Ewkinos at the LHC*

- In the light of the Higgs boson.
- Nearly degeneracy a real challenge.

Tao Han, Univ. of Pittsburgh

SUSY @ the Near Energy Frontier, FNAL
Nov. 11, 2013

* TH, Sanjay Padhi, Shufang Su: arXiv:1309.5966

With respect to Gaugino/Higgsino masses M_1, M_2 and μ:
Categorize the theory into 6 distinctive cases

Comprehensive scan in M_1, M_2 and μ and study the decays characteristics, signal classification

Exploring LHC **reach for the electroweak sector**
charginos, Neutralinos with the help of the Higgs boson

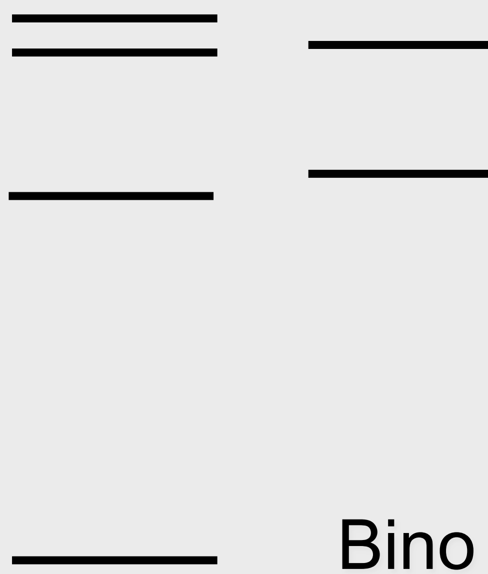
TH, Sanjay Padhi, and Shufang Su, **arXiv:1309.5966**

◉ **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, $\tan\beta$

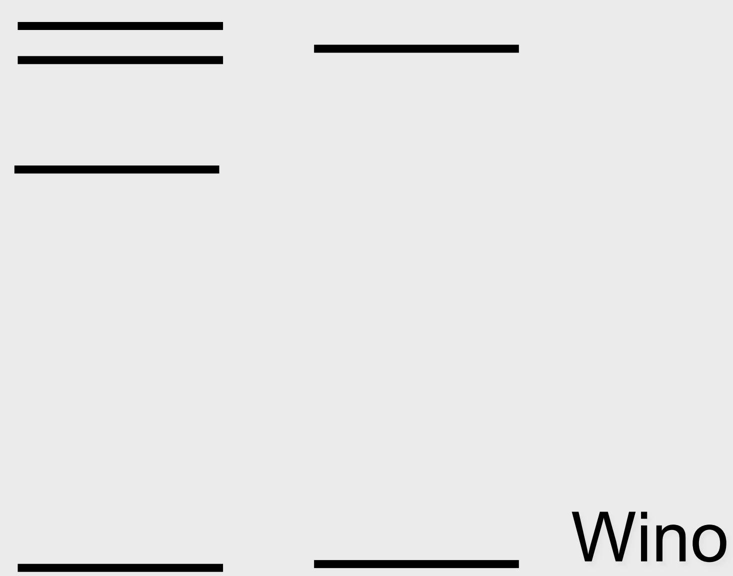
Order of M_1, M_2 and μ :

Bino LSP
$M_1 < M_2, \mu$



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

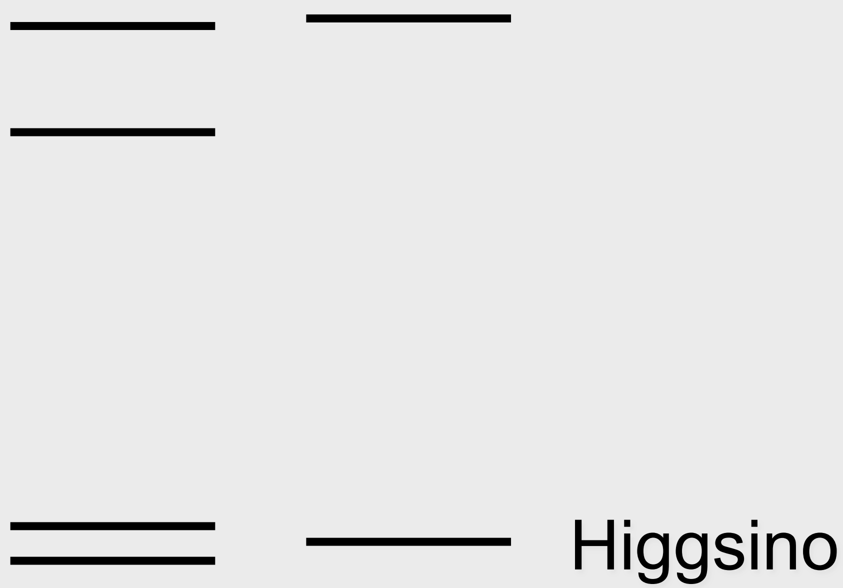
Wino LSP
$M_2 < M_1, \mu$



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, ...

"Natural SUSY"?

Overall, Six cases

New Terminology:

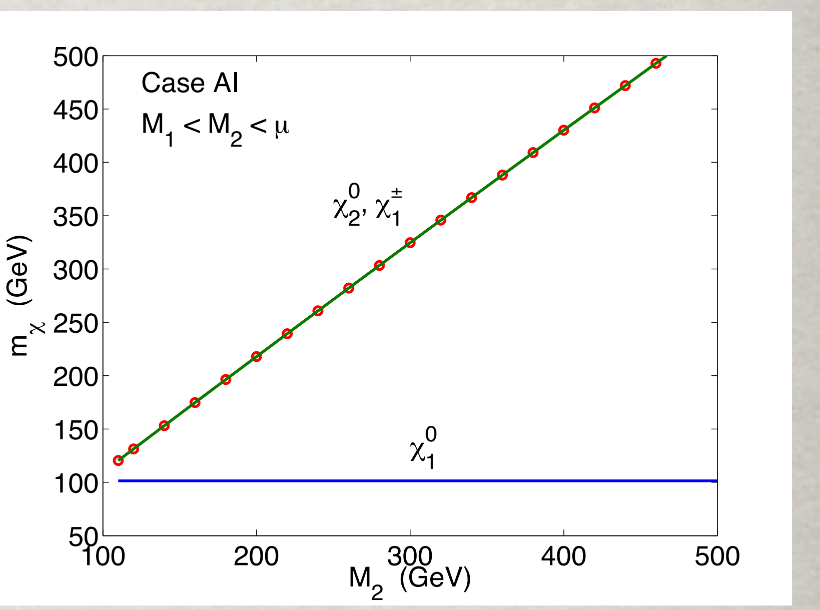
LSP(s): usual LSP+degenerate states

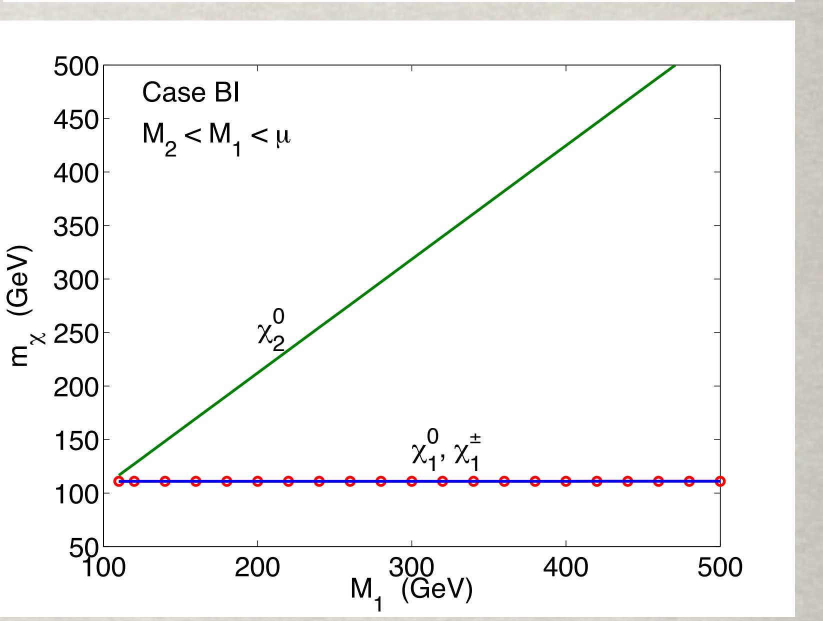
NLSP(s): 2nd set low-lying (degenerate) states

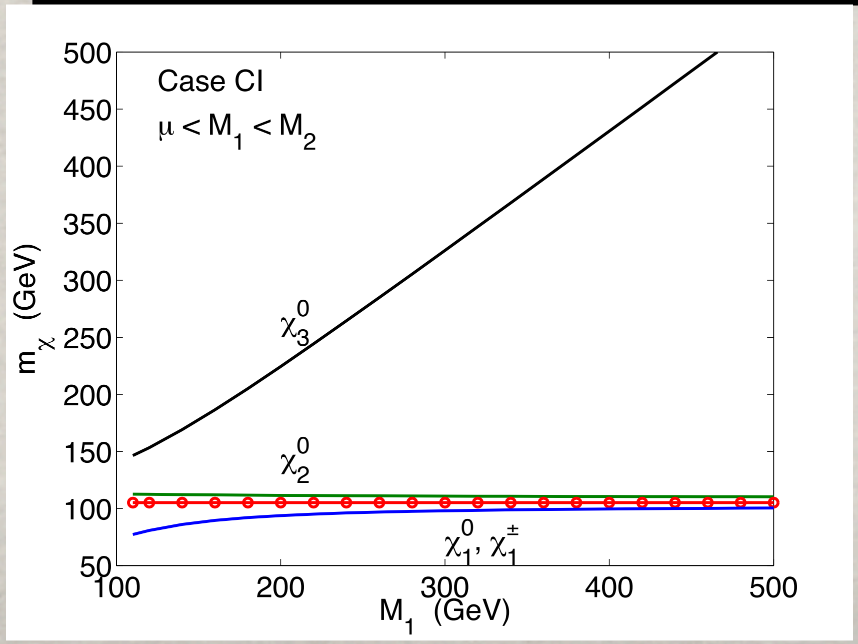
Case AI: **Bino LSP-Wino NLSP** $M_1 < M_2 < \mu$
Case AII: **Bino LSP-Higgsino NLSP** $M_1 < \mu < M_2$

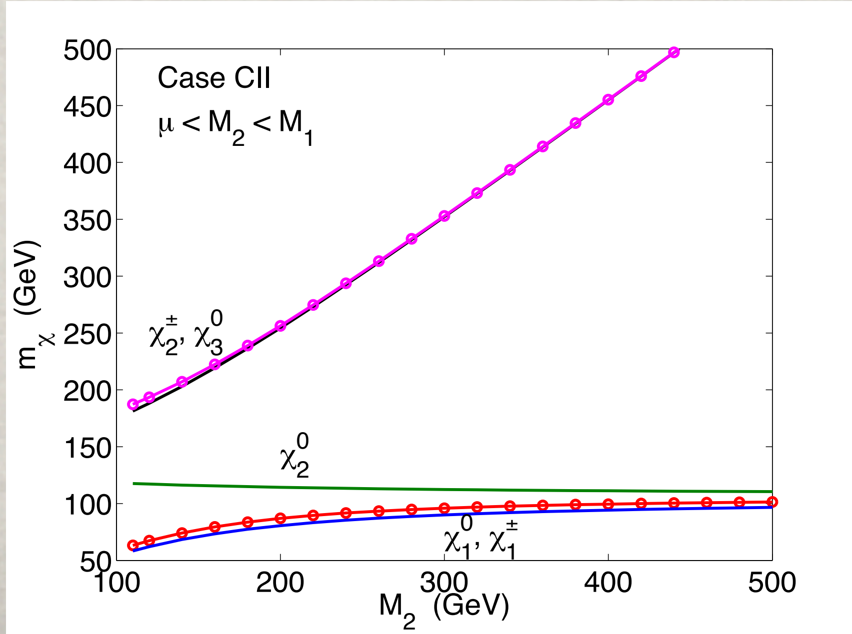
Case BI: **Wino LSP-Bino NLSP** $M_2 < M_1 < \mu$
Case BII: **Wino LSP-Higgsino NLSP** $M_2 < \mu < M_1$

Case CI: **Higgsino LSP-Bino NLSP** $\mu < M_1 < M_2$
Case CII: **Higgsino LSP-Wino NLSP** $\mu < M_2 < M_1$

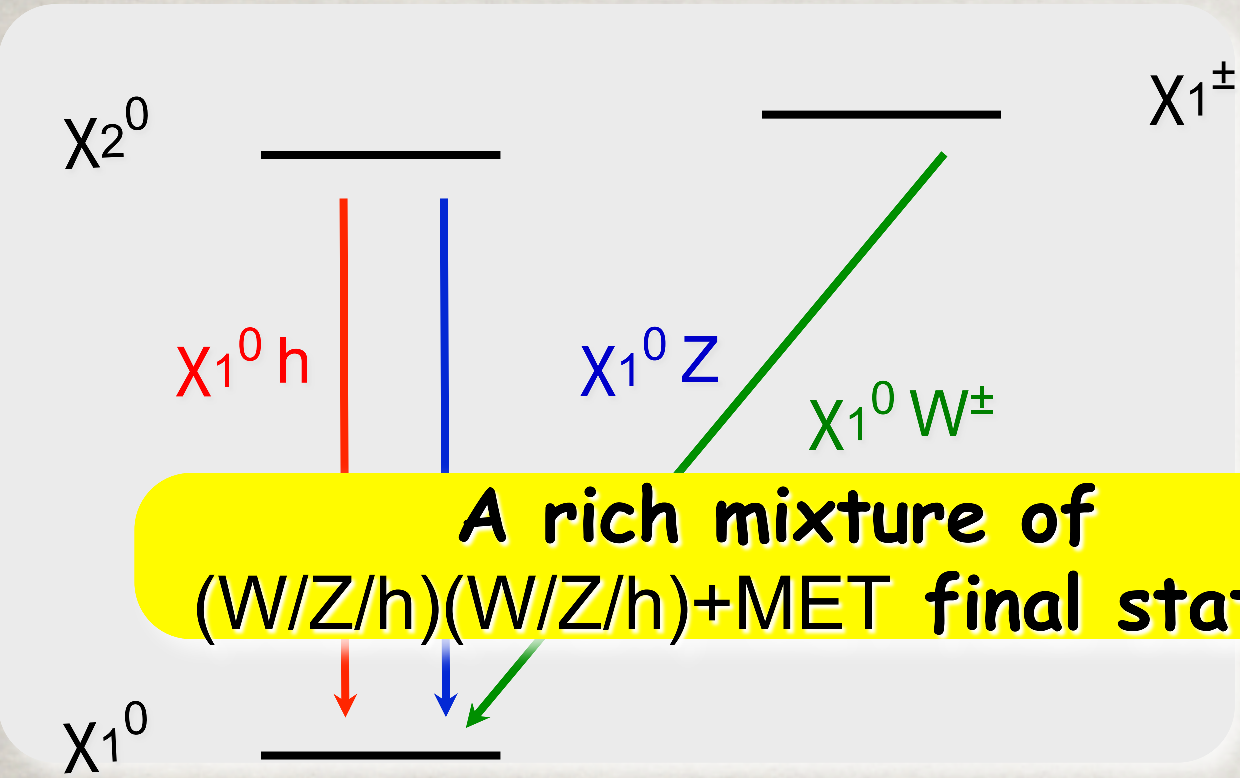






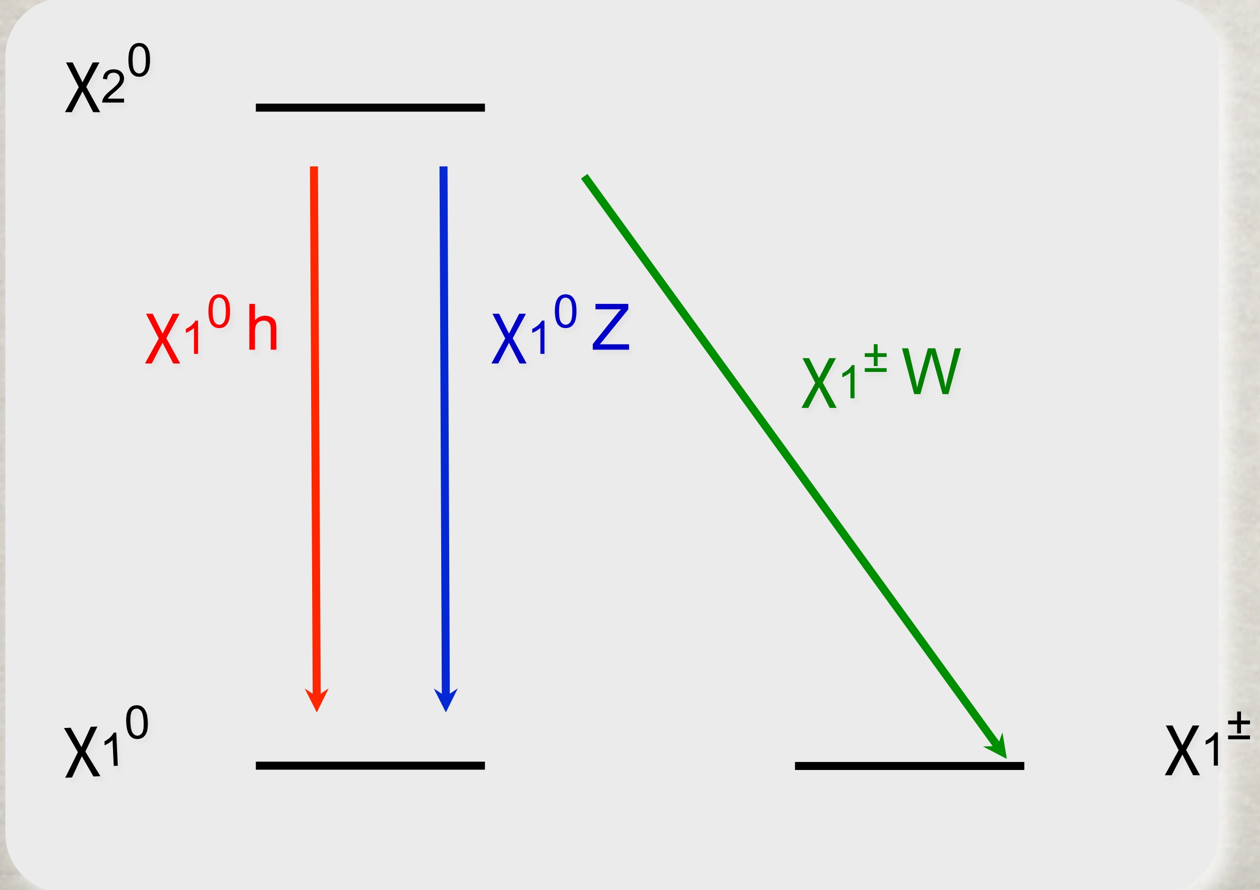


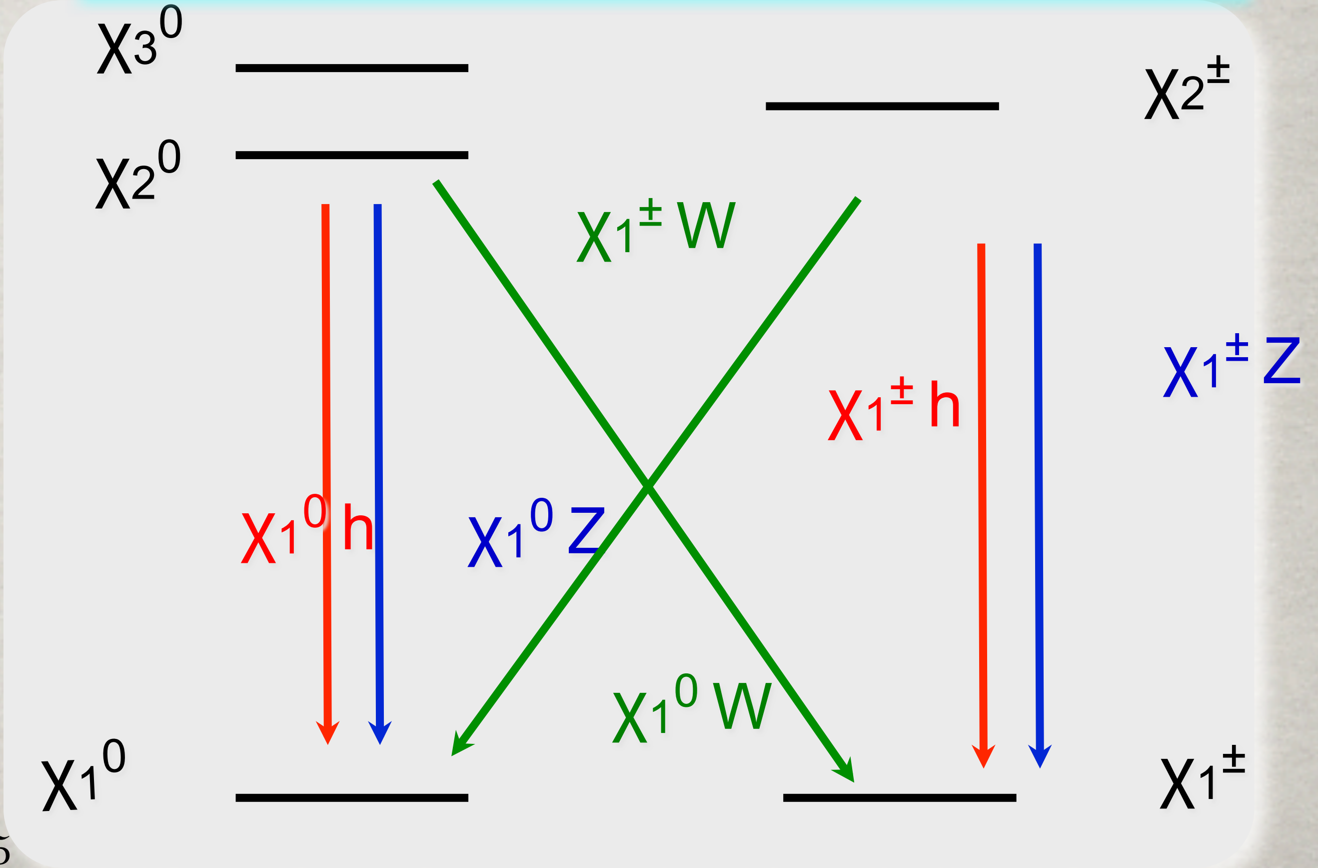
Decay of heavy neutralino and chargino



A rich mixture of (W/Z/h)(W/Z/h)+MET final states!

- Gunion et. al., Int. J. Mod. Phys. A2 (1987) 1145
- Gunion and Haber, PRD 37 (1988) 2515
- Bartl et. al., PLB 216 (1989) 233
- Djouadi et. al., hep-ph/0104115
- Datta et. al., hep-ph/0303095
- Huitu et. al., arXiv: 0808.3094
- Gori et. al., arXiv: 1103.4138
- Stal and Weiglein, arXiv: 1108.0595
- Baer et. al., arXiv: 1201.2949
- Ghosh et. al., arXiv:1202.4937
- Howe and Saraswat, arXiv: 1208.1542
- Arbey et. al., arXiv: 1212.6865,
- T. Han, S. Padhi and SS, arXiv:1309.5966

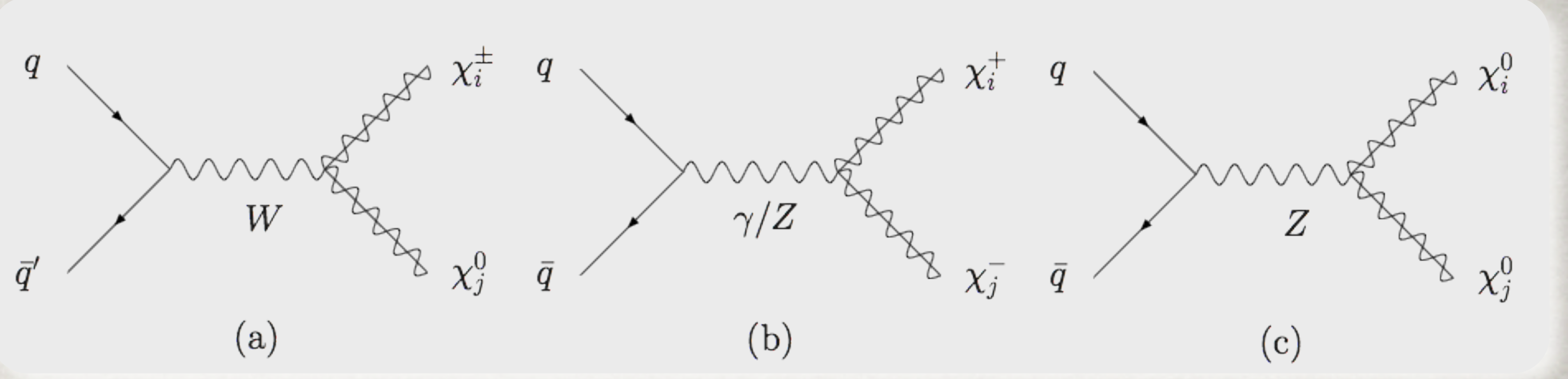




Leading Production

Dominant production:

- **Wino pair production:** $\chi^+\chi^-$, $\chi^\pm\chi^0$
- **Higgsino pair production:** $\chi^+\chi^-$, $\chi^\pm\chi^0$, $\chi^0_i\chi^0_j$



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

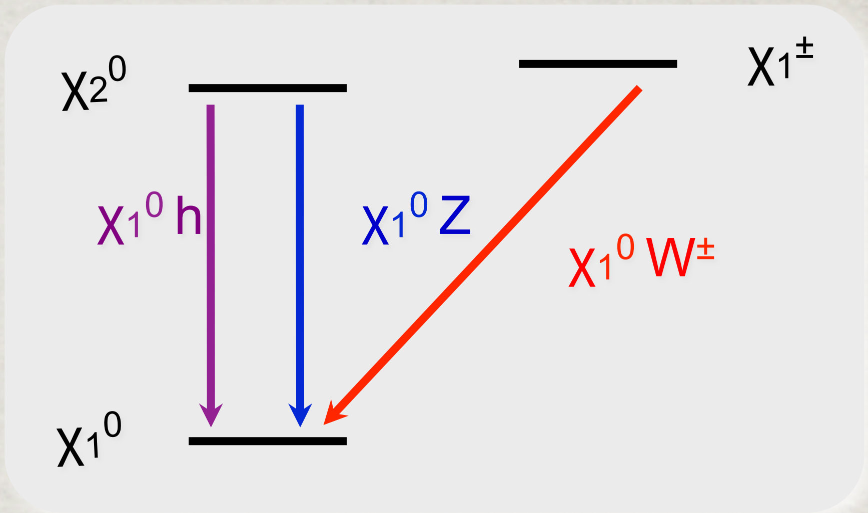
$$XY = W^+W^-,\ W^\pm W^\pm,\ WZ,\ Wh,\ Zh,\ ZZ, \text{ and } hh$$

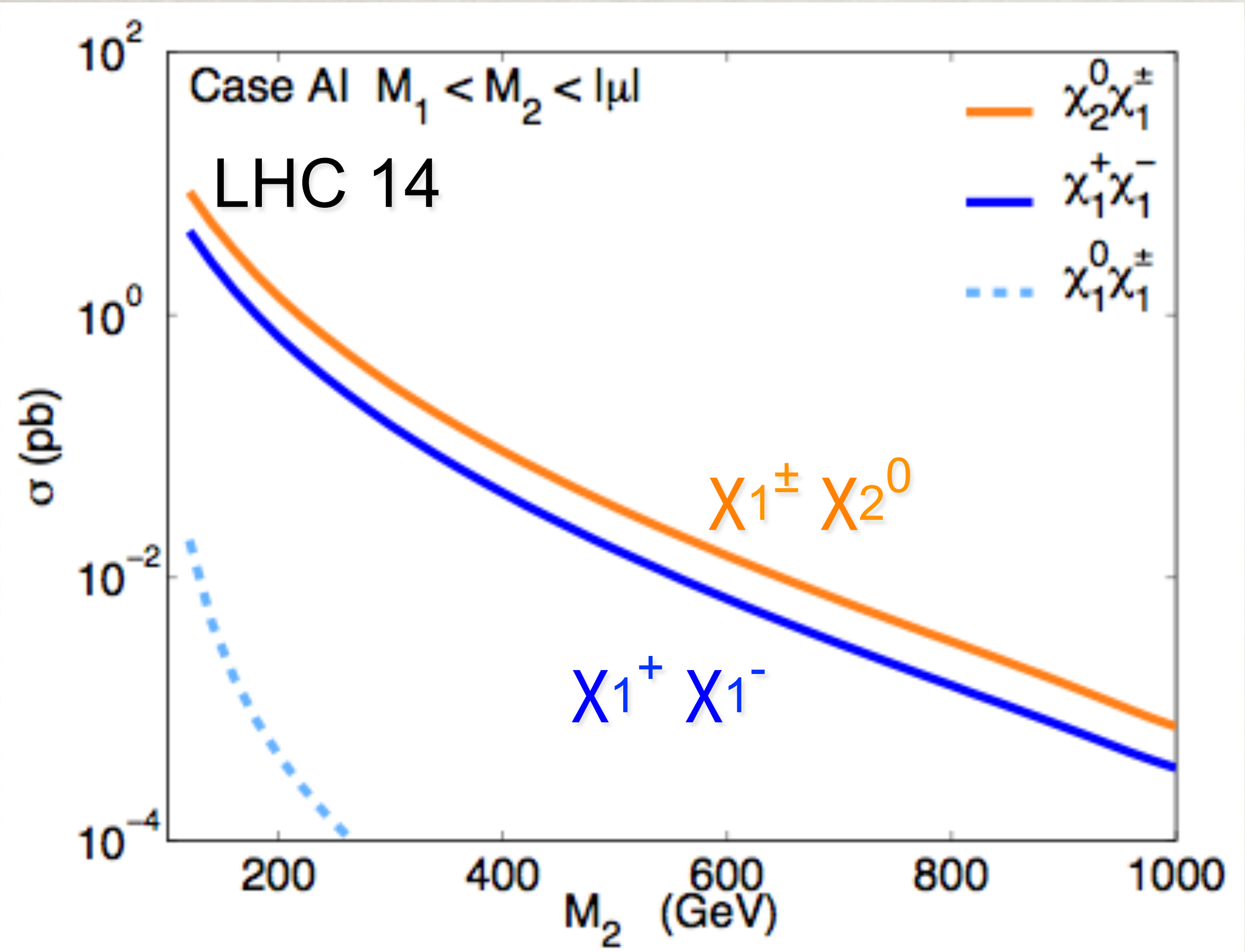
- Br(WZ) < 100%, **sometime highly suppressed**
- Wh **complementary to WZ channel: new discovery potential**
- Zh **could also be important**
- hh **usually is small**

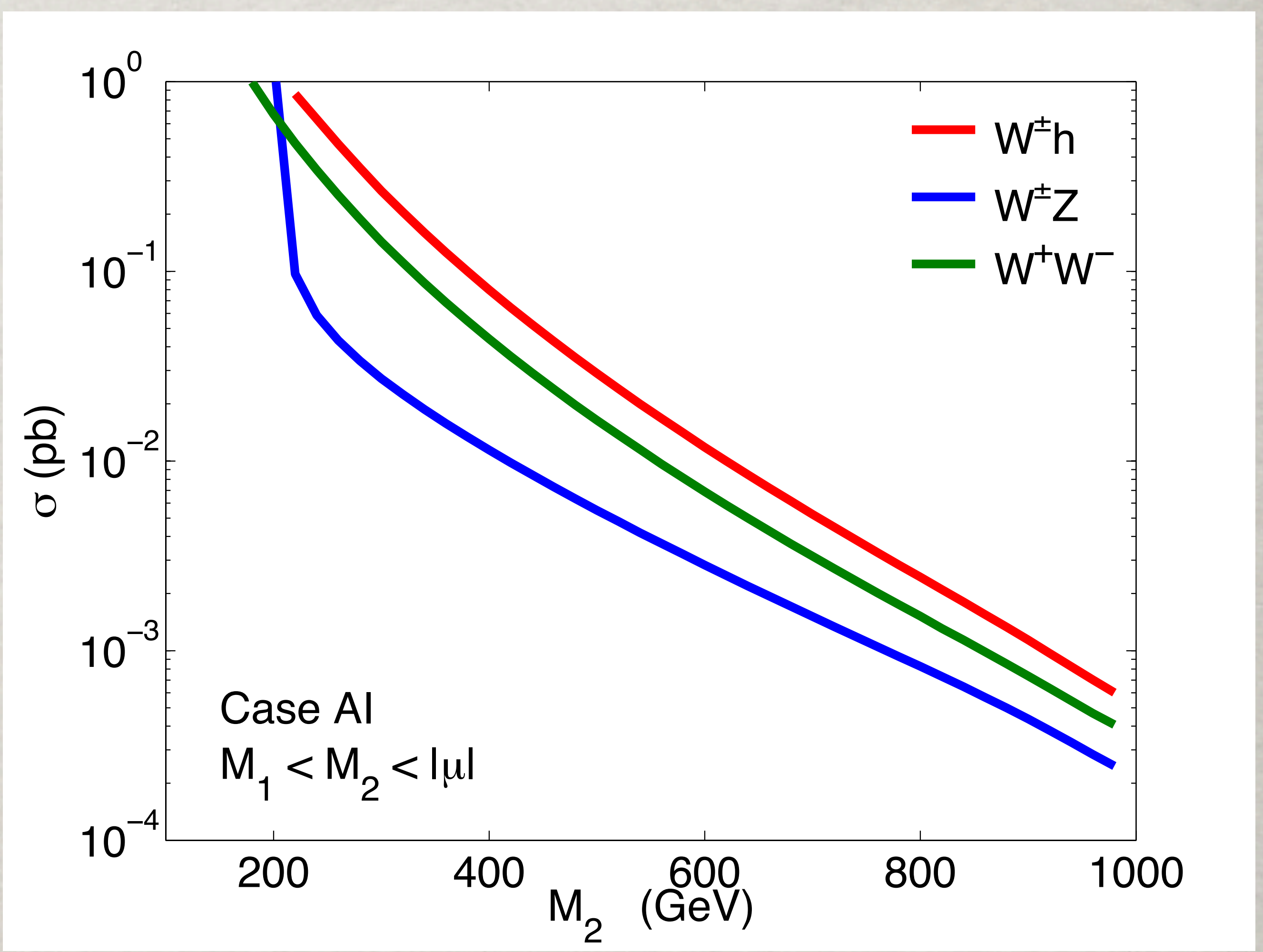
(Sub-leading Production: $X_i X_j$ + jets, and VBF at the end.)

Case AI: Bino LSP - Wino NLSP

Case AI: $M_1 < M_2 < \mu$

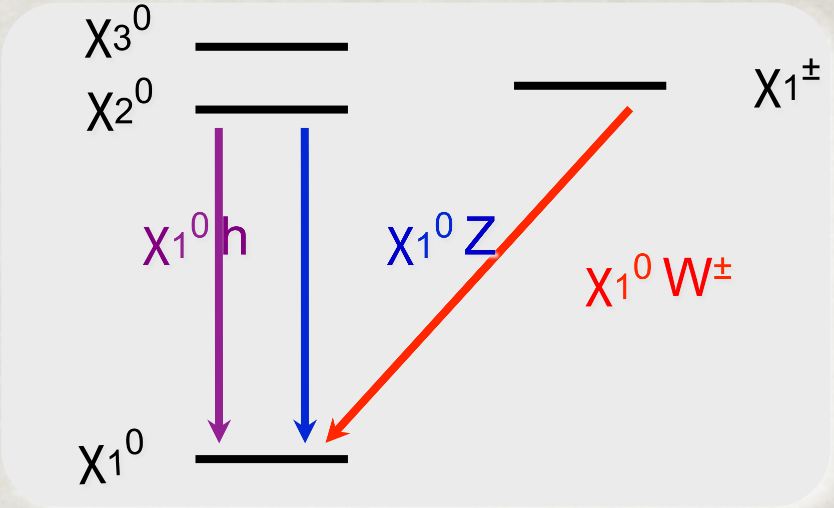


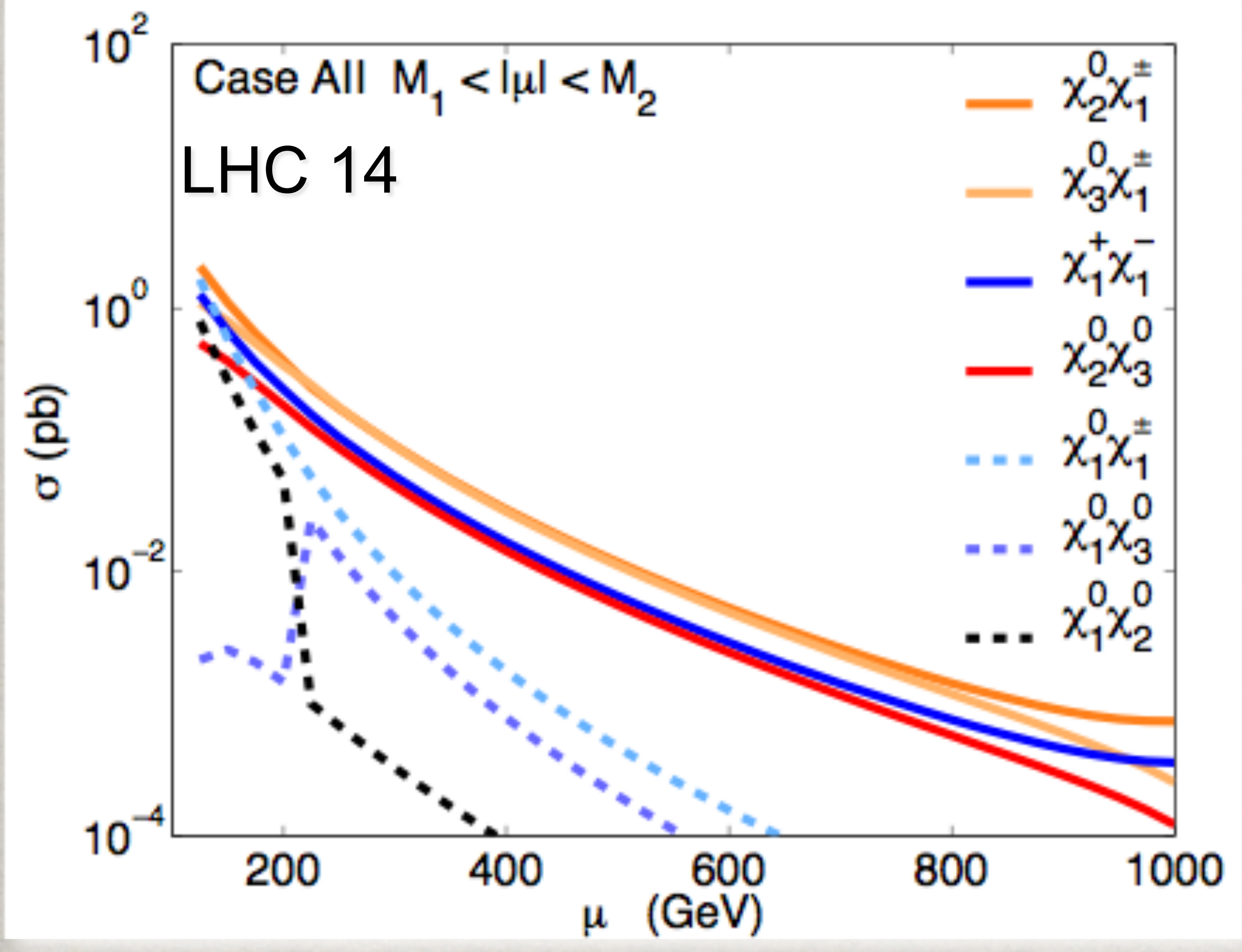


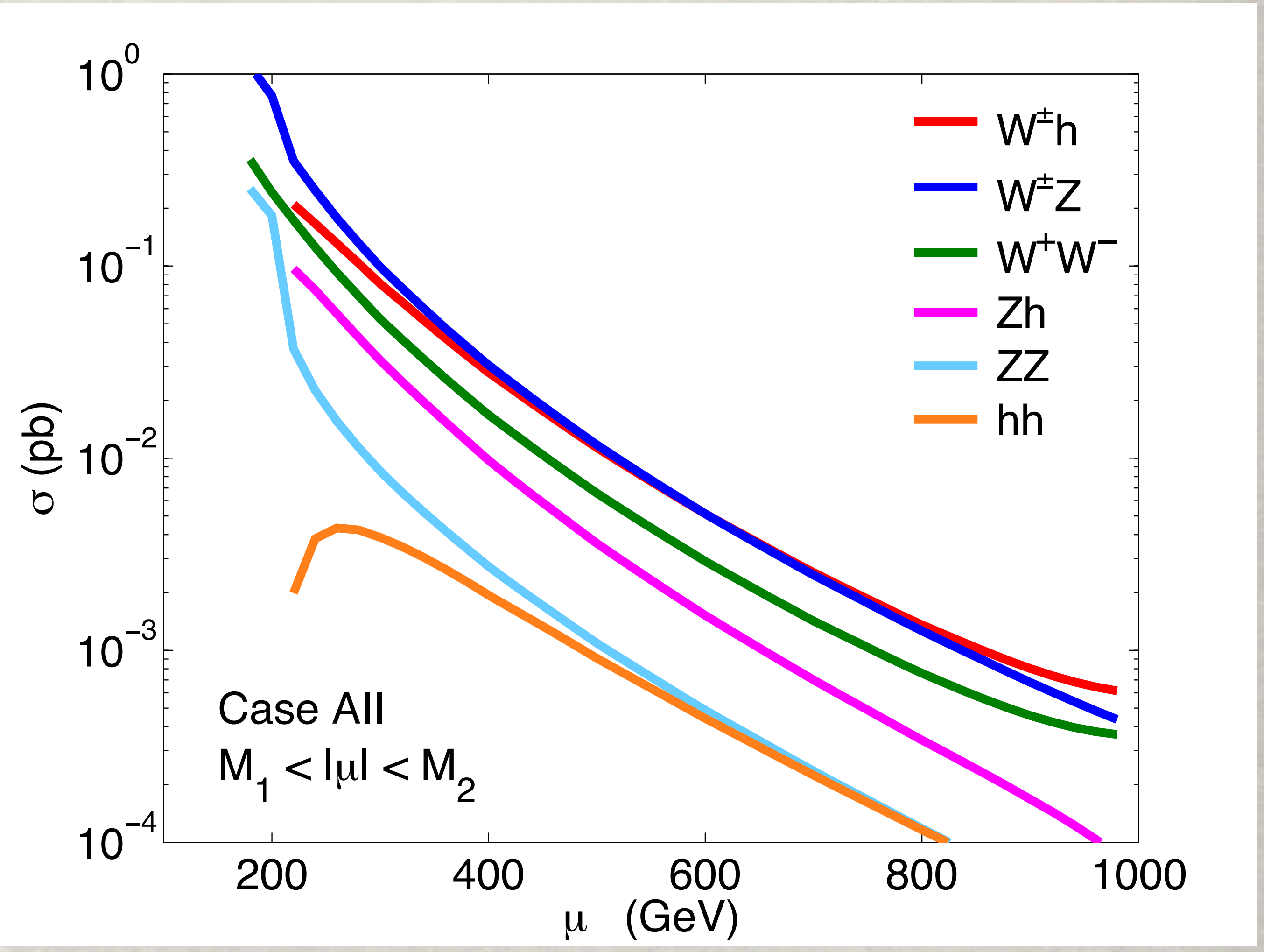


Case AII: Bino LSP - Higgsino NLSP

Case AII: $M_1 < \mu < M_2$







Case A signals:

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

new discovery potential

current WZ+MET limit weakened

	NLSPs and Decay Br's		Production	Total Branching Fractions (%)						
				W^+W^-	$W^\pm W^\pm$	WZ	Wh	Zh	ZZ	hh
Case AI	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\mp \chi_2^0$			16	84			
	$\chi_2^0 \to \chi_1^0 h$	84%(96–70%)	$\chi_1^+ \chi_1^-$	100						
Case AII	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\pm \chi_2^0$			25	75			
	$\chi_2^0 \to \chi_1^0 h$	75%(90–70%)	$\chi_1^\pm \chi_3^0$			78	22			
	$\chi_3^0 \to \chi_1^0 Z$	78%(90–70%)	$\chi_1^+ \chi_1^-$	100						
			$\chi_2^0 \chi_3^0$					64	20	16

Wh **comparable to** WZ **channel**

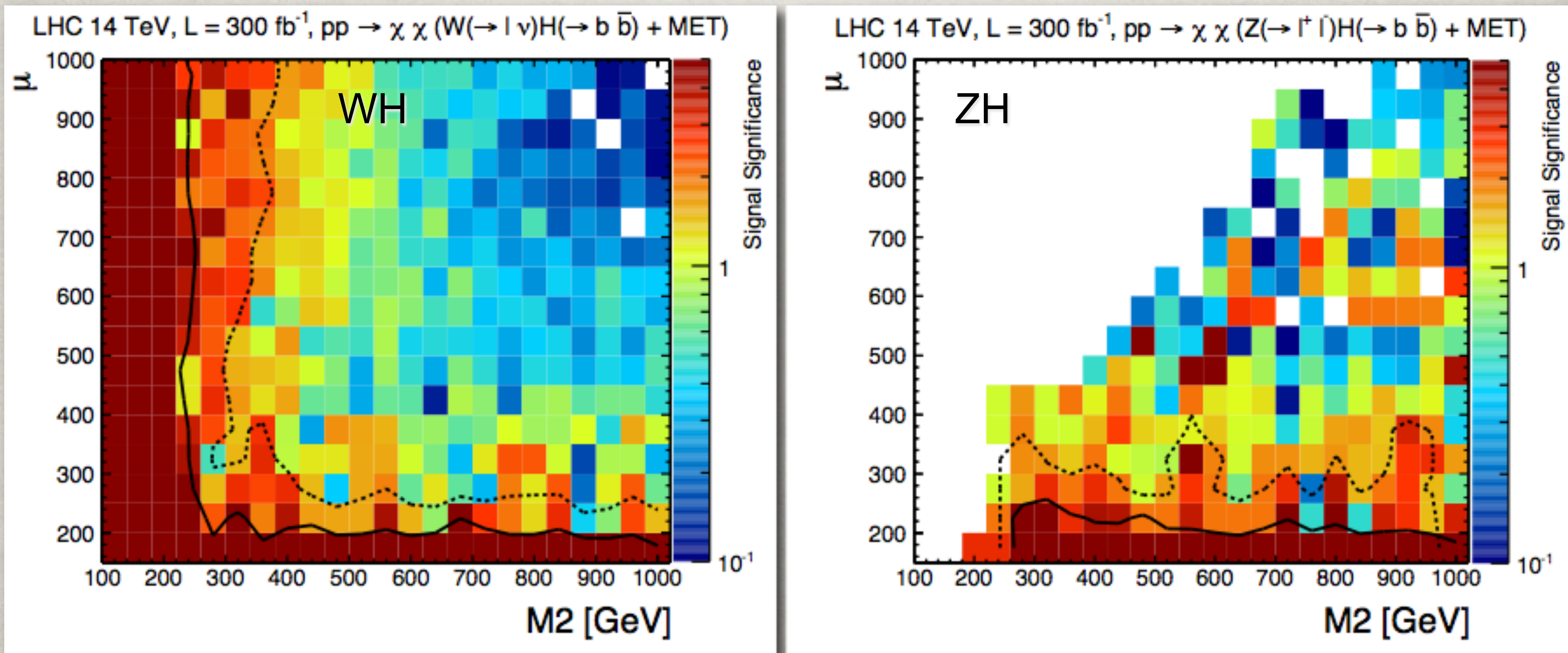
W h:

1. Exactly one lepton with $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.5$ and veto any isolated track with $p_T > 10$ GeV within the tracker acceptance of $|\eta| < 2.5$ as well as hadronic τ's with $p_T > 20$ GeV and $|\eta| < 2.5$.
2. Exactly two b-tag jets with $p_T^{b_1,b_2} > 50, 30$ GeV, $|\eta^b| < 2.5$ and are expected to be in one hemisphere of the transverse plane.
3. Invariant mass of the b-jets must be within 100 GeV$< m_{bb} < 150$ GeV.
4. Transverse mass ($M_T^{\not{E}_T,h}$) between $\not{E}_T$ and the Higgs > 200 GeV and $\not{E}_T > 100$ GeV.
5. Difference in azimuthal angle $\Delta\phi^{\not{E}_T,h} > 2.4$ between $\not{E}_T$ and the Higgs boson.

Z h:

1. Exactly two opposite sign same flavor leptons (OSSF) with $p_T^{\ell_1,\ell_2} > 50, 20$ GeV, $|\eta^\ell| < 2.5$ and veto any isolated track with $p_T > 10$ GeV within the tracker acceptance of $|\eta| < 2.5$ as well as hadronic τ's with $p_T > 20$ GeV and $|\eta| < 2.5$.
2. Exactly two b-tag jets with $p_T^{b_1,b_2} > 50, 30$ GeV, $|\eta^b| < 2.5$ and are expected to be in one hemisphere of the transverse plane.
3. Invariant mass of the b-jets must be within 100 GeV$< m_{bb} < 150$ GeV.
4. Invariant mass of OSSF dileptons be within 76 GeV$< m_{\ell^+\ell^-} < 106$ GeV.
5. $\not{E}_T > 50$ GeV.
6. Difference in azimuthal angle $\Delta\phi^{\not{E}_T,h} > 1.0$ between $\not{E}_T$ and the Higgs boson.

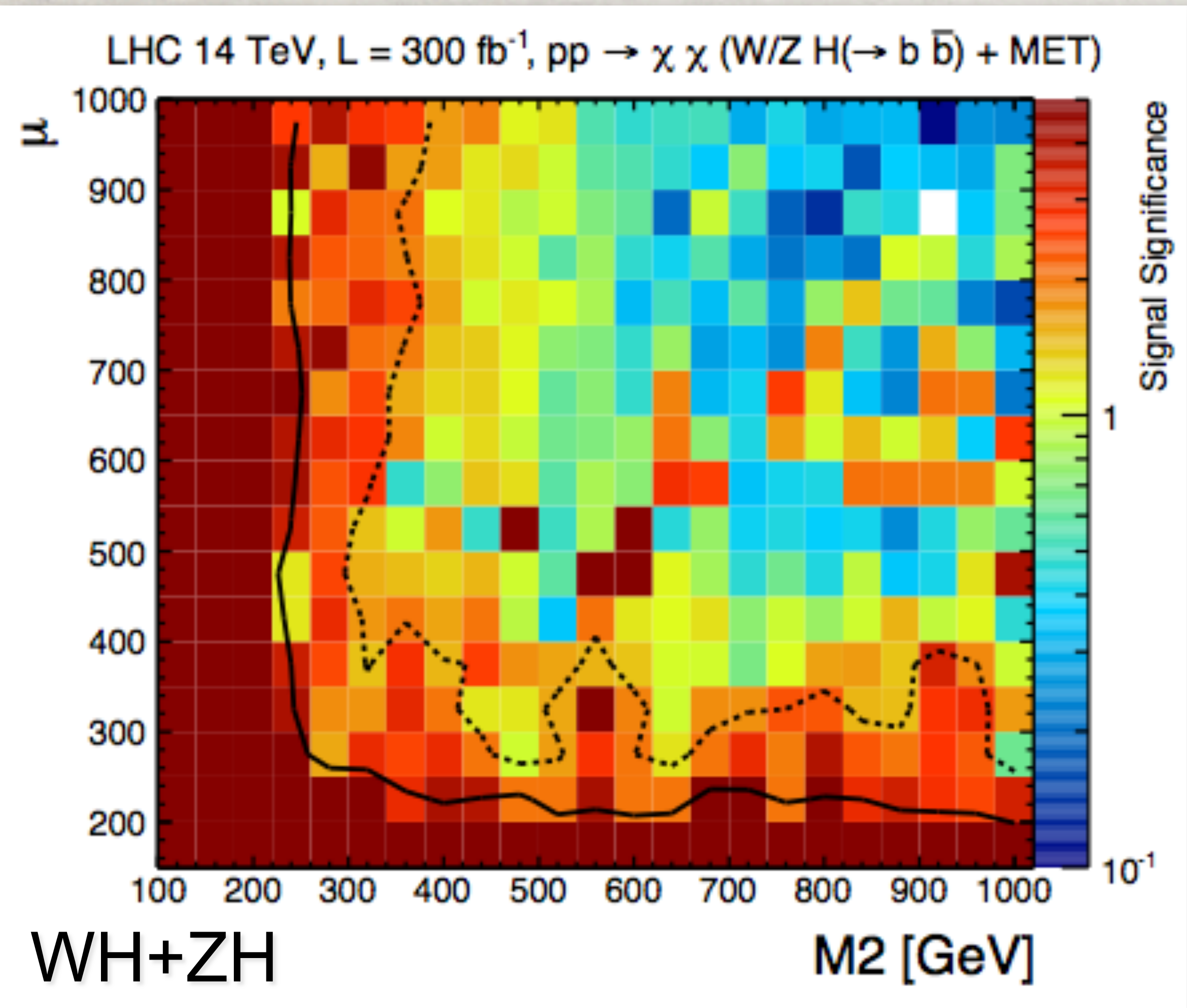
Neutralino/Chargino search: Wh/Zh Channels

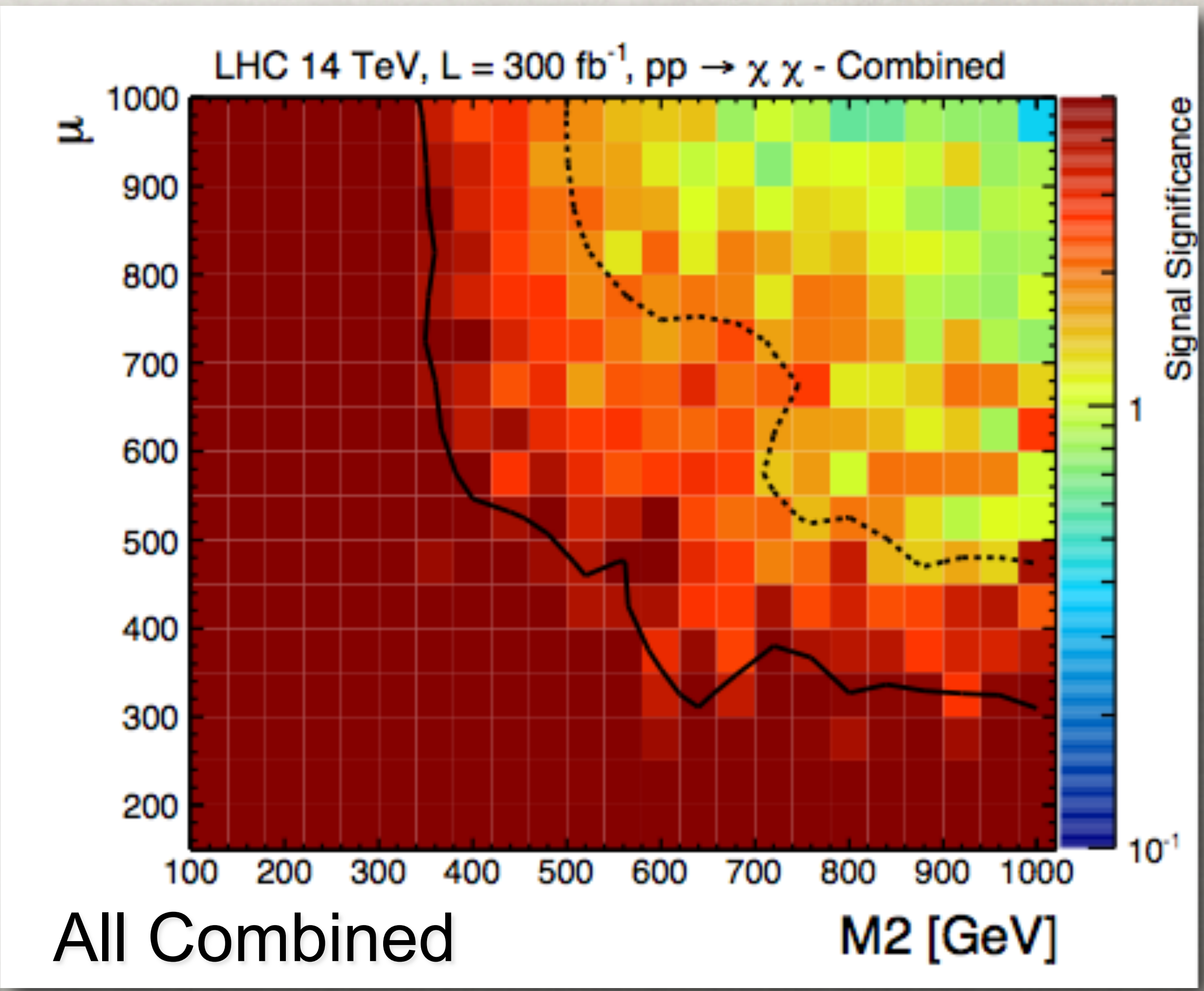


Unique signal !
Wh **complementary to** WZ **channels !**

TH, Sanjay Padhi, Shufang Su:
arXiv:1309.5966

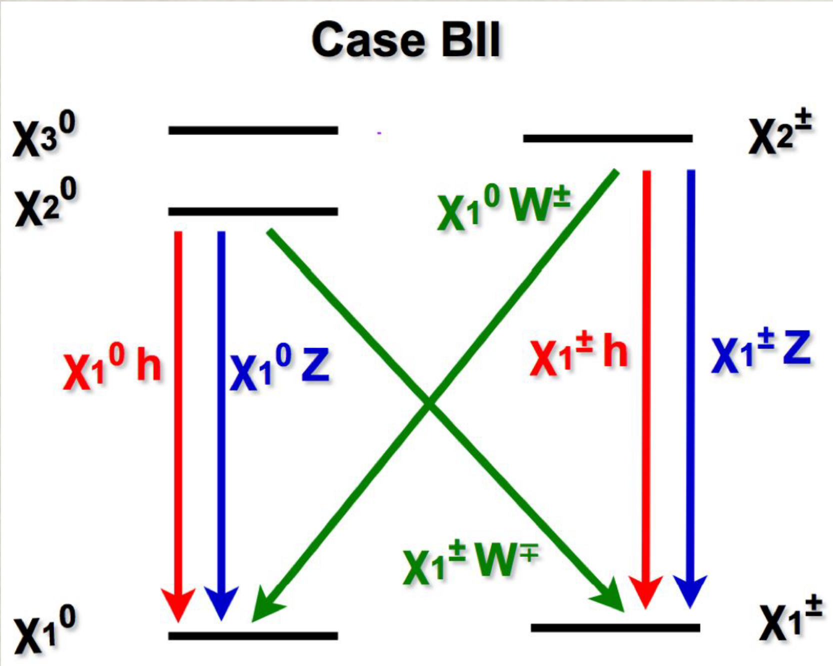
Neutralino/Chargino search: Combined

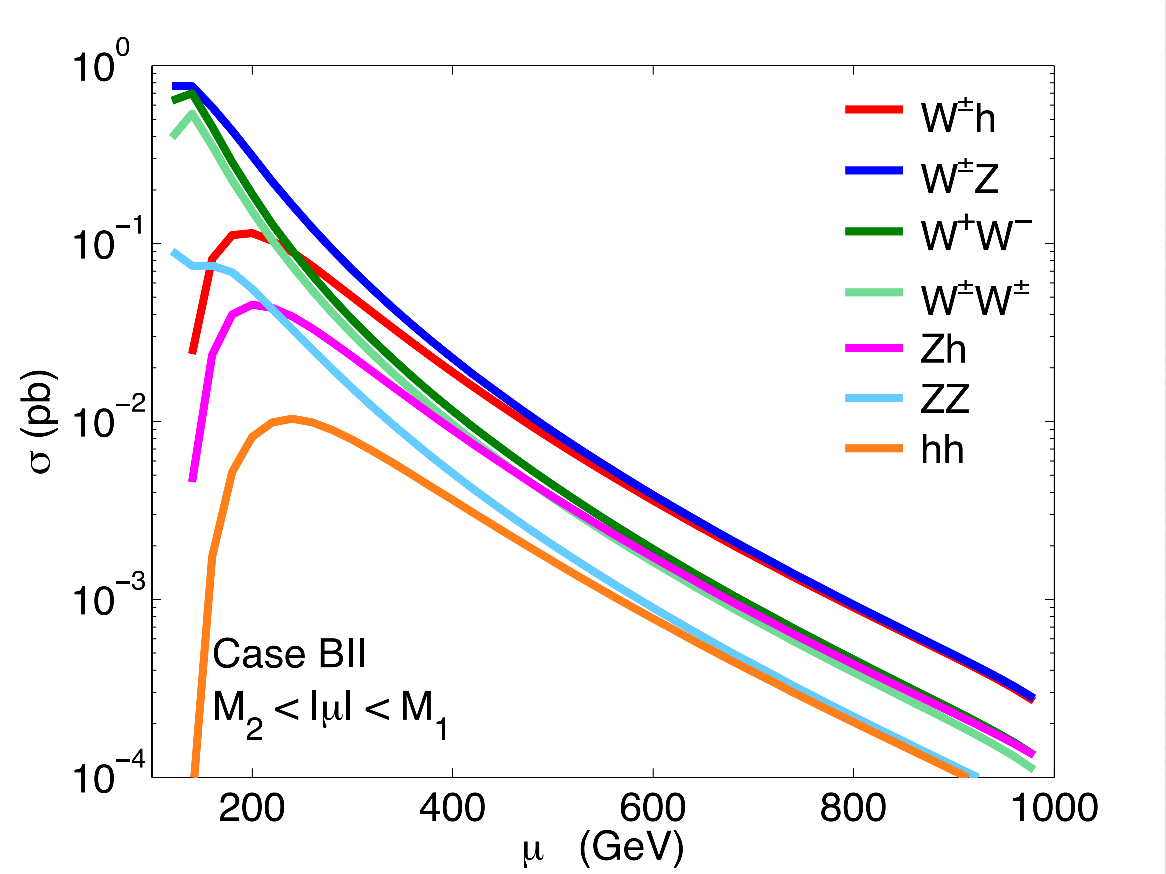




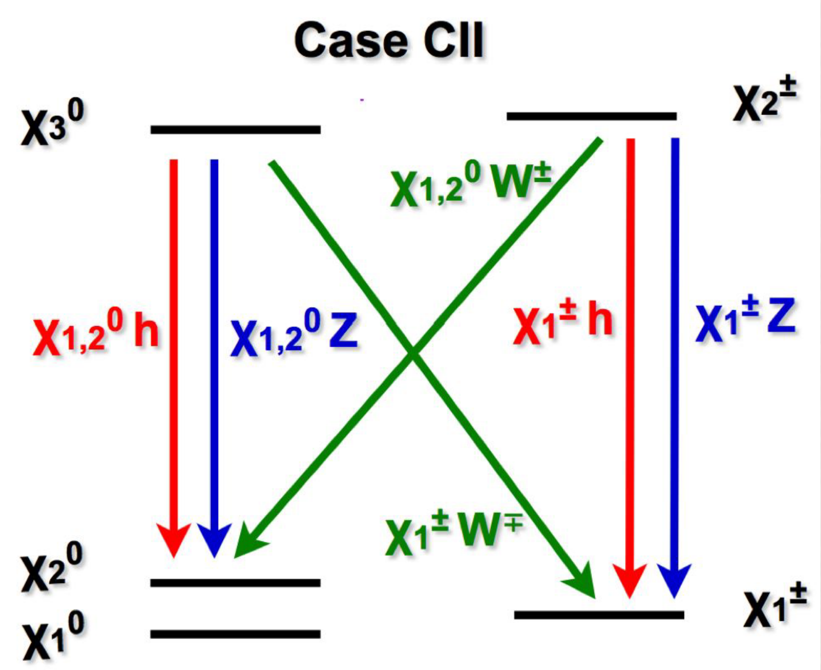
Mass parameters	95% C.L. (5σ) reach $2b$-tag from $h \to b\bar{b}$	95% C.L. (5σ) reach combined
Case AI: $\mu \gg M_2 \sim m_{\chi_1^\pm,\chi_2^0}$	380 GeV (250 GeV)	500 GeV (350 GeV)
Case AII: $M_2 \gg \mu \sim m_{\chi_1^\pm,\chi_{2,3}^0}$	350 GeV (220 GeV)	480 GeV (320 GeV)
Case A: $M_2 \approx \mu \sim m_{\chi_1^\pm,\chi_{2,3}^0}$	400 GeV (270 GeV)	700 GeV (500 GeV)

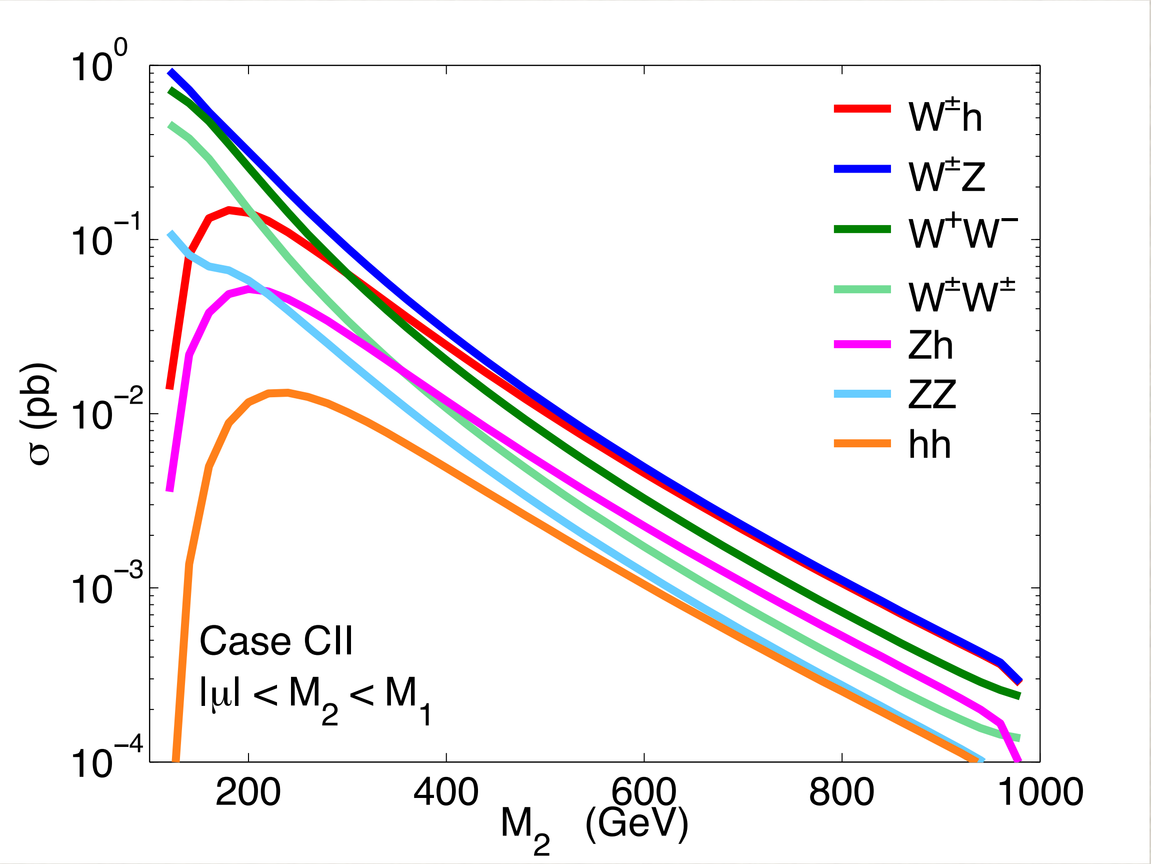
Case BII $M_2 < \mu < M_1$





Case CII $\mu < M_2 < M_1$

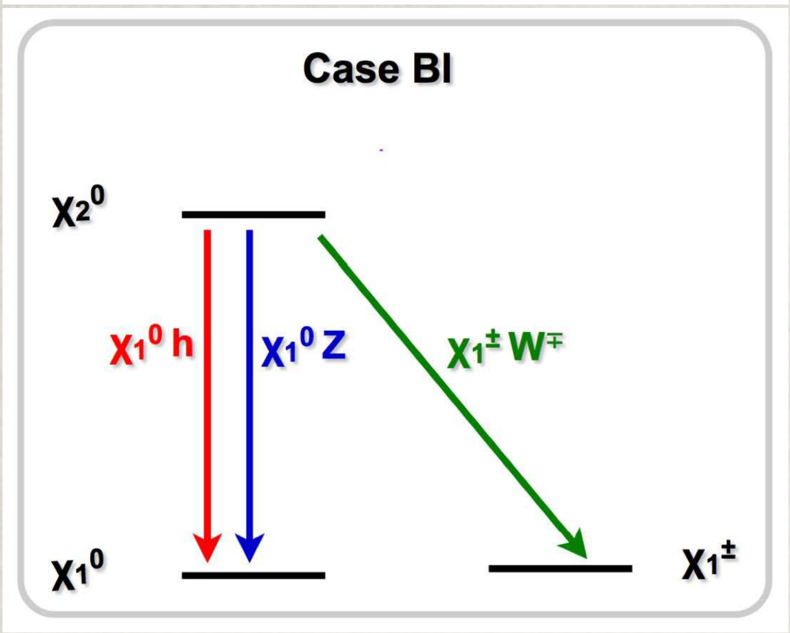


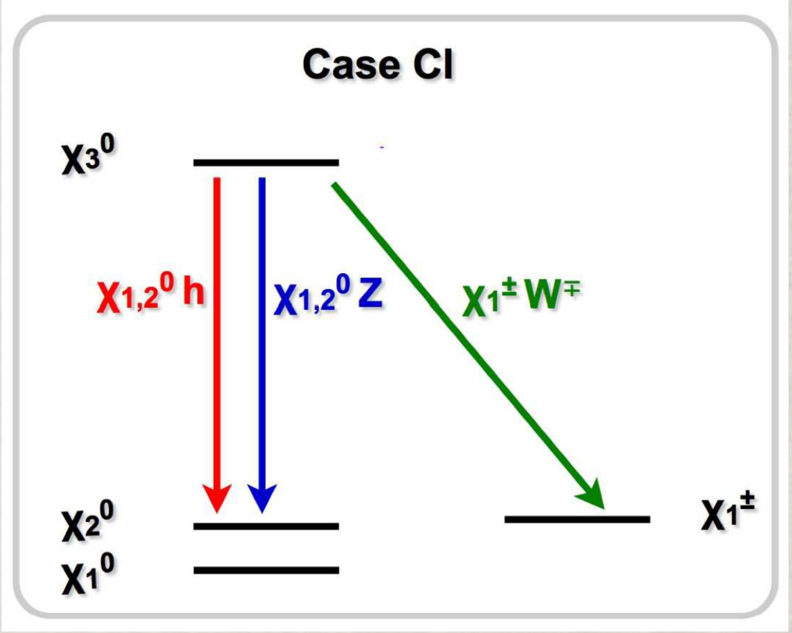


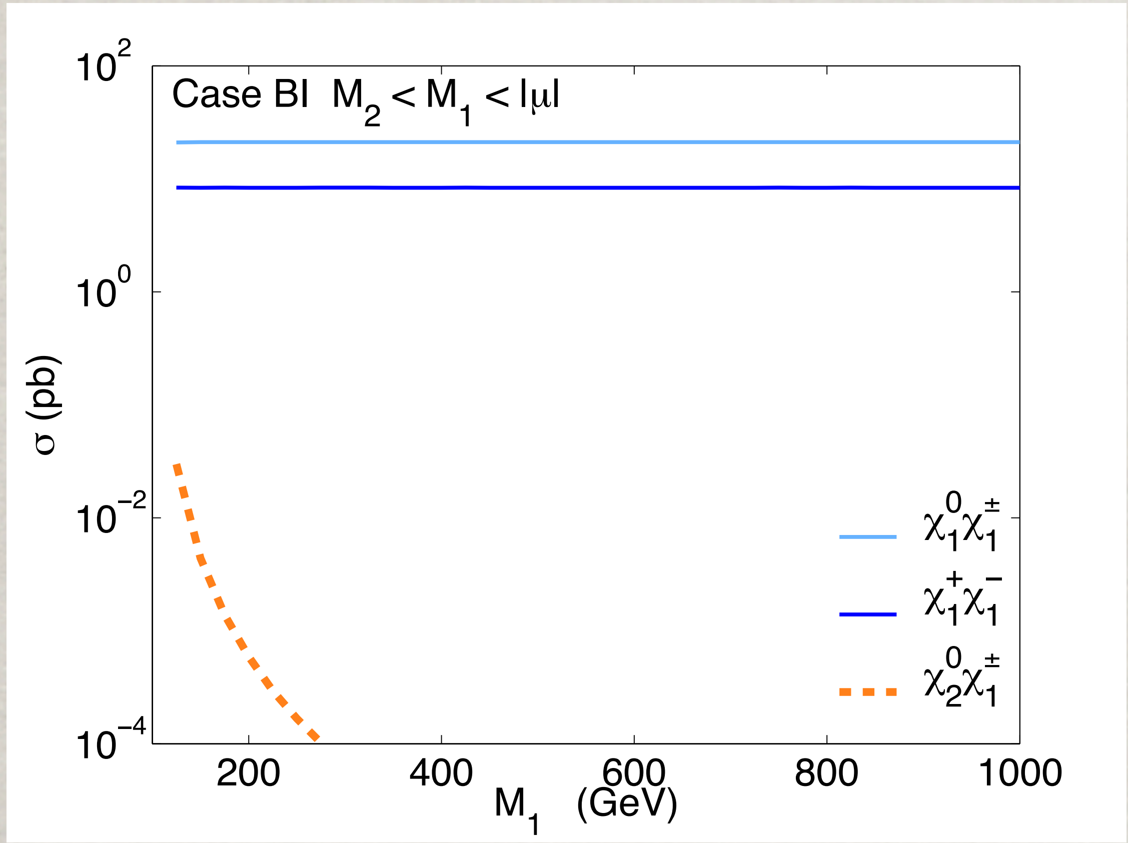
Similar reach to Case A.

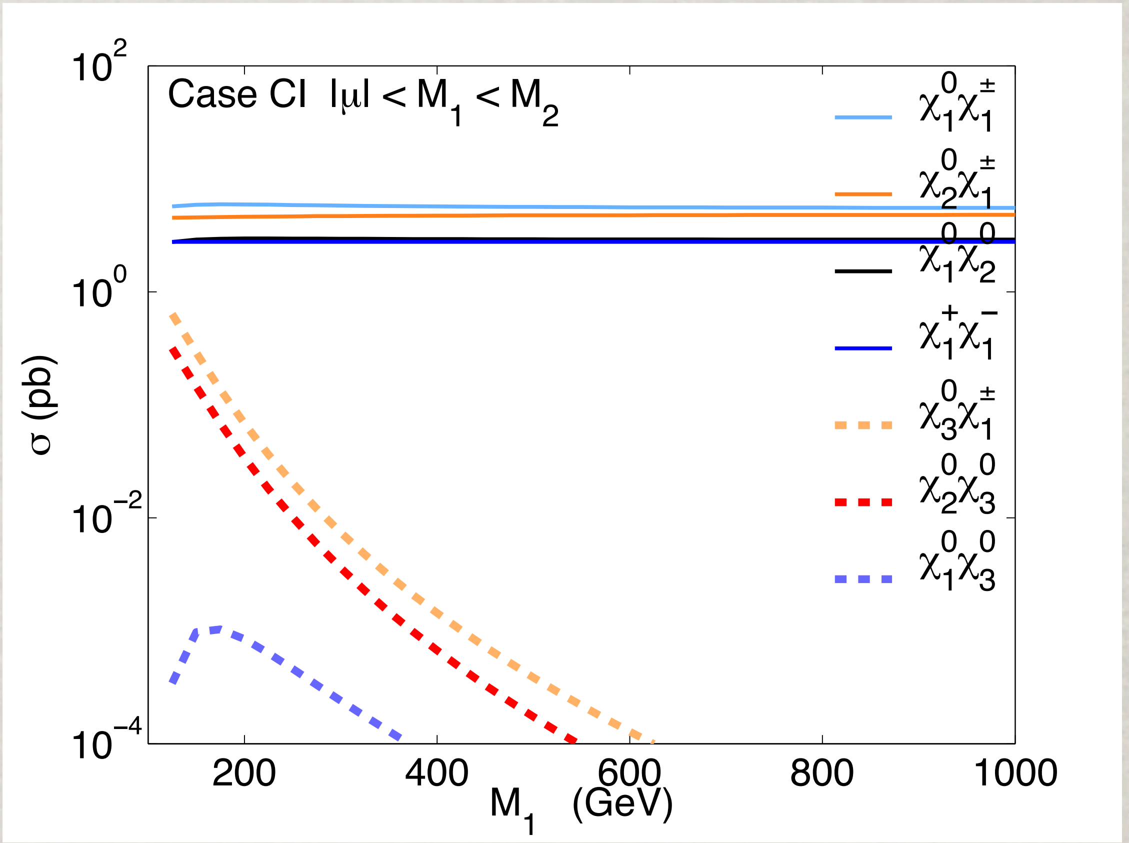
Case BI $M_2 < M_1 < \mu$

Case CI $\mu < M_1 < M_2$









Very difficult:

NLSP production small; LSP nearly degenerate.

Compressed Spectrum/Nearly Degenerate LSP's

If the missing particle (LSP) mass is close to that of the parent, then the missing KINETIC energy is small.

* ISR Mono jet + E_T^{miss} + soft l's

  1, 2, 3 soft leptons observed?

  pT(l) > 10 GeV, pT(j) > 30 GeV:

  (S. Gori's talk)

- Current mono jet+E_T^{miss} may put weak bounds
- Work by ATLAS/CMS?

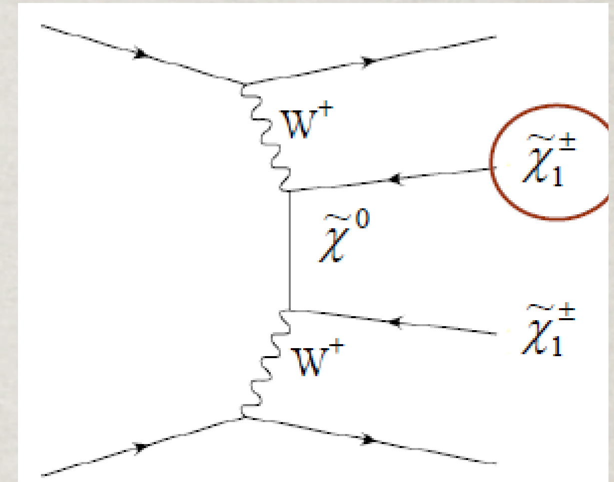
* Giudice, TH, L.-T. Wang, K. Wang: arXiv:1004.4902

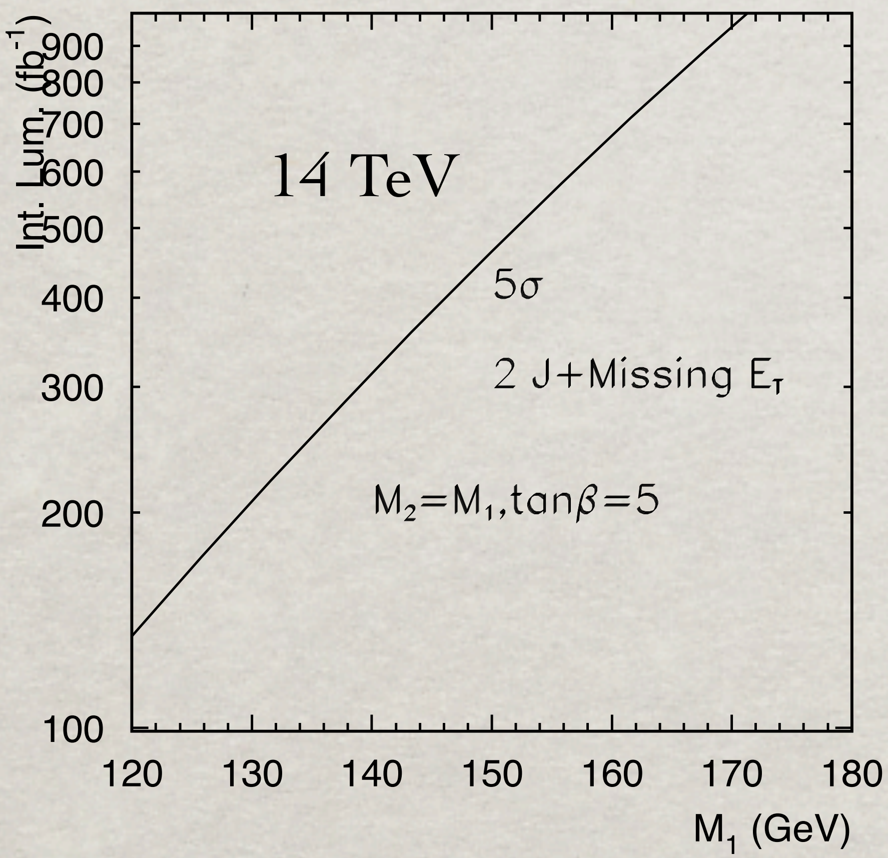
\+ S. Gori, S. Jung, L.-T. Wang, arXiv:1004.4902

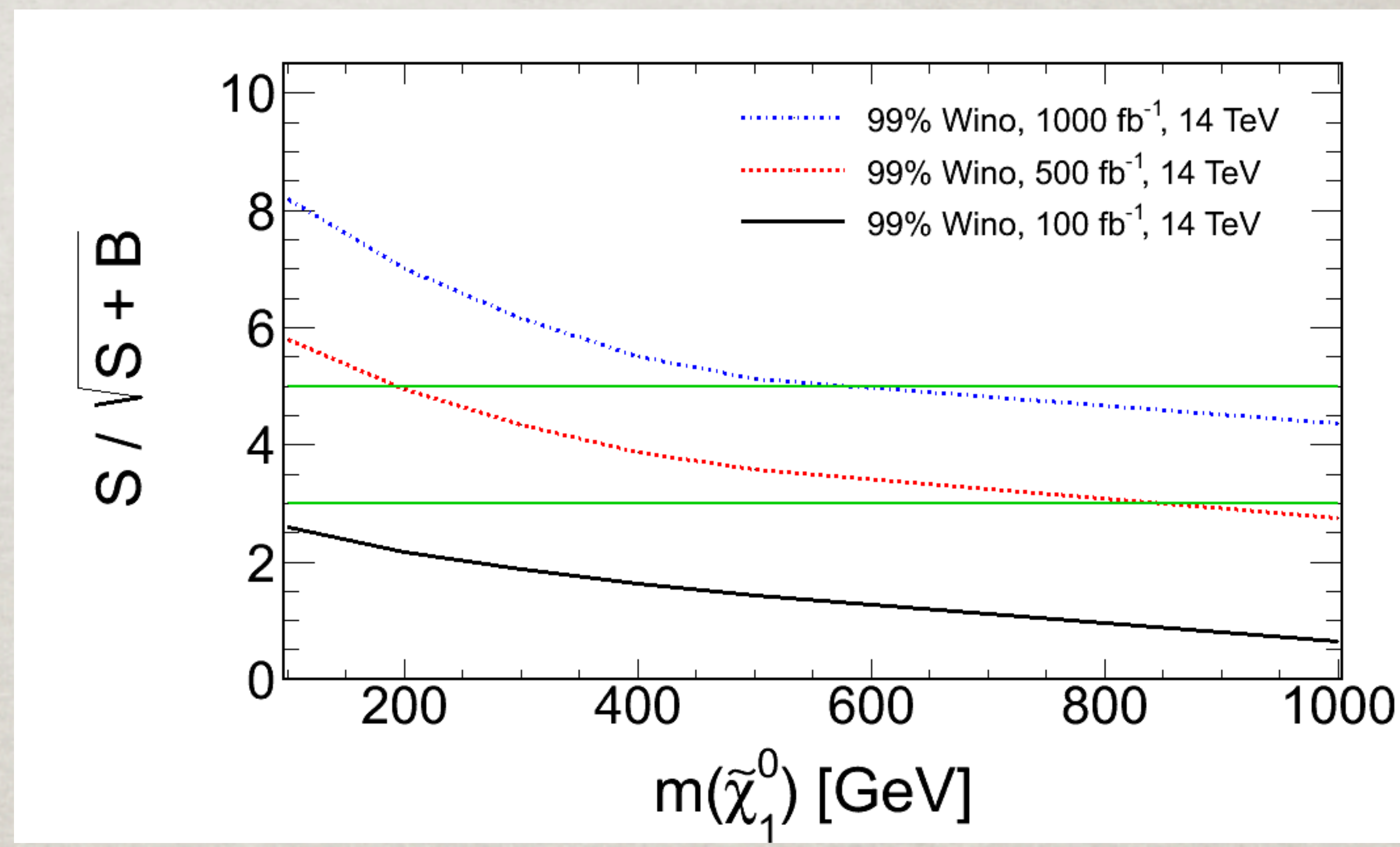
Compressed Spectrum/Nearly Degenerate LSP's

* VBF: 2 jets + E_T^{miss} + soft l's

* Giudice, TH, L.-T. Wang, K. Wang: **arXiv:1004.4902**







* B. Dutta, T. Kamon et al., **arXiv:1210.0964; arXiv:1304.7779; arXiv:1308.0355.**

Concluding Remarks

Channel	Signal (LHC)	Signal (ILC)
W^+W^-	**OS2L + MET**	hadronic (4j), semileptonic, leptonic final states +MT
$W^\pm W^\pm$	**SS2L + MET**	
WZ	**3L + MET**	
Wh	1L + bb + MET	
Zh	**OS2l +bb + MET**	
LSP pair	Mono-jet, VBF	ISR photon + soft

Wh **and** Zh **channels comparable/complementary: M ~ 500-700 GeV**

Compressed/nearly degenerate spectrum: Very difficult (for 200 GeV or so) !

May need cleaner environment like the ILC.

Case B Signals

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

	NLSPs and Decay Br's		Production	Total Branching Fractions (%)						
				W^+W^-	$W^\pm W^\pm$	WZ	Wh	Zh	ZZ	hh
Case BI	ILC, ISR analyses for Wino LSP pair									
Case BII	$\chi_2^\pm \to \chi_1^0 W^\pm$	35%	$\chi_2^\pm \chi_2^0$	12	12	33	23	10	9	2
	$\chi_2^\pm \to \chi_1^\pm Z$	35%	$\chi_2^\pm \chi_3^0$	12	12	27	29	11	3	7
	$\chi_2^\pm \to \chi_1^\pm h$	30%	$\chi_2^+ \chi_2^-$	12		25	21	21	12	9
	$\chi_2^0 \to \chi_1^\pm W^\mp$	67%	$\chi_2^0 \chi_3^0$	23	23	23	21	7	2	2
	$\chi_2^0 \to \chi_1^0 Z$	26%(30–24%)								
	$\chi_3^0 \to \chi_1^\pm W^\mp$	68%								
	$\chi_3^0 \to \chi_1^0 h$	24%(30–23%)								

Wh comparable to WZ channel

Case C Signals

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

	NLSPs and Decay Br's	Production	Total Branching Fractions (%)						
			W^+W^-	$W^\pm W^\pm$	WZ	Wh	Zh	ZZ	hh
Case CI	**ILC, $X_{1,2}^0 X_3^0$ pair or ISR analyses for Higgsino LSP pair**								
Case CII	$\chi_2^\pm \to \chi_{1,2}^0 W^\pm$ 51 %	$\chi_2^\pm \chi_3^0$	14	14	26	24	11	6	5
	$\chi_2^\pm \to \chi_1^\pm Z$ 26 %	$\chi_2^+ \chi_2^-$	26		27	23	12	7	5
	$\chi_2^\pm \to \chi_1^\pm h$ 23 %								
	$\chi_3^0 \to \chi_1^\pm W^\mp$ 54 %								
	$\chi_3^0 \to \chi_{1,2}^0 Z$ 24 %								
	$\chi_3^0 \to \chi_{1,2}^0 h$ 22 %								

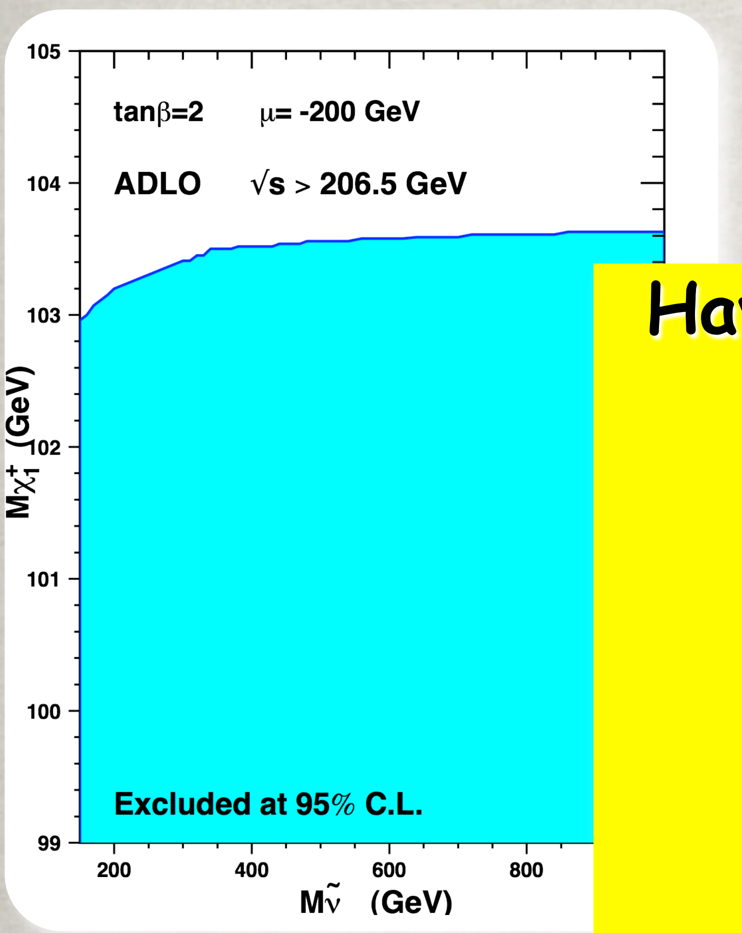
Wh **comparable to** WZ **channel**

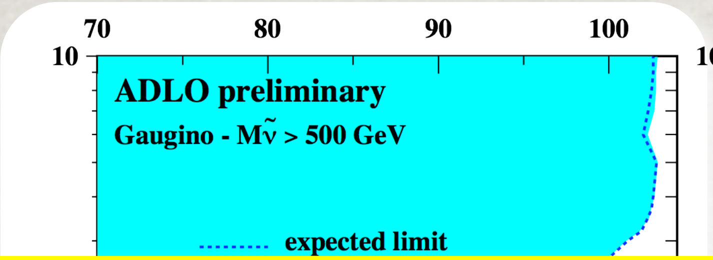
Current limits: neutralino/chargino

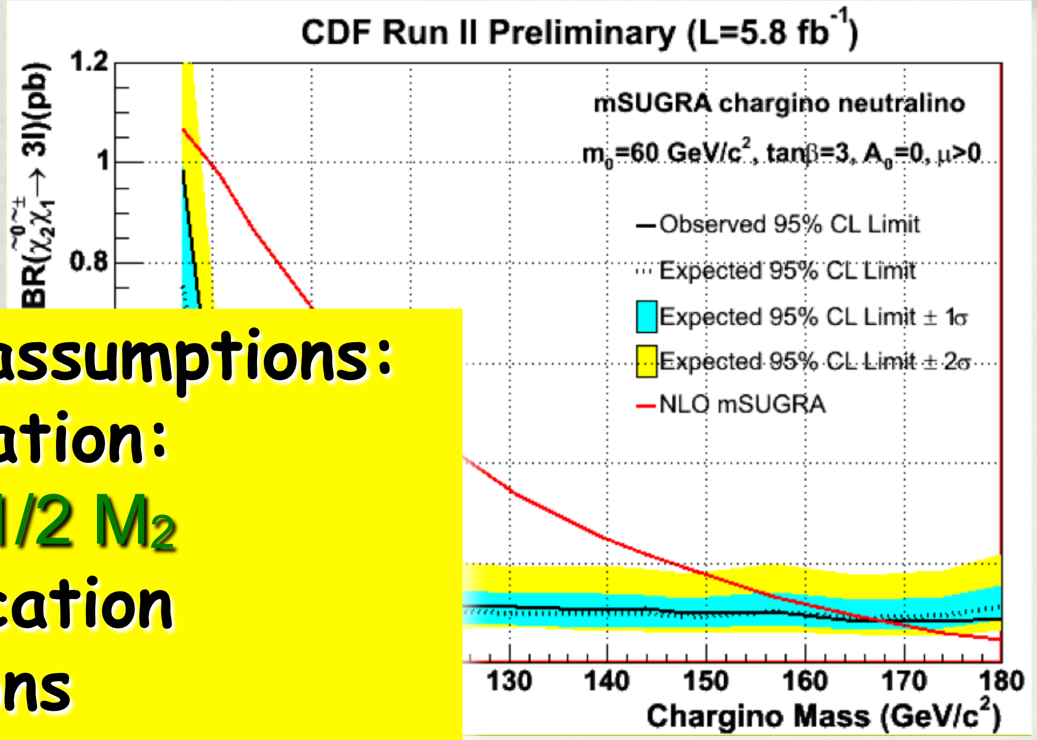
canonical case

degenerate case

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







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**
- ...

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

LEPSUSYWG/01-03.1

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

LEPSUSYWG/02-04.1

167 GeV
tanβ=3, A_0=0)

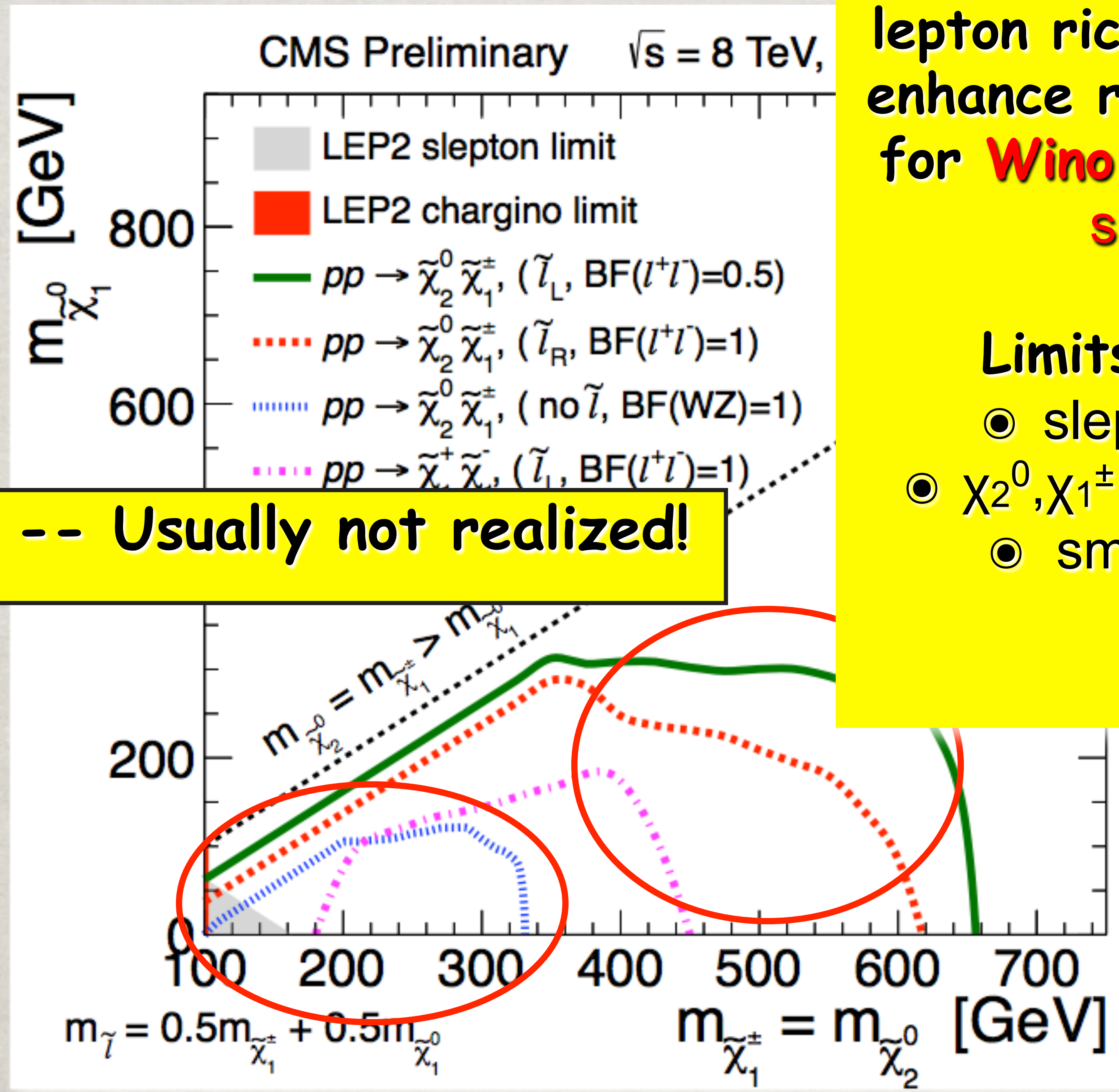
ote 10636
D0: arXiv:0901.0646

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

CMS limits

dilepton/trilepton + MET

CMS PAS SUS-12-022



100% WZ Br -- Usually not realized!

lepton rich final states to enhance reach: only works for Wino NLSP with light slepton_L.

Limits weaker for

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