ Br(Z) ~ Br(W±) = 33%

T. Han

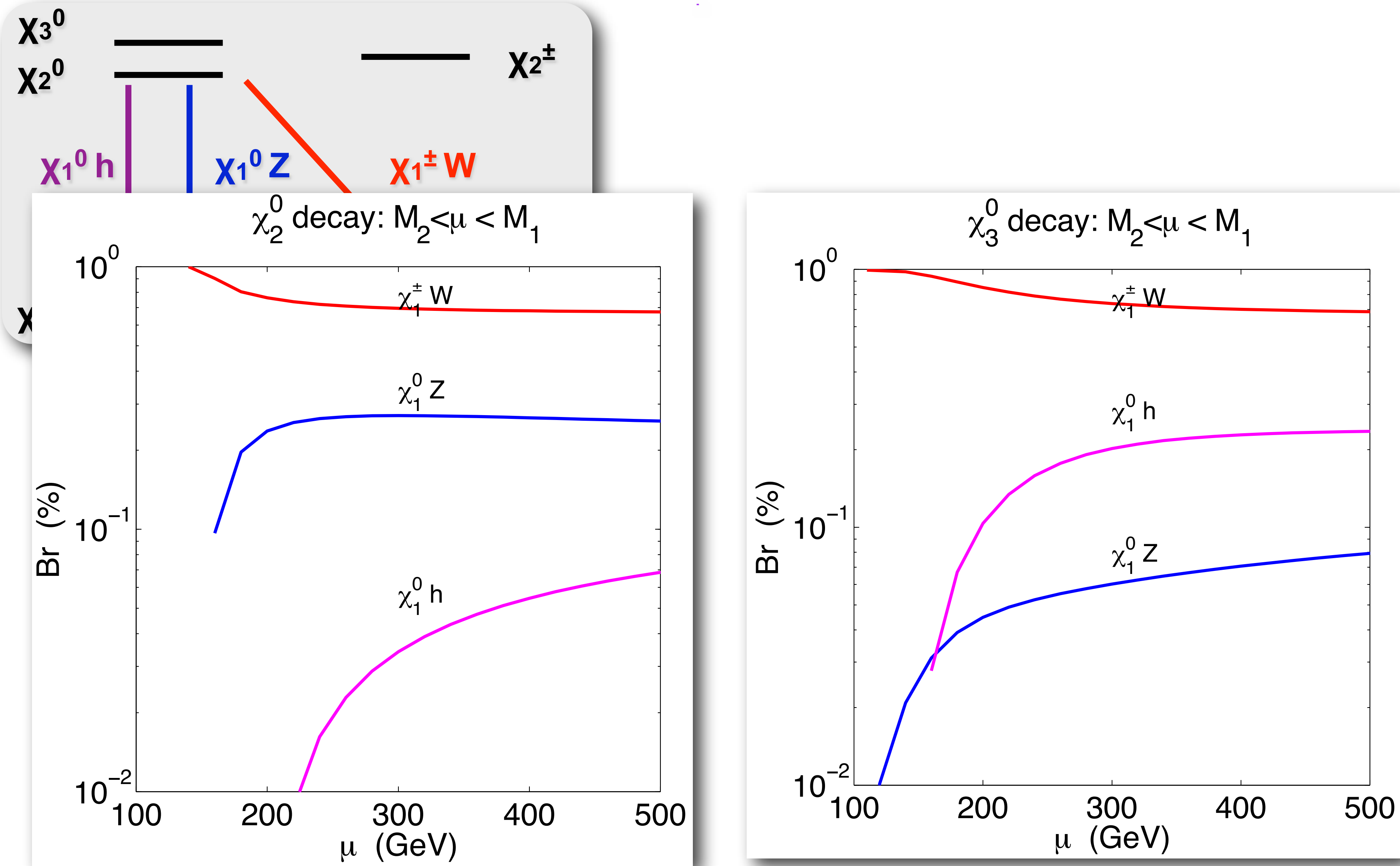
Case BII: Wino LSP- Higgsino NLSP



Case BII: Wino LSP- Higgsino NLSP



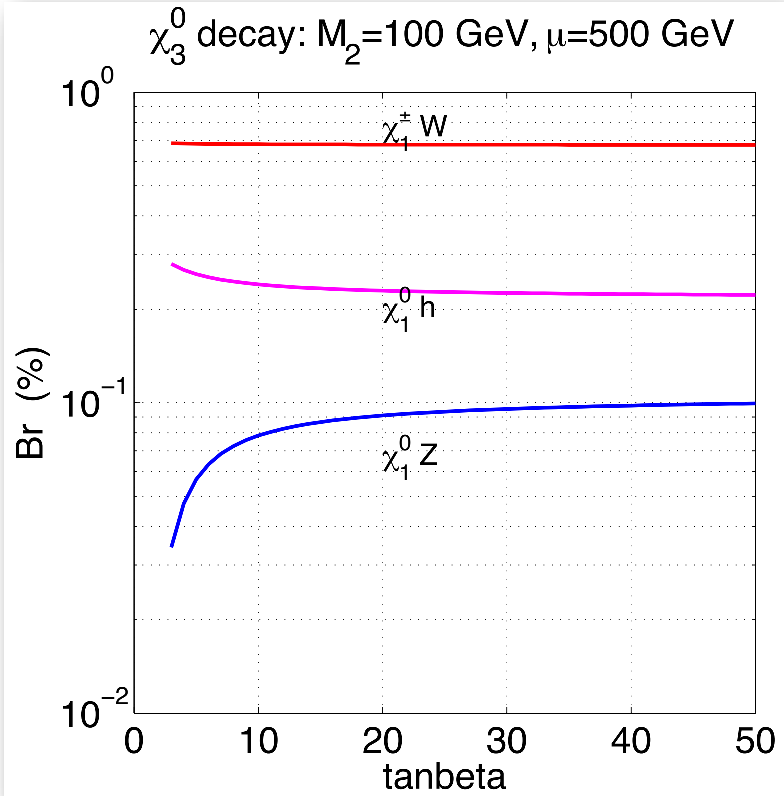
Case BII: Wino LSP- Higgsino NLSP



Case BII: Wino LSP- Higgsino NLSP

$$\chi^0_{2,3} \approx \frac{1}{\sqrt{2}}(\tilde{H}^0_d \pm \tilde{H}^0_u)$$

$$\Gamma(\chi^0_{2,3} \to \chi^0_1 h) \propto (s_\beta \mp c_\beta)^2 \left[(\mu \mp M_2)^2 - m_h^2\right],$$
$$\Gamma(\chi^0_{2,3} \to \chi^0_1 Z) \propto (s_\beta \pm c_\beta)^2 \left[(\mu \pm M_2)^2 - m_Z^2\right],$$
$$\Gamma(\chi^0_{2,3} \to \chi^+_1 W^-) = \Gamma(\chi^0_{2,3} \to \chi^-_1 W^+) \propto 2\left[\mu^2 + M_2^2 - m_W^2\right].$$



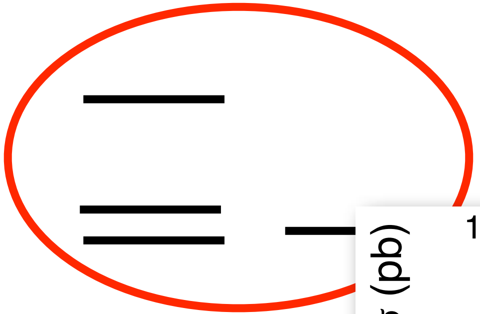
- χ_2^0 dominantly decay into Z
- χ_3^0 dominantly decay into h

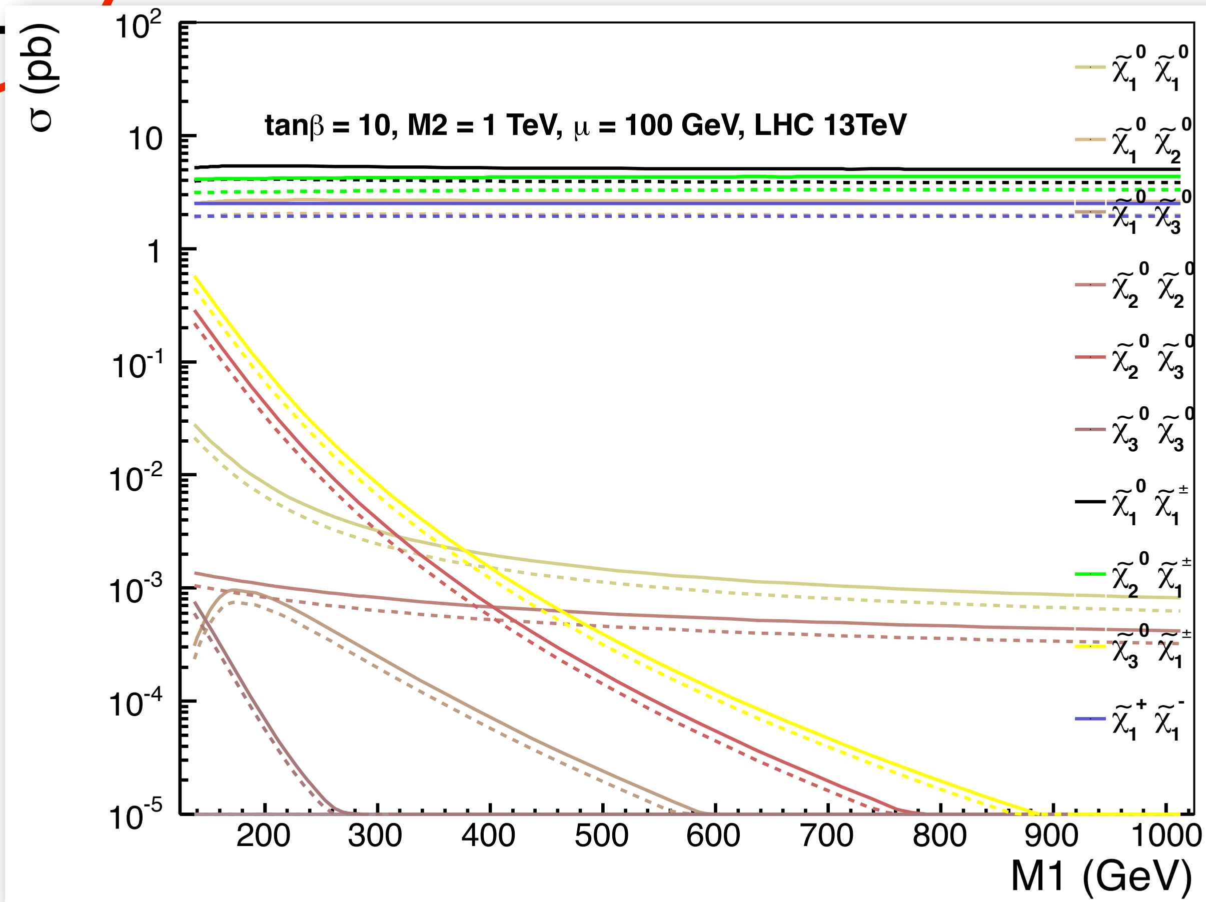
$$\boxed{\Gamma_{\chi_1^+ W^-} = \Gamma_{\chi_1^- W^+} \approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_1^0 h}.}$$

large tanβ, large μ, Br(h) ~ Br(Z) ~ 1/4 Br(W±) = 16.7%

Production: Higgsino LSP - Bino NLSP

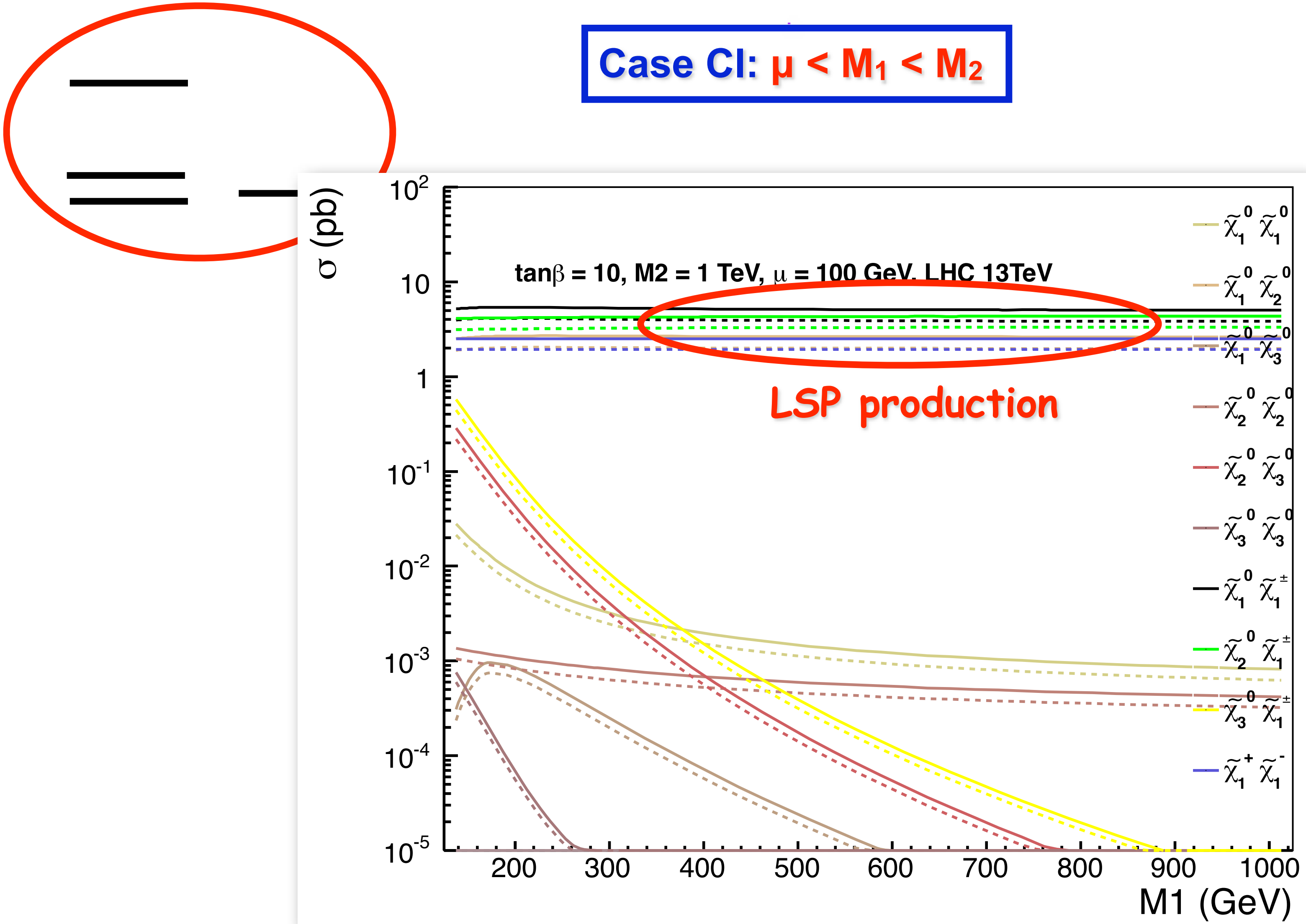
Case CI: $\mu < M_1 < M_2$





Production: Higgsino LSP - Bino NLSP

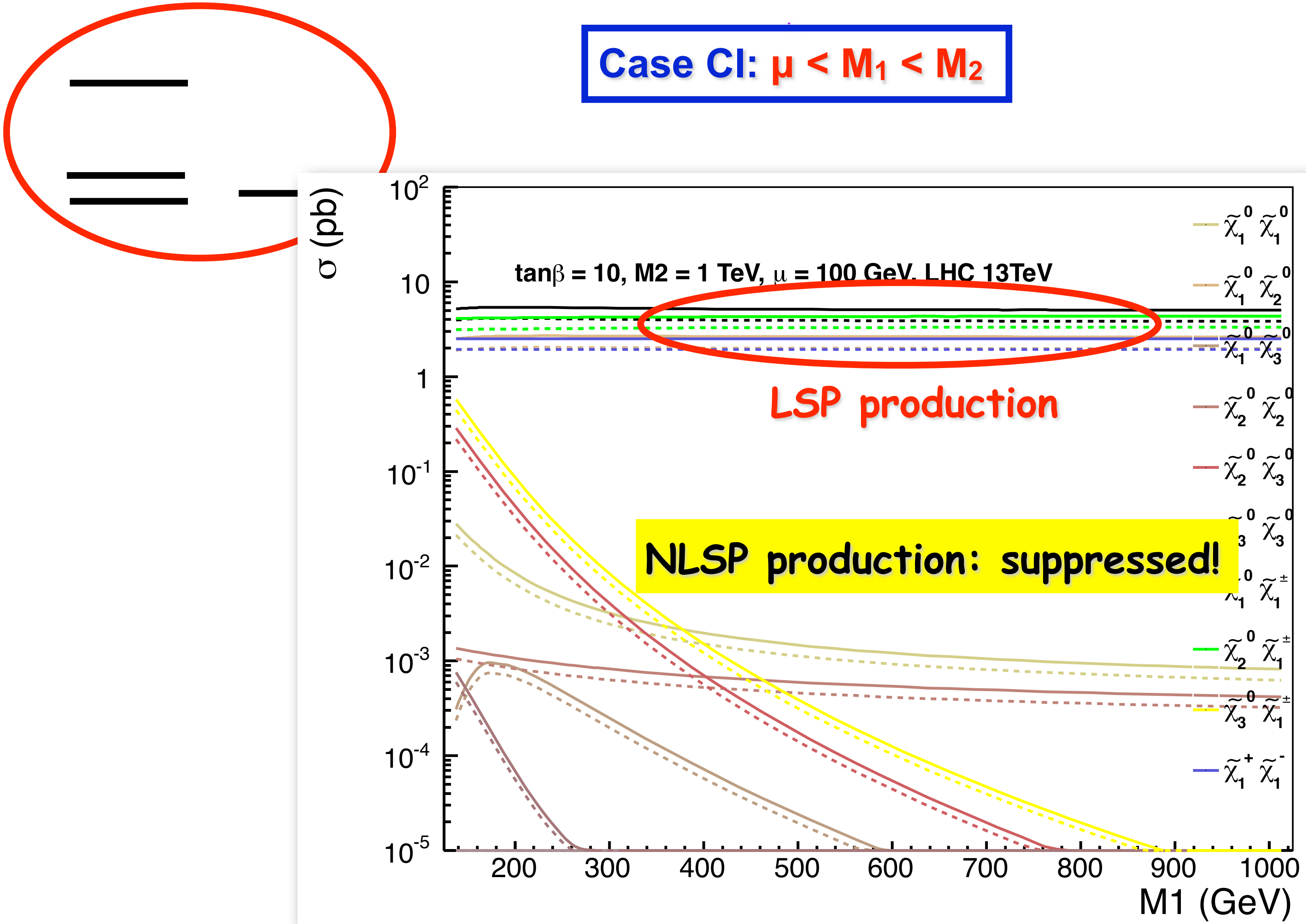
Case CI: $\mu < M_1 < M_2$



T. Han

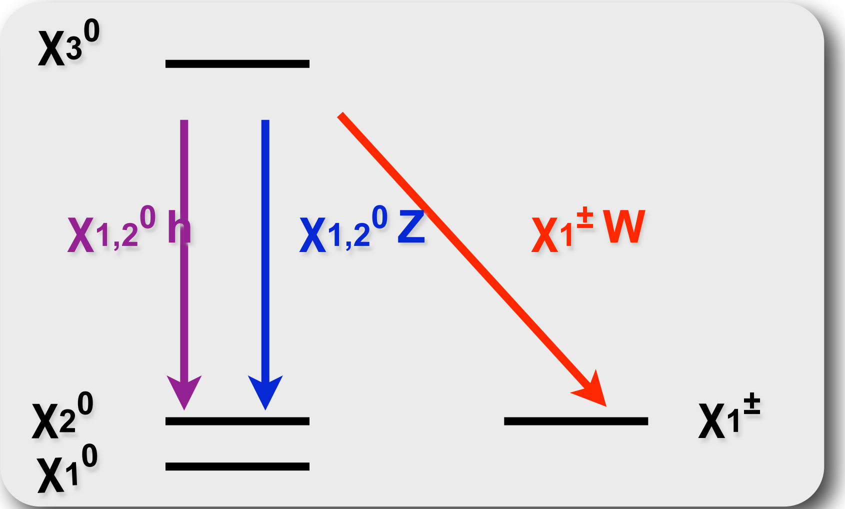
Production: Higgsino LSP - Bino NLSP

Case CI: $\mu < M_1 < M_2$



T. Han

Case CI: Higgsino LSP- Bino NLSP



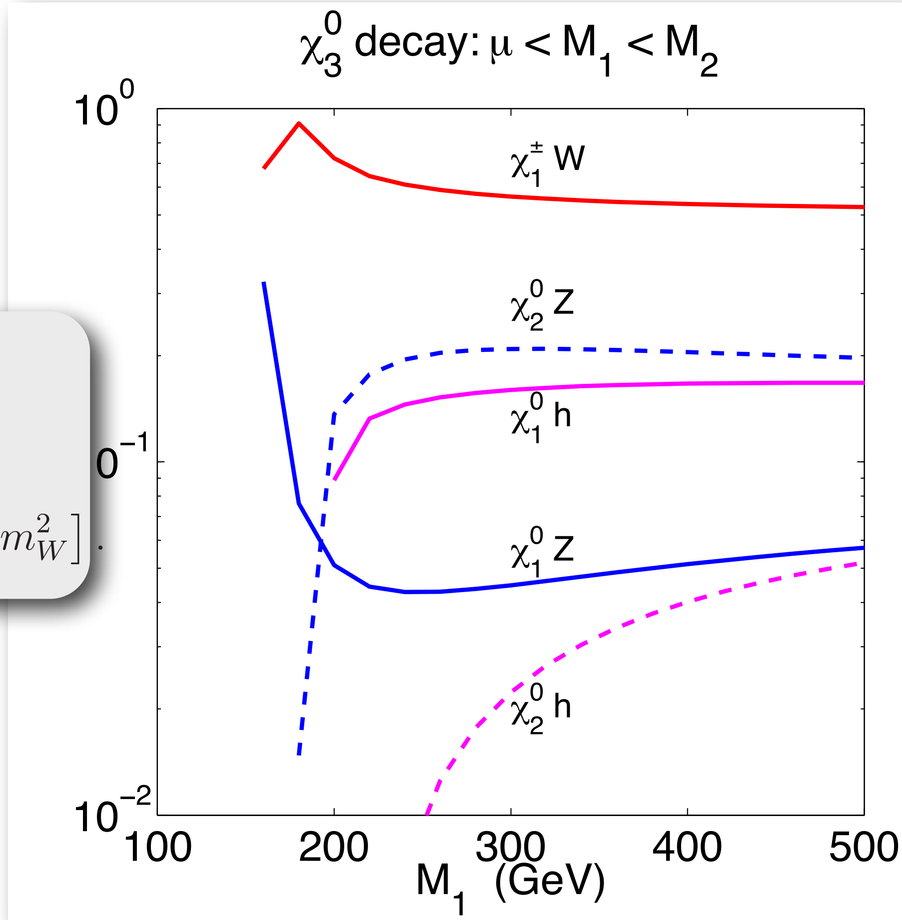
$$\chi^0_{1,2} \approx \frac{1}{\sqrt{2}}(\tilde{H}^0_d \mp \tilde{H}^0_u)$$

$$\Gamma(\chi^0_3 \to \chi^0_{1,2} h) \propto (s_\beta \pm c_\beta)^2 \left[(M_1 \pm \mu)^2 - m_h^2\right],$$

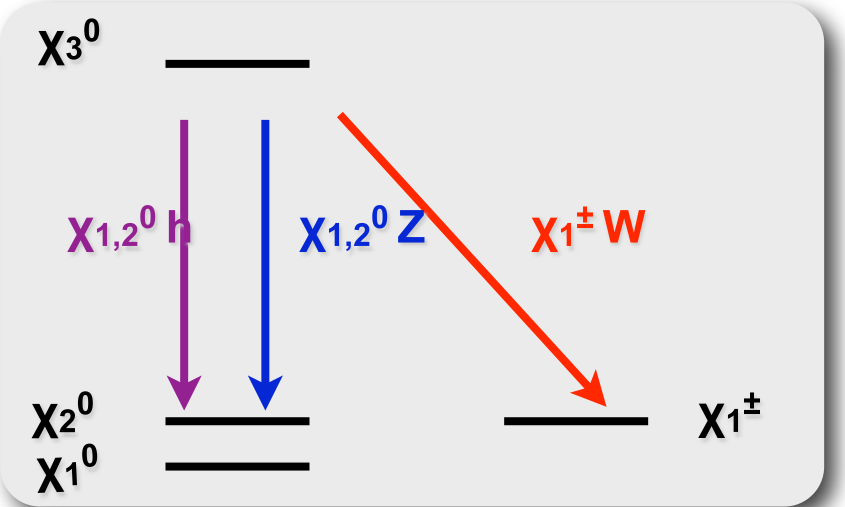
$$\Gamma(\chi^0_3 \to \chi^0_{1,2} Z) \propto (s_\beta \mp c_\beta)^2 \left[(M_1 \mp \mu)^2 - m_Z^2\right],$$

$$\Gamma(\chi^0_3 \to \chi^+_1 W^-) = \Gamma(\chi^0_3 \to \chi^-_1 W^+) \propto 2\left[M_1^2 + \mu^2 - m_W^2\right].$$

$$\boxed{\begin{aligned} &\Gamma_{\chi_1^+ W^-} = \Gamma_{\chi_1^- W^+} \\ &\approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_1^0 h} \approx \Gamma_{\chi_2^0 Z} + \Gamma_{\chi_2^0 h} \\ &\approx \Gamma_{\chi_1^0 h} + \Gamma_{\chi_2^0 h} \approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_2^0 Z}. \end{aligned}}$$



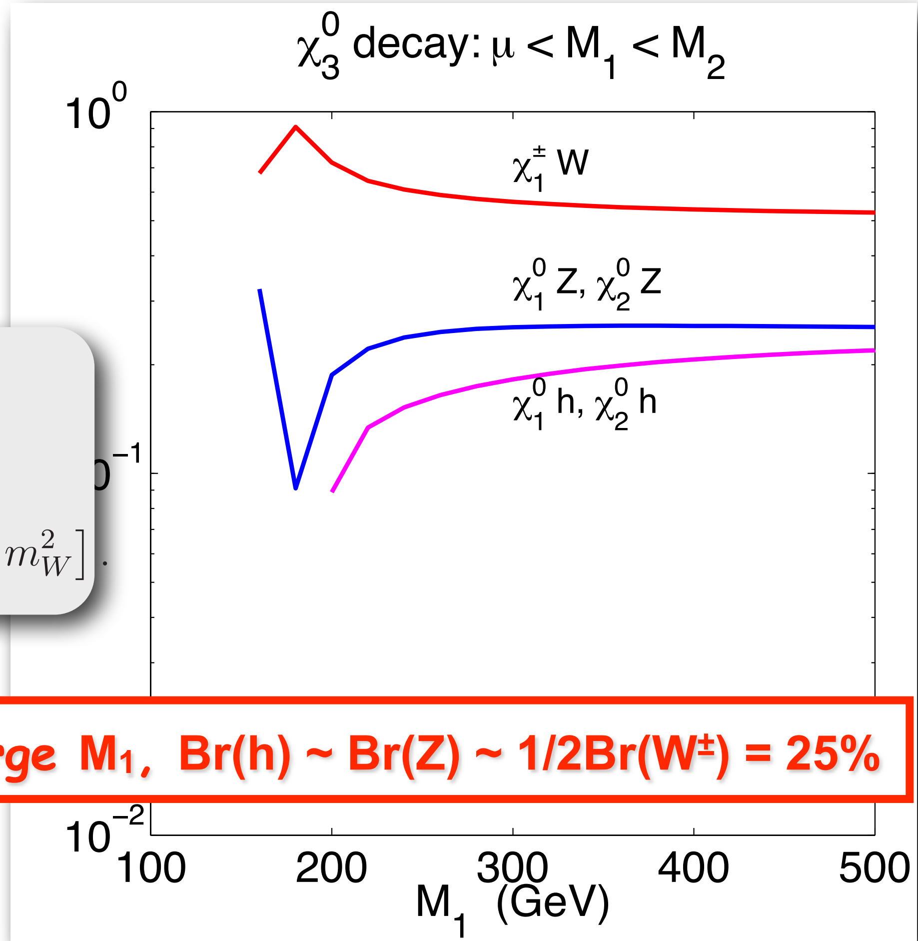
Case CI: Higgsino LSP- Bino NLSP



$$\chi^0_{1,2} \approx \frac{1}{\sqrt{2}}(\tilde{H}^0_d \mp \tilde{H}^0_u)$$

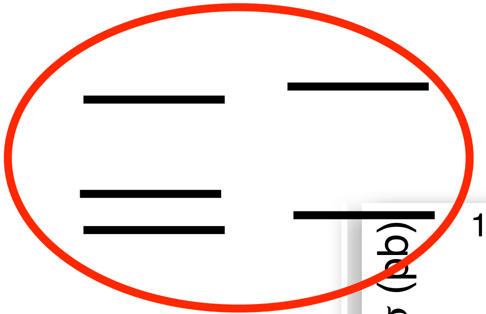
$$\Gamma(\chi^0_3 \to \chi^0_{1,2} h) \propto (s_\beta \pm c_\beta)^2 \left[(M_1 \pm \mu)^2 - m_h^2\right],$$
$$\Gamma(\chi^0_3 \to \chi^0_{1,2} Z) \propto (s_\beta \mp c_\beta)^2 \left[(M_1 \mp \mu)^2 - m_Z^2\right],$$
$$\Gamma(\chi^0_3 \to \chi^+_1 W^-) = \Gamma(\chi^0_3 \to \chi^-_1 W^+) \propto 2\left[M_1^2 + \mu^2 - m_W^2\right].$$

$$\boxed{\begin{aligned} &\Gamma_{\chi_1^+ W^-} = \Gamma_{\chi_1^- W^+} \\ &\approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_1^0 h} \approx \Gamma_{\chi_2^0 Z} + \Gamma_{\chi_2^0 h} \\ &\approx \Gamma_{\chi_1^0 h} + \Gamma_{\chi_2^0 h} \approx \Gamma_{\chi_1^0 Z} + \Gamma_{\chi_2^0 Z}. \end{aligned}}$$

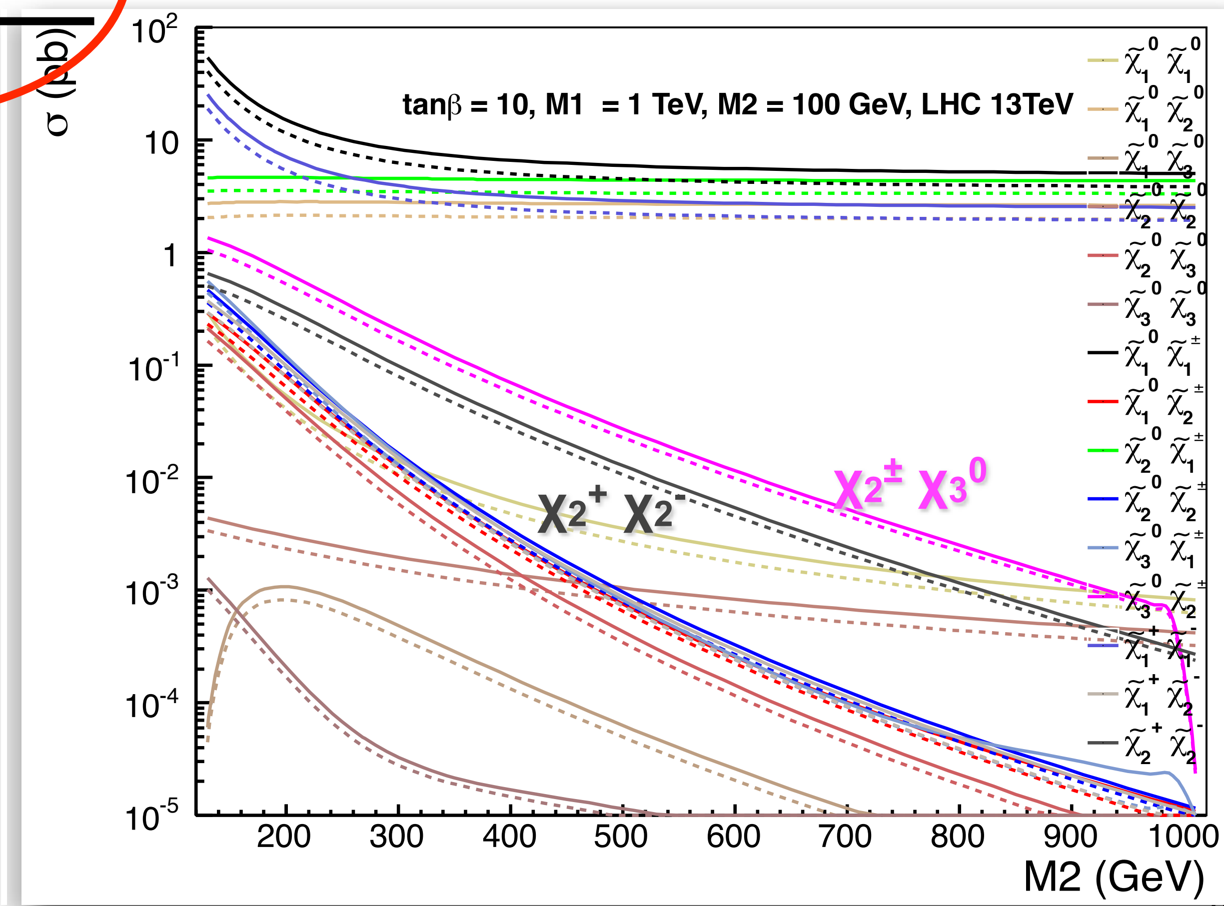


large M_1, $Br(h) \sim Br(Z) \sim 1/2 Br(W^\pm) = 25\%$

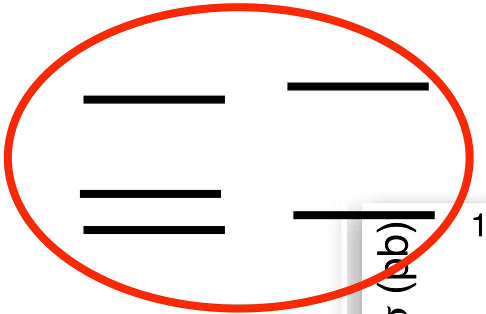
Production: Higgsino LSP - Wino NLSP



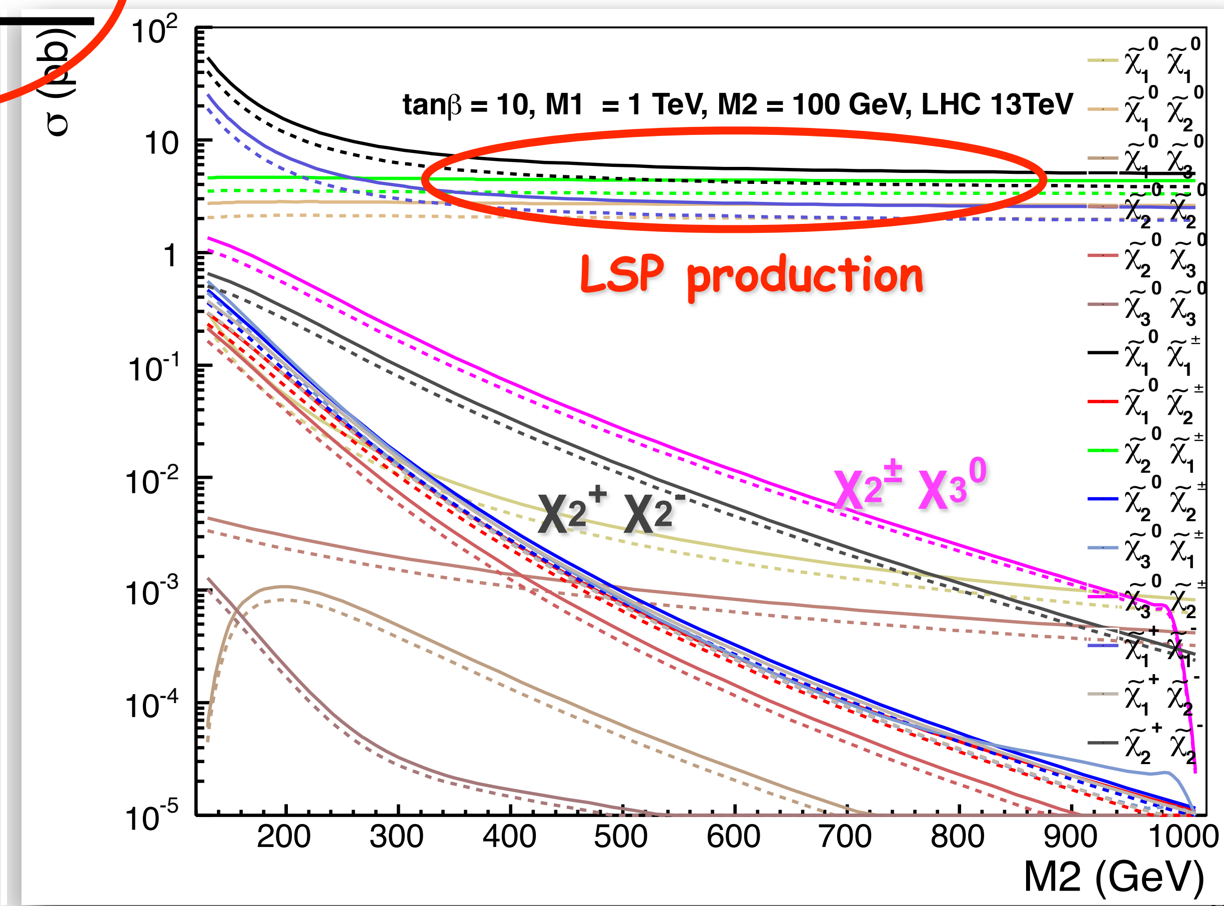
Case CII: $\mu < M_2 < M_1$



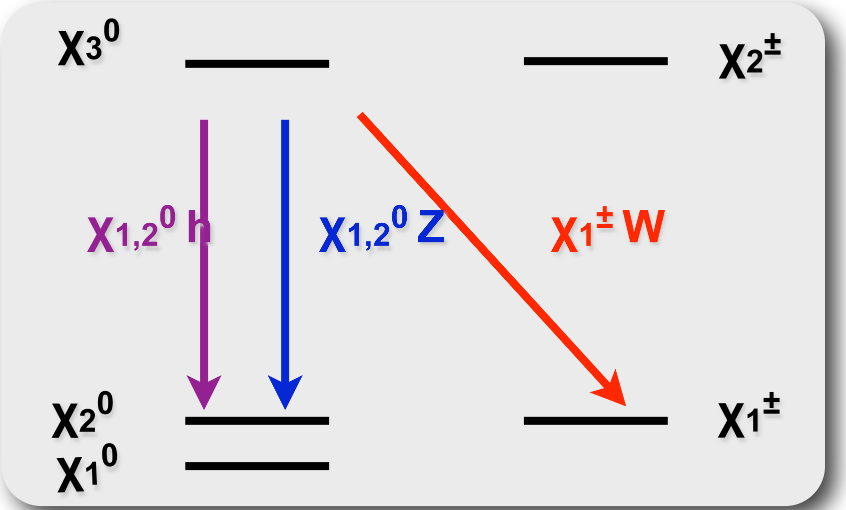
Production: Higgsino LSP - Wino NLSP



Case CII: $\mu < M_2 < M_1$

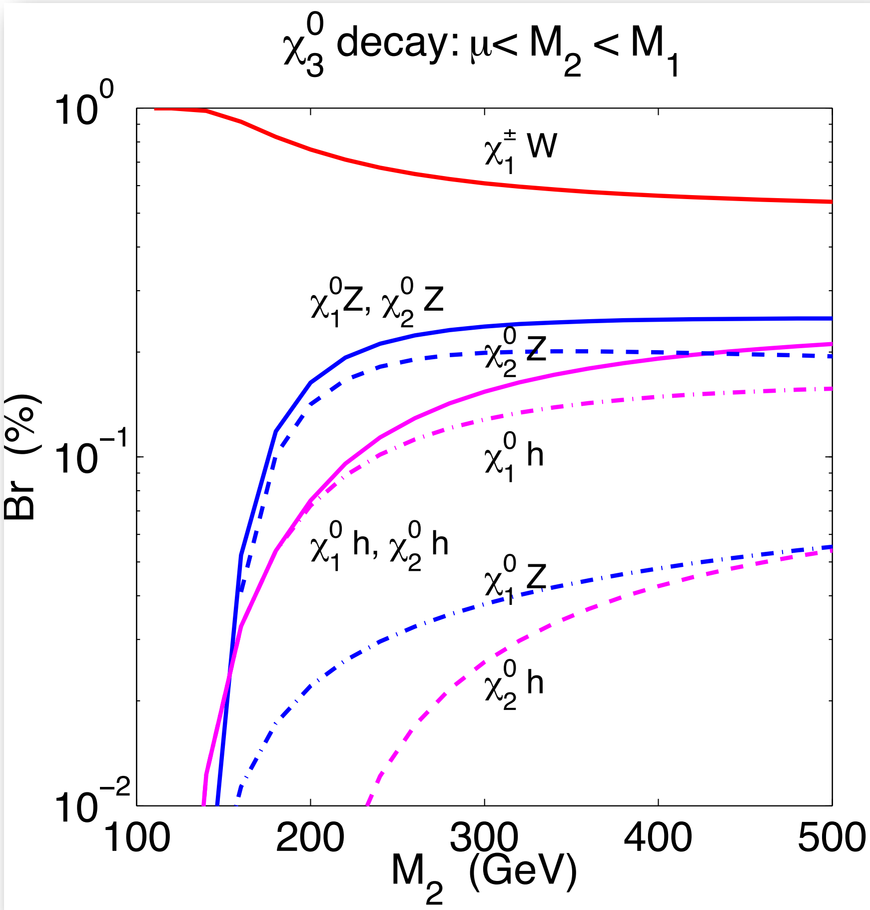


Case CII: Higgsino LSP- Wino NLSP

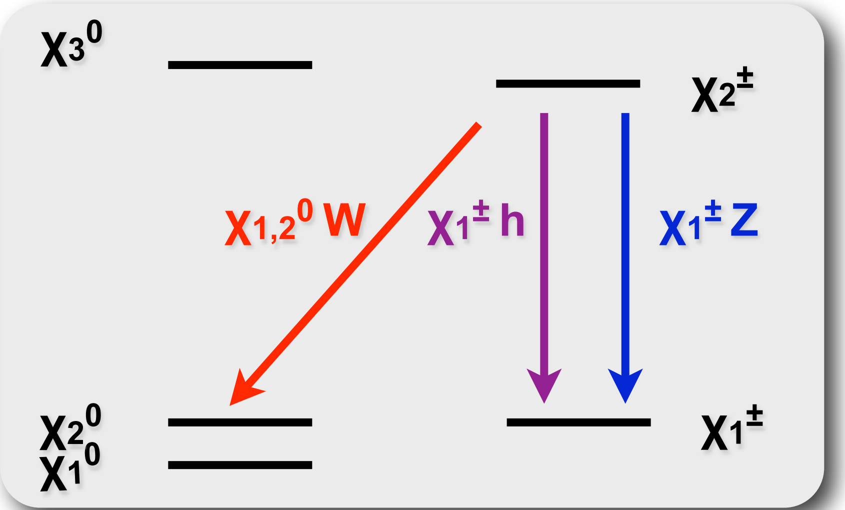


Similar to case CI

large M_2, $Br(h) \sim Br(Z) \sim 1/2Br(W^\pm) = 25\%$

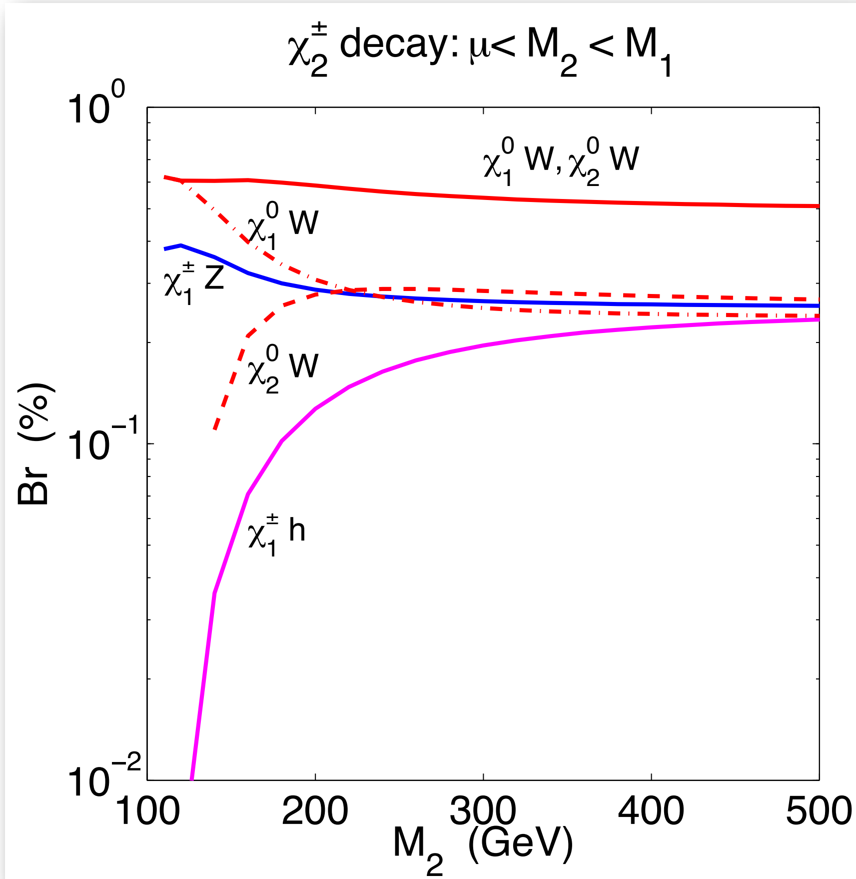


Case CII: Higgsino LSP- Wino NLSP



$$\Gamma_{\chi_1^0 W} : \Gamma_{\chi_2^0 W} : \Gamma_{\chi_1^\pm Z} : \Gamma_{\chi_1^\pm h} \approx 1:1:1:1$$

large M_2, Br(h) ~ Br(Z) ~ 1/2Br($W^\pm$) = 25%



T. Han

Summary

$$\sigma_{XY}^{\rm tot} = \sum_{i,j} \sigma(\chi_i \chi_j) \times Br(\chi_i \chi_j \to XY),$$

$$XY = W^+W^-,\ W^\pm W^\pm,\ WZ,\ Wh,\ Zh,\ ZZ,\ \text{and } hh$$

- **Br(WZ) < 100%, sometime highly suppressed**
- **Wh complementary to WZ channel: new discovery potential**
- **Zh could also be important**
- **hh usually is small**

LHC searches

Channel	Signal
W^+W^-	OS2L + MET
$W^\pm W^\pm$	SS2L + MET
WZ	3L + MET
Wh	1L + bb + MET
Zh	OS2l +bb + MET

simulated using Delphes + published resolution functions

LHC searches

Channel	Signal
W^+W^-	OS2L + MET
$W^\pm W^\pm$	SS2L + MET
WZ	3L + MET
Wh	1L + bb + MET
Zh	OS2l +bb + MET

simulated using Delphes + published resolution functions

LHC searches

◉ **Wh channel: 1l+jets + MET**

- Isolated e(μ), Pt > 30(20) GeV, |eta| < 2.5
- Veto any additional e/μ with Pt > 10 GeV, |eta| < 2.5
- Veto any Taus or isolated Tracks
- 2 Jets Pt > 30 GeV, |eta| < 2.5
- Veto 3rd Jet with Pt > 20 GeV
- 2 bjets with Pt > 30 GeV, |eta| < 2.5
- 2 bjets in one hemi-sphere
- Invariant mass of two bjets 100 < M_{bb} (GeV) < 140
- MT (MET and the Higgs) > 200 GeV
- MET > 50 GeV

Signal regions:
(MT, MET) > (200, 50), (600, 50), (200, 100), (600,100) GeV

10 fb-1

Processes	MET > 50, MT > 200 (Baseline)	MET > 50, 200< MT < 400	MET > 50, 400 < MT < 600	MET > 50, MT > 600	MET > 100, MT > 200	MET > 100, 200 < MT < 400	MET > 100, 400 < MT < 600	MET > 100, MT > 600
Total bg	46.15 ± 12.01	43.27 ± 11.96	2.40 ± 1.02	0.48 ± 0.48	33.63 ± 10.69	30.75 ± 10.63	2.40 ± 1.02	0.49 ± 0.48

LHC searches

◉ **Wh channel: 1l+jets + MET**

- Isolated e(μ), Pt > 30(20) GeV, |eta| < 2.5
- Veto any additional e/μ with Pt > 10 GeV, |eta| < 2.5
- Veto any Taus or isolated Tracks
- 2 Jets Pt > 30 GeV, |eta| < 2.5
- Veto 3rd Jet with Pt > 20 GeV
- 2 bjets with Pt > 30 GeV, |eta| < 2.5
- 2 bjets in one hemi-sphere
- Invariant mass of two bjets 100 < M_{bb} (GeV) < 140
- MT (MET and the Higgs) > 200 GeV
- MET > 50 GeV

Signal regions:

(MT, MET) > (200, 50), (600, 50), (200, 100), (600,100) GeV

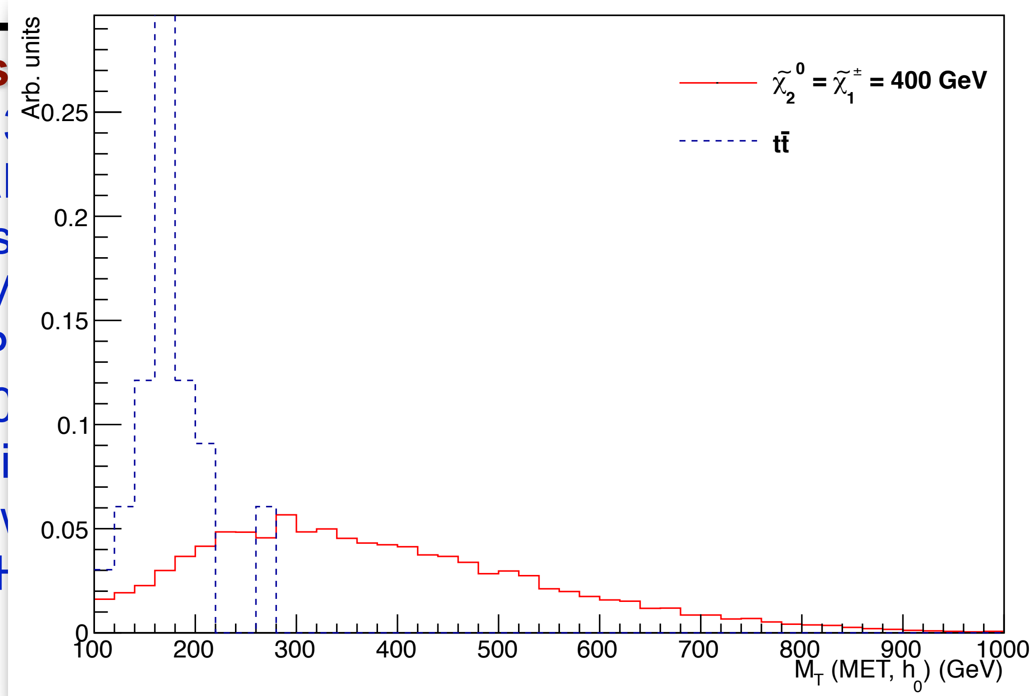
10 fb-1

Processes	MET > 50, MT > 200 (Baseline)	MET > 50, 200< MT < 400	MET > 50, 400 < MT < 600	MET > 50, MT > 600	MET > 100, MT > 200	MET > 100, 200 < MT < 400	MET > 100, 400 < MT < 600	MET > 100, MT > 600
Total bg	46.15 ± 12.01	43.27 ± 11.96	2.40 ± 1.02	0.48 ± 0.48	33.63 ± 10.69	30.75 ± 10.63	2.40 ± 1.02	0.49 ± 0.48

LHC searches

◉ **Wh channel: 1l+jets**

- Isolated e(μ), Pt > 3
- Veto any additional
- Veto any Taus or is
- 2 Jets Pt > 30 GeV
- Veto 3rd Jet with P
- 2 bjets with Pt > 30
- 2 bjets in one hemi
- Invariant mass of tw
- MT (MET and the H
- MET > 50 GeV



Signal regions:
(MT, MET) > (200, 50), (600, 50), (200, 100), (600,100) GeV

10 fb-1

Processes	MET > 50, MT > 200 (Baseline)	MET > 50, 200< MT < 400	MET > 50, 400 < MT < 600	MET > 50, MT > 600	MET > 100, MT > 200	MET > 100, 200 < MT < 400	MET > 100, 400 < MT < 600	MET > 100, MT > 600
Total bg	46.15 ± 12.01	43.27 ± 11.96	2.40 ± 1.02	0.48 ± 0.48	33.63 ± 10.69	30.75 ± 10.63	2.40 ± 1.02	0.49 ± 0.48

LHC searches

- **Zh signal: OS2l+ bb + MET**
  - Isolated e(μ), Pt > 20/10 GeV, |eta| < 2.5
  - Invariant mass of OS dileptons 76 GeV < m_{ll} < 106 GeV
  - Veto any additional e(μ) with Pt > 10 GeV, |eta| < 2.5
  - 2 Jets Pt > 30 GeV, |eta| < 2.5
  - 2 bjets with Pt > 30 GeV, |eta| < 2.5
  - 2 bjets in One hemi-sphere
  - Invariant mass of two bjets 90 GeV < M_{bb} < 150 GeV
  - MT (MET and the Higgs) > 200 GeV
  - MET > 50 GeV

Signal regions:
High MET: (MT, MET) > (200,50) GeV

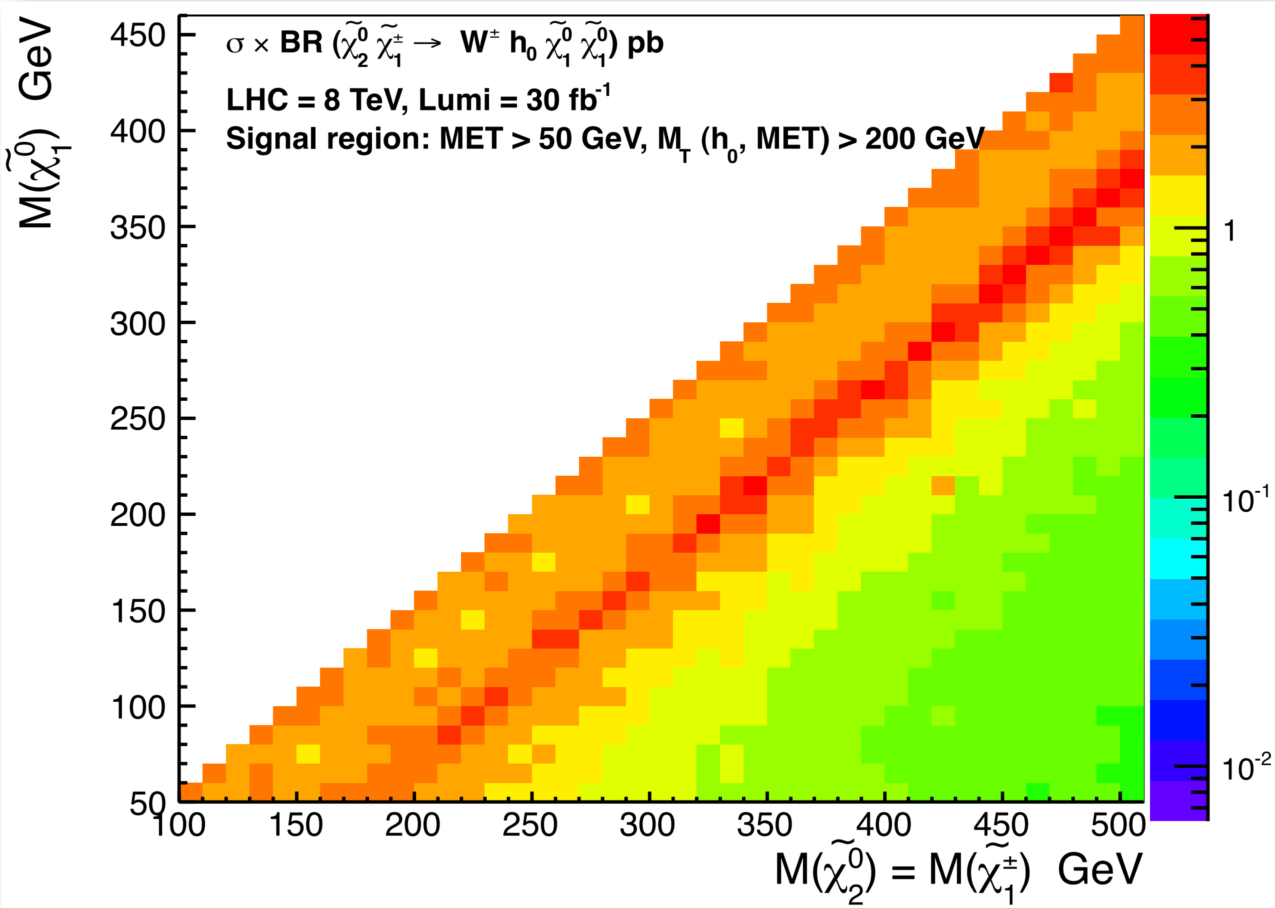
10 fb-1

Processes	MET > 50, MT > 200 (Baseline)	MET > 50, 200< MT < 400	MET > 50, 400 < MT < 600	MET > 50, MT > 600	MET > 100, MT > 200	MET > 200, 200 < MT < 400	MET > 100, 400 < MT < 600	MET > 100, MT > 600
Total	5.97 ± 5.22	5.87 ± 5.22	0.13 ± 0.13	0.00093 ± 0.0006	0.45 ± 0.23	0.31 ± 0.19	0.13 ± 0.13	0.00093 ± 0.0006

95% CL upper limit on cross sections

Wh: 1l+jets + MET

95% C.L. upper limit on signal cross section



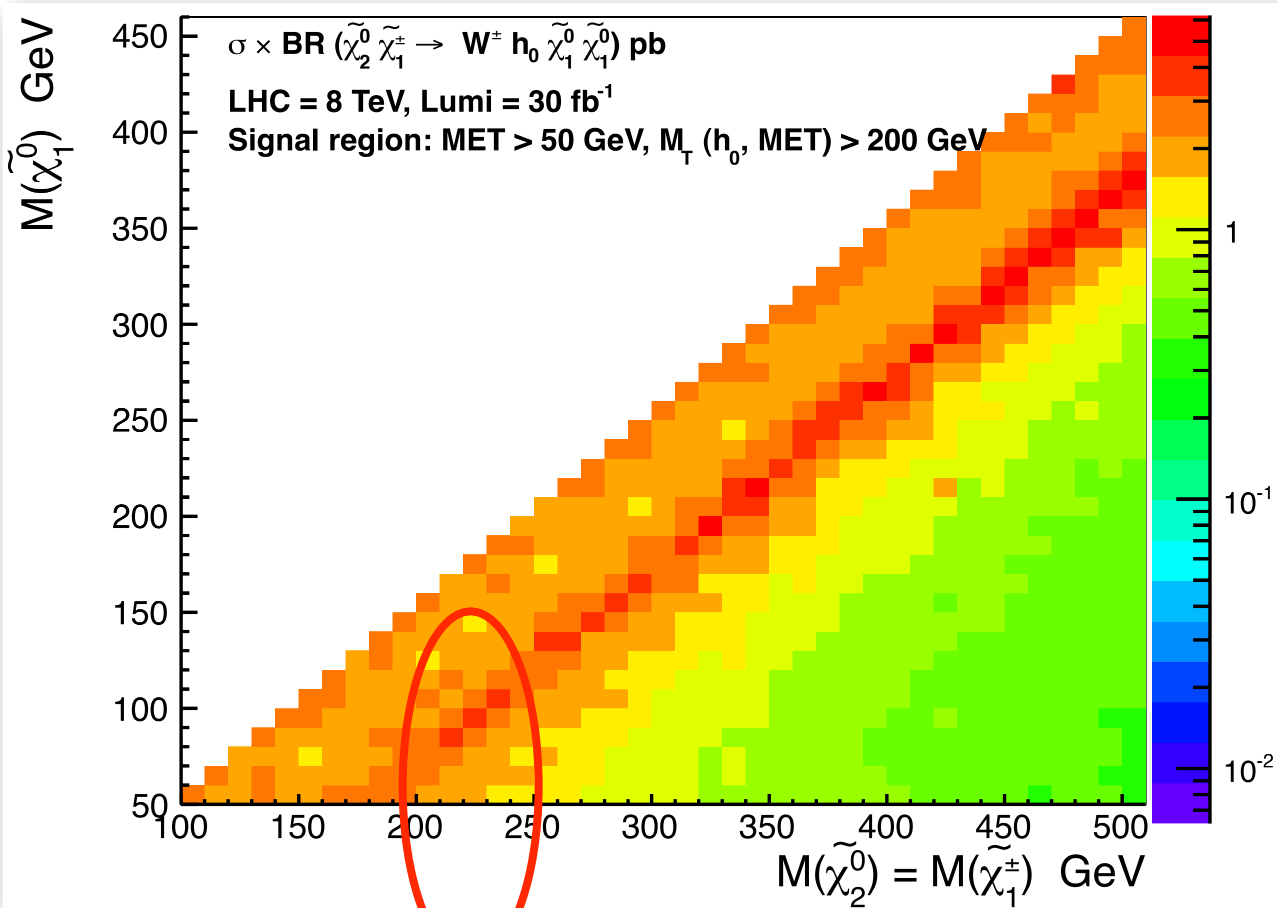
T. Han

◉ low M_T cut has better reach!

95% CL upper limit on cross sections

Wh: 1l+jets + MET

95% C.L. upper limit on signal cross section



- low M_T cut has better reach!

Conclusions

- LHC has great reach for colored particles, but more studies needed to explore LHC potential for EW particles.
- MSSM EW-ino sector: neutralinos, charginos, M_1, M_2, μ, $\tan\beta$
- Six cases with different ordering of M_1, M_2, μ

	Case A	Case B	Case C
I	$M_1 < M_2 < \mu$	$M_2 < M_1 < \mu$	$\mu < M_1 < M_2$
II	$M_1 < \mu < M_2$	$M_2 < \mu < M_1$	$\mu < M_2 < M_1$

- Dominant neutralino/chargino pair production and decay
- Wh and WZ final states are complementary:
  - current WZ limit weakened
  - Wh: new discovery potential
- LHC reach of neutralinos/charginos with final states including h: Wh, Zh...

Conclusions

- LHC has great reach for colored particles, but more studies needed to explore LHC potential for EW particles.
- MSSM EW-ino sector: neutralinos, charginos, M_1, M_2, μ, $\tan\beta$
- Six cases with different ordering of M_1, M_2, μ

	Case A	Case B	Case C
I	$M_1 < M_2 < \mu$	$M_2 < M_1 < \mu$	$\mu < M_1 < M_2$
II	$M_1 < \mu < M_2$	$M_2 < \mu < M_1$	$\mu < M_2 < M_1$

- Dominant neutralino/chargino pair production and decay
- Wh and WZ final states are complementary:
  - current WZ limit weakened
  - Wh: new discovery potential
- LHC reach of neutralinos/charginos with final states including h: Wh, Zh...