SUSY or not, what is the evidence? Status and perspectives of collider searches – Part IIA

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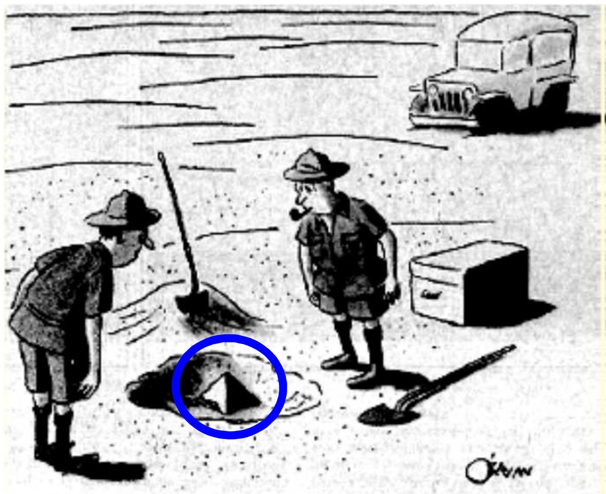
Lectures at Niels Bohr Institute



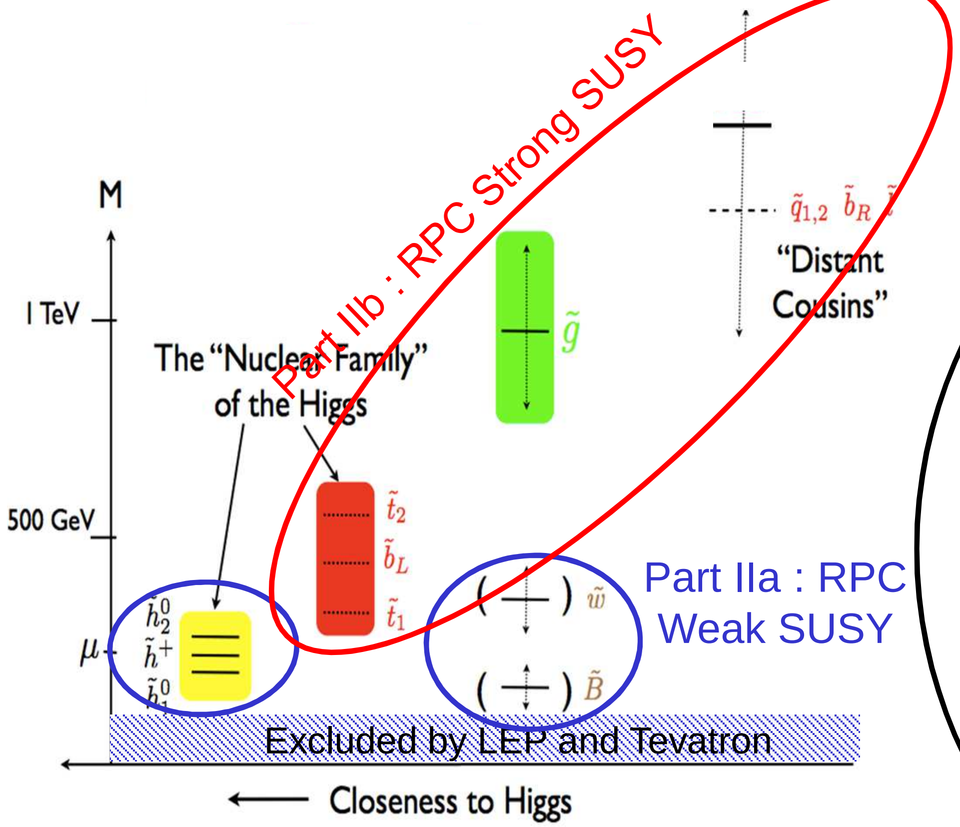
“This could be the discovery of the century. Depending, of course, on how far down it goes”

Part II (3 lectures + 2 exercises)
Direct SUSY searches at LHC

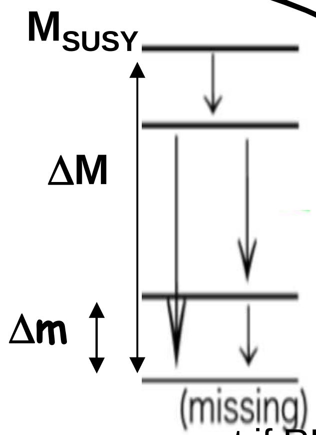
W 30-Oct	Th 31-Oct	Fr 01-Nov
--	Lecture IIA **Exercise 1**	Lecture IIC **Exercise 2**
Lecture IA Lecture IB	**Exercise 1** Lecture IIB	**Exercise 2** Lecture III

Lecture Part II

"Theories are like fishing : only he who casts can catch"
Novalis (1772-1801)



Part IIc: R-Parity Violated, Long-Lived Particles, beyond MSSM

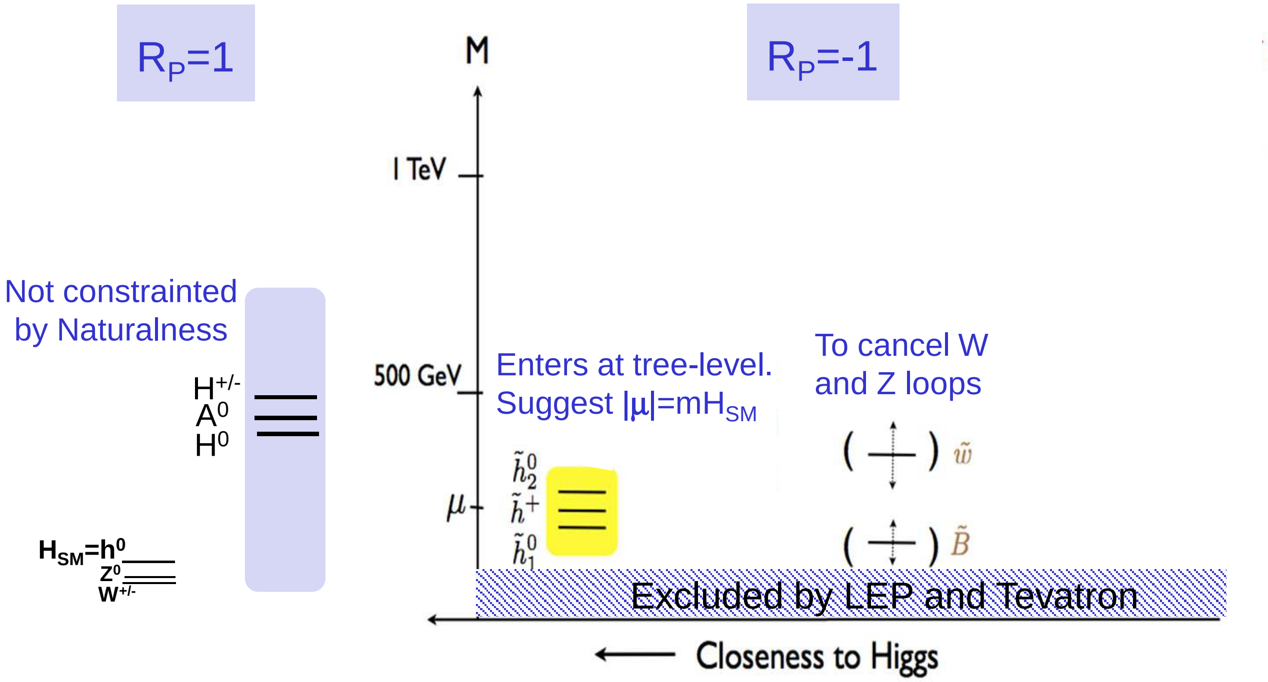


or not if RPV

1. Low Δ**m**, tiny RPV, weak coupling to $\tilde{G}$
   Long Lived or meta-stable sparticles
2. 'Sizeable' RPV
   Multileptons, No Z, jet resonances, LFV
3. MSSM Extensions?
   Scalar Gluon
4. Un-natural SUSY ?

Lecture Part IIa

Assume all strongly interaction particles decorrelated (conservative)



Reminder: EW scale is the only scale that we know before GUT/Planck scale

Parameters of the EW sector

$R_P=1$

1- Standard Model

$\phi_{Higgs} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v+H^0+iH^0) \end{pmatrix}$

$$W^0, B, \mathrm{Im}(H^0) \longrightarrow \gamma, Z \quad (\theta_W \sim 30^0)$$
$$W^+, W^-, H^+, H^- \xrightarrow{\text{EWSB}} W^+, W^-$$
$$\mathrm{Re}H^0 \longrightarrow H$$

1 param. (m_H)

$$V(\phi^\dagger\phi) = -\frac{m_H^2}{2}\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$v = \sqrt{m_H^2/(2\lambda)} = (\sqrt{2}G_F)^{-1/2} \simeq 246 \text{ GeV}$$

2- SUSY

$H_d = \begin{pmatrix} (v_d + \phi_d^0 + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix}$ $H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$

EWSB

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Gauge Bosons	1	+1	W^+, W^-, W^0, B	W^+, W^-, Z^0, γ
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$

θ_W and α $\cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}$

2 param. m_A*, $\tan\beta = v_u/v_d$

*Masses of other Higgses are related to m_A at tree-level

$R_P=-1$

2- SUSY: Each **gauge** field has a partner with S-1/2 in the vector multiplet

$c_W = \cos\theta_W$
$s_W = \sin\theta_W$
$c_\beta = \cos\beta$
$s_\beta = \sin\beta$

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

Mixing

Bino, Wino, Higgsino → **Neutralinos**

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$

Charginos

$$\begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix}$$

Masses of Gauge Eigenstates

Bino Wino Higgsino

4 param. M1, M2, μ, $\tan\beta$

Parameters of the EW sector

$R_P=1$

1- Standard Model

$\phi_{Higgs} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v+H^0+iH^0) \end{pmatrix}$

$$W^0, B, \mathrm{Im}(H^0) \longrightarrow \gamma, Z \quad (\theta_W \sim 30^0)$$
$$W^+, W^-, H^+, H^- \xrightarrow{\text{EWSB}} W^+, W^-$$
$$\mathrm{Re}H^0 \longrightarrow H$$

1 param. (m_H)

$$V(\phi^\dagger\phi) = -\frac{m_H^2}{2}\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$v = \sqrt{m_H^2/(2\lambda)} = (\sqrt{2}G_F)^{-1/2} \simeq 246 \text{ GeV}$$

2- SUSY

$H_d = \begin{pmatrix} (v_d + \phi_d^0 + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix}$ $H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$

EWSB

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Gauge Bosons	1	+1	W^+, W^-, W^0, B	W^+, W^-, Z^0, γ
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$

θ_W and α $\cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}$

2 param. m_A*, $\tan\beta = v_u/v_d$

*Masses of other Higgses are related to m_A at tree-level

$R_P=-1$

Bino, Wino, Higgsino — **Neutralinos**

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$

Mixing — **Charginos**

Bino-Wino case:
Most favorable

Higgsino case:
Hardest but most natural

Masses of Gauge Eigenstates

Bino Wino Higgsino

4 param. M1, M2, μ, $\tan\beta$

SUSY Higgses (R_P=1)

$$H_d = \begin{pmatrix} (v_d + \phi_d^0 + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix} \quad H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$$

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$

EWSB

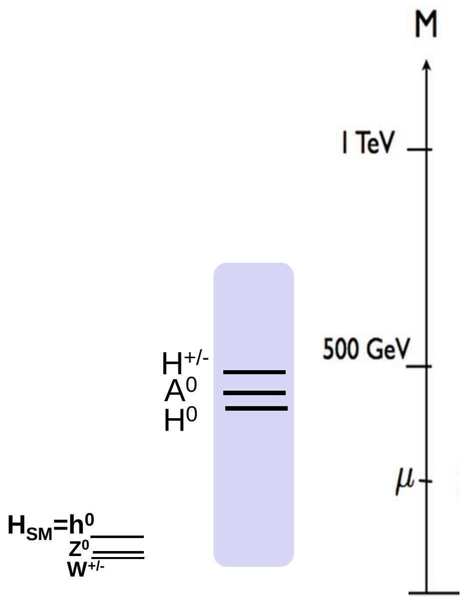
One mixing angle α $\quad \cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)}$

Tree level relations (mA, tanβ)

$\tan\beta > 1$

- $m_{H^\pm}^2 = m_A^2 + m_W^2 \rightarrow m_A^2 + m_W^2$
- $m_{H^0}^2 = m_A^2 + m_Z^2/2(1-2\cos^2(2\beta)) \rightarrow m_A^2 - m_Z^2/2$
- **$m_{h^0}^2 < m_Z^2 \cos^2(2\beta) \rightarrow < m_Z^2$**

- $m_A^2 = 2|\mu|^2 + m_{Hu}^2 + m_{Hd}^2$
- $v^2 = v_u^2 + v_d^2$

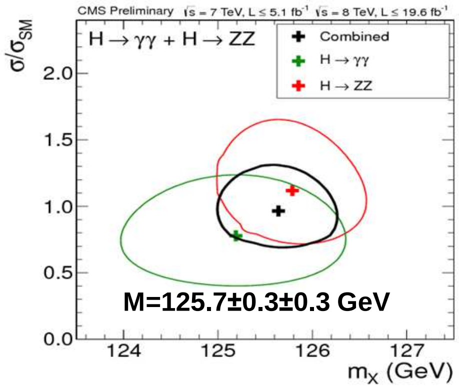


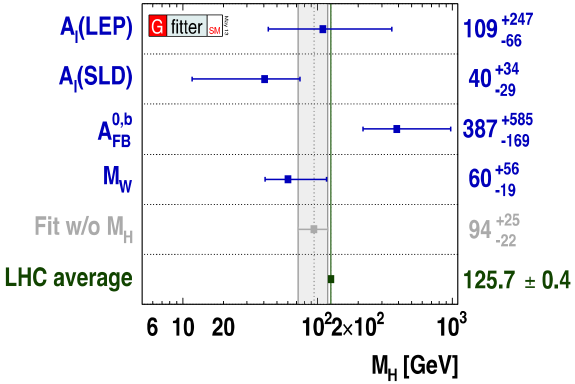
SUSY Higgses (1)

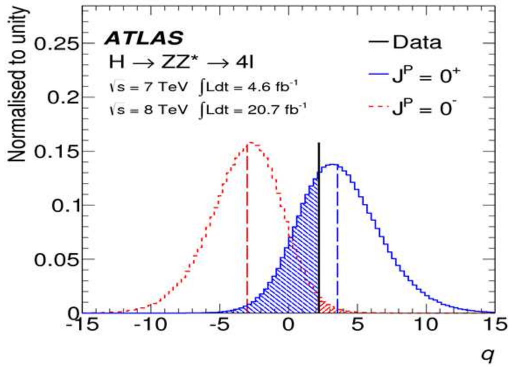
ATLAS-CONF-2013-14, CMS-PAS-HIG-13-005

❑ One Higgs (H) has been discovered !

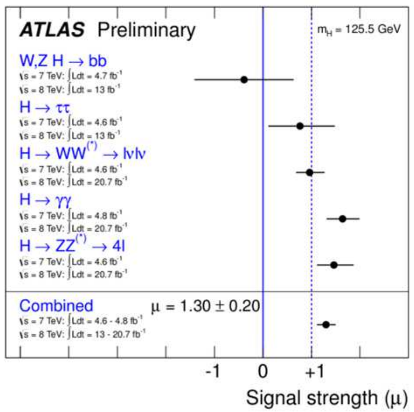
- Properties agree with the SM expectations: m_H~126 GeV (EWK Fit 94+/-25), $J^P=0^+$ …

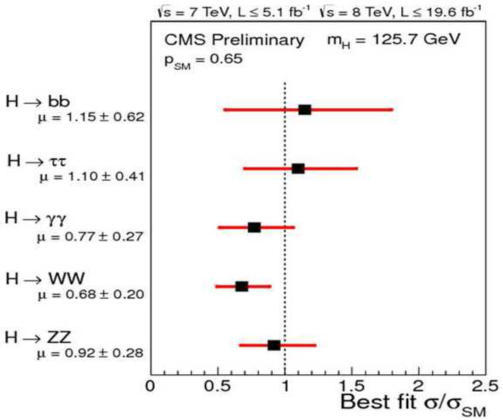


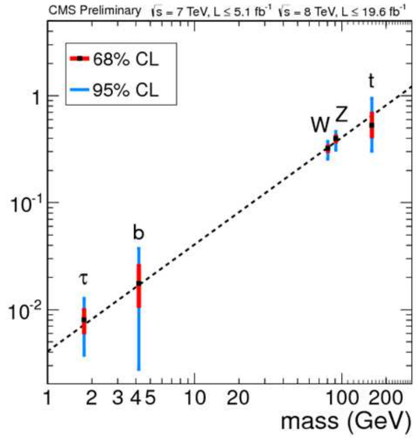




- … and also couplings to SM particles







SUSY Higgses (2)

❑ Can it be one of the neutral SUSY Higgses ?

- **m=126 GeV** : h^0 mass **<** m_Z (135 GeV) at LO (NLO), no theo. bounds on H^0, A^0 → **h^0, H^0, A^0**
- **$J^P=0^+$** like h^0 and H^0, but not A^0 → **h^0, H^0**
- **Couplings**: Need one SM Higgs-like particle and have two case depending on α

Case 1: $\cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)} \xrightarrow{m_A^2 \gg m_Z^2} 0$ → **h^0** *(H^0 heavy and degenerate with A^0, $H^{+/-}$)*

- **Gauge couplings** *(=0 for A^0,$H^{+/-}$ at tree level)*

$$g_{h^0WW} = g\, m_W \sin(\beta-\alpha) \rightarrow g\, m_W$$
$$g_{h^0ZZ} = \frac{g}{\cos\theta_W} m_Z \sin(\beta-\alpha) \rightarrow g\, m_Z/\cos\theta_W$$
$$g_{H^0WW} = g\, m_W \cos(\beta-\alpha) \rightarrow 0$$
$$g_{H^0ZZ} = \frac{g}{\cos\theta_W} m_Z \cos(\beta-\alpha) \rightarrow 0$$

- **Fermion couplings wrt SM** ($m_A^2 \gg m_Z^2$)

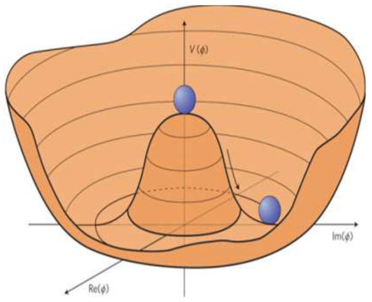
$$h^0 b\bar{b}: \quad -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \quad \rightarrow 1$$
$$h^0 t\bar{t}: \quad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \quad \rightarrow 1$$
$$H^0 b\bar{b}: \quad \frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) \quad \rightarrow \tan\beta$$
$$H^0 t\bar{t}: \quad \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) \quad \rightarrow -(\tan\beta)^{-1}$$

Case 2: $\cos^2(\beta-\alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_A^2(m_{H^0}^2 - m_{h^0}^2)} \xrightarrow{m_A^2 \sim m_Z^2} 1$ → **H^0** *(h^0 is lighter, A^0, $H^{+/-}$ also light)*

Yes ! h^0 looks very much like SM Higgs *(H=H^0 not yet fully excluded though)*

SUSY Higgses (3)

- **If $H=h^0$ → Impact on MSSM parameters** (Higgs potential and μ)



$V(\phi) = m^2\phi^2 + \lambda\phi^4$

- $m^2 = -m_H^2/2 = -(89\ \text{GeV})^2$ → $\mathbf{m^2 = |\mu|^2 \underbrace{+m_{Hu}^2 + \Delta m_{Hu}^2}_{-\Delta\mu^2}}$
- $\lambda = m_H^2/(2v^2) = 0.13$
- $v^2 = -m^2/\lambda = (246\ \text{GeV})^2$

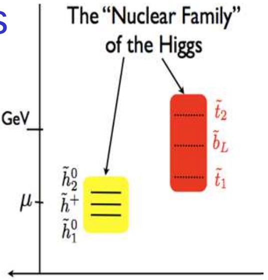
If want to keep $|\Delta\mu^2| < |\mu|^2$ → $|\mu| < 200$ *GeV*

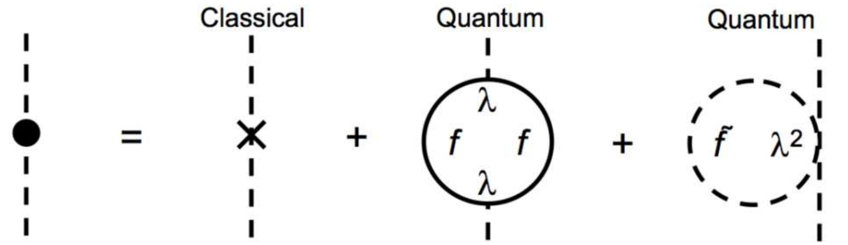
SUSY Higgses (4)

❑ If $H=h^0$ ➔ Impact on MSSM parameters (Higgs and stop mass)

- Want **low** radiative corrections

$m_h^2 = (m_h^2)_0 - \Delta m_h^2 = 126^2$





$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

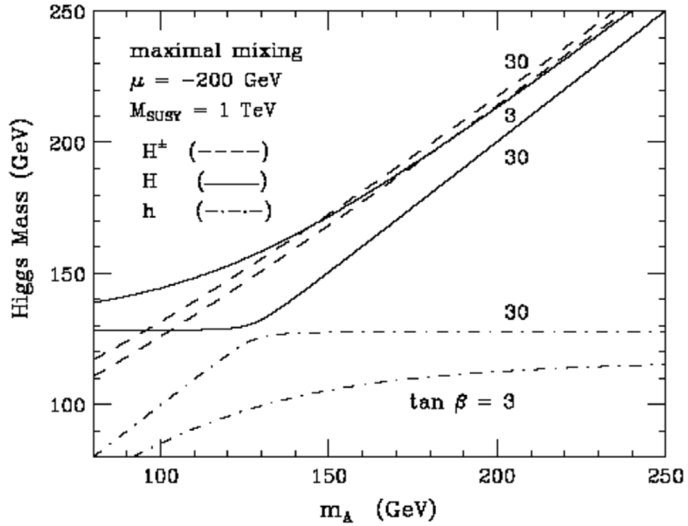
$$+ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

Small fine tuning ➔ light $\tilde{t}_1$

- Need **high** rad. corrections to match 126 GeV

$$m_h^2 \approx M_Z^2\cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2} - \frac{1}{12}\frac{X_t^4}{M_{\rm SUSY}^4}\right]$$

$126^2 = 91^2 + 87^2$ $\quad M_{SUSY}^2 = (m_{t1}^2 + m_{t2}^2)/2$



A 126 GeV h^0 ➔ heavy $\tilde{t}_1$ or large X_t

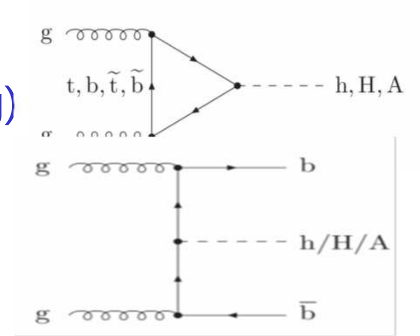
➔ Some tension …

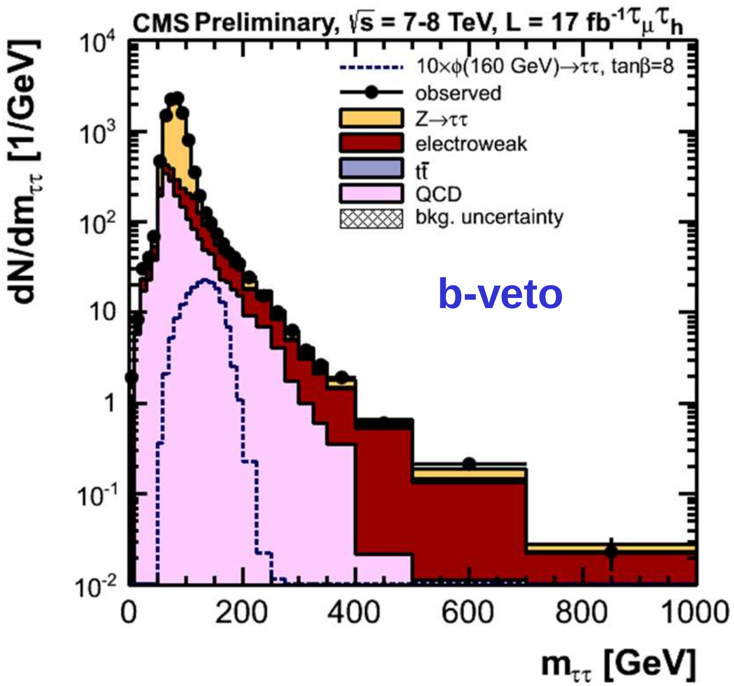
SUSY Higgses (5)

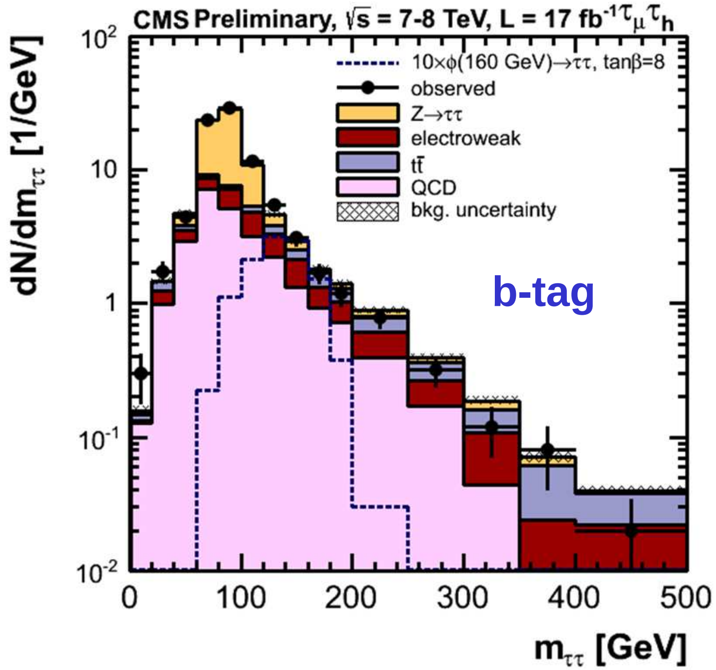
CMS-HIG-12-050

❑ Neutral Higgses searches : ϕ=A/H/h

- Production: gg→ϕ or gg→bϕ,bbϕ → 2 types of signal regions (b-veto,b-tag)
- Coupling *(prefer down-type fermions)* : $\phi\rightarrow\tau\tau$(10%), bb (90%)
  - ✓ Choose $\tau\tau$ since bb more challenging experimentally
- Main background : Z→$\tau\tau$ and Electroweak





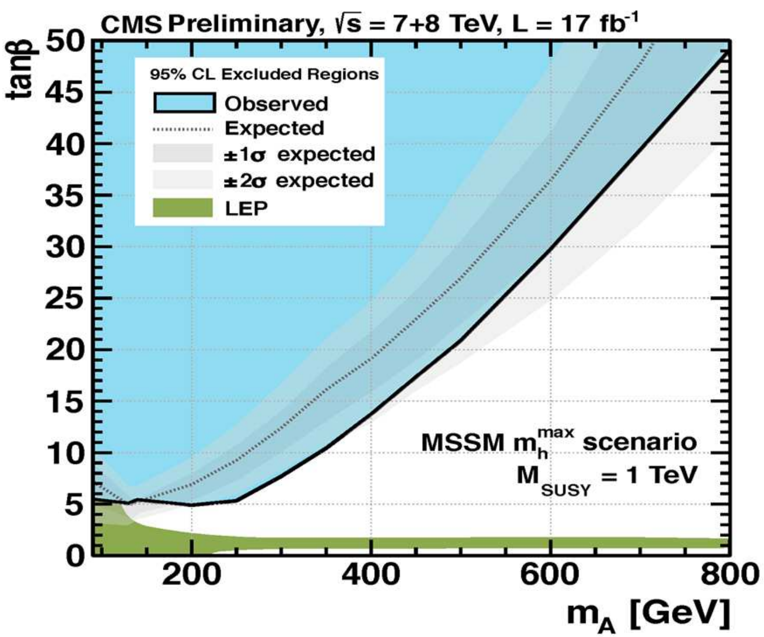


SUSY Higgses (6)

CMS-HIG-12-050

❑ Combine all channels ϕ=A/H/h → $\tau_{had}\tau_{lep}$, $\tau_{lep}\tau_{lep}$

- Put limits in a ``conservative" MSSM Model (m_h^{max})
  - ✓ M1=100 GeV, M2=μ = 200 GeV *(gluino and stop decoupled at 1 TeV to have low radiative corrections)*
- Most of the remaining phase space compatible with m_h^0=126 GeV



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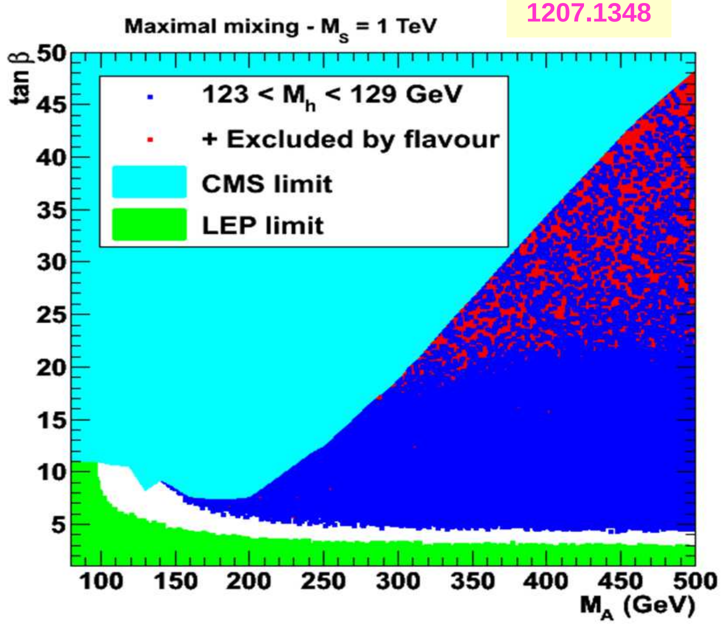


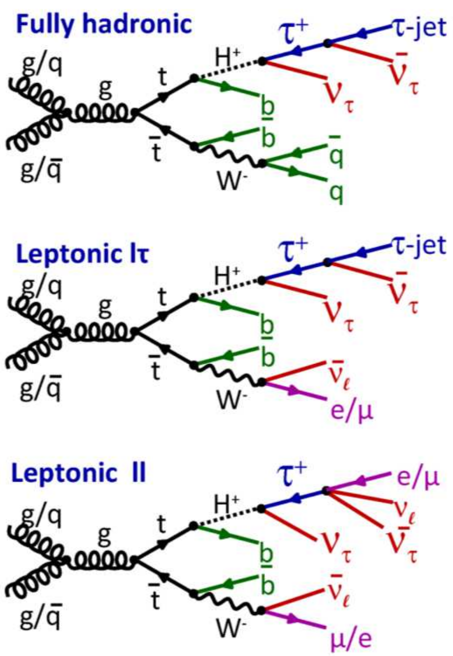
Favor high mass neutral SUSY Higgses

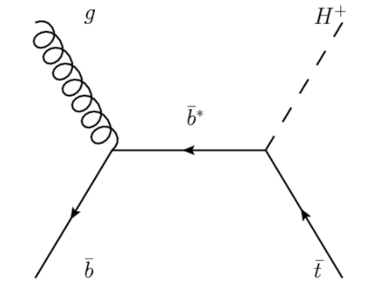
SUSY Higgses (7)

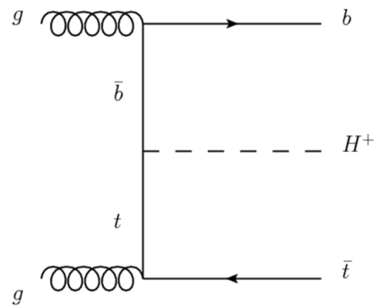
ATLAS-HIGGS-2013-090

❑ Charged Higgs : $H^{+/-} \rightarrow \tau\nu$

- An elementary **charged scalar** particle : clearly indicate new physics beyond SM !
- Coupling *(prefer down-type fermions)* : BR ($H \rightarrow \tau\nu$) = 100% for $\tan\beta > 1$
- Production: m_H+/- < m_t : Produce via $t \rightarrow bH^{+/-}$ m_H+/- > m_t : produced like $t(b)H^{+/-}$





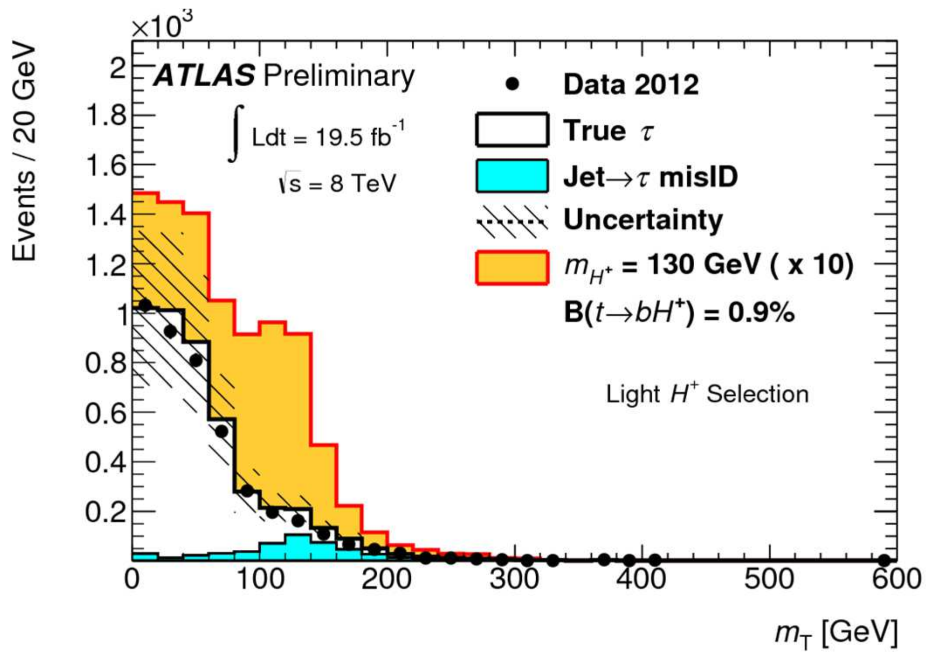


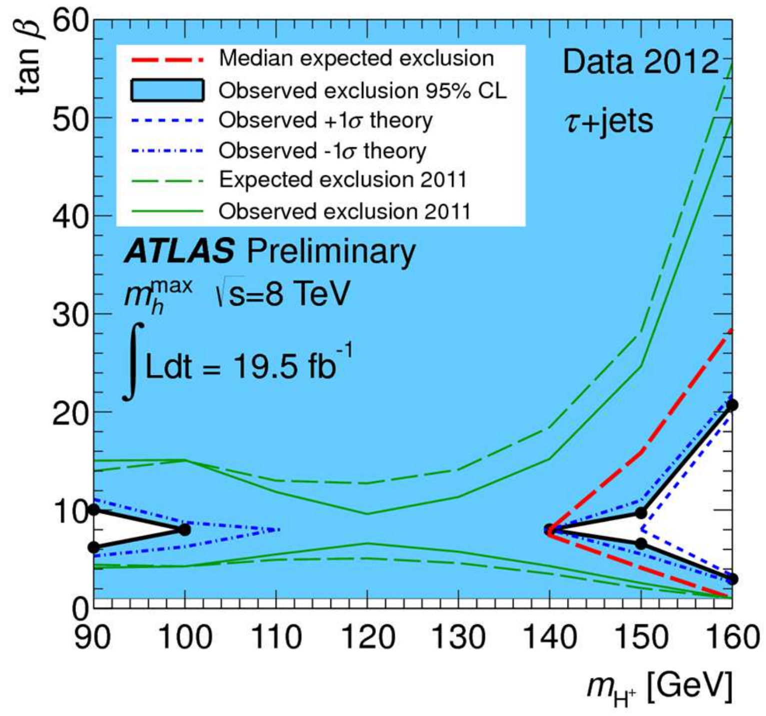
SUSY Higgses (8)

ATLAS-HIGGS-2013-090

❑ Charged Higgs ($H^{+/-} \rightarrow \tau\nu$) and $m_H < m_t$

- Select: =1 hadronic tau (medium) and W→jj
- Background dominated by true tau coming from ttbar



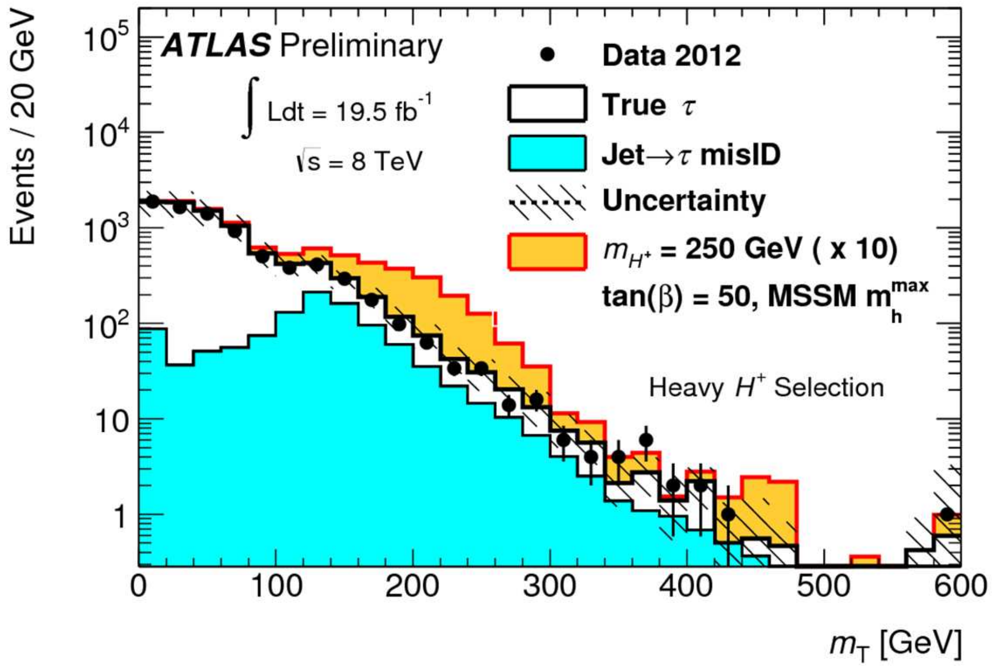


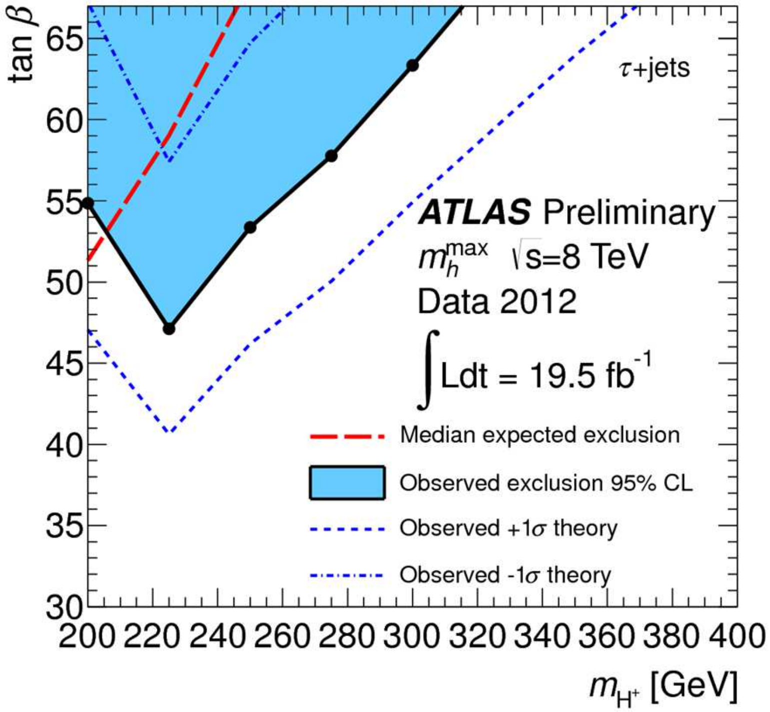
SUSY Higgses (9)

ATLAS-HIGGS-2013-090

❑ Charged Higgs ($H^{+/-} \rightarrow \tau\nu$) and $m_H > m_t$

- Select: =1 hadronic tau (medium) and W→jj
- Background now dominated by fake taus

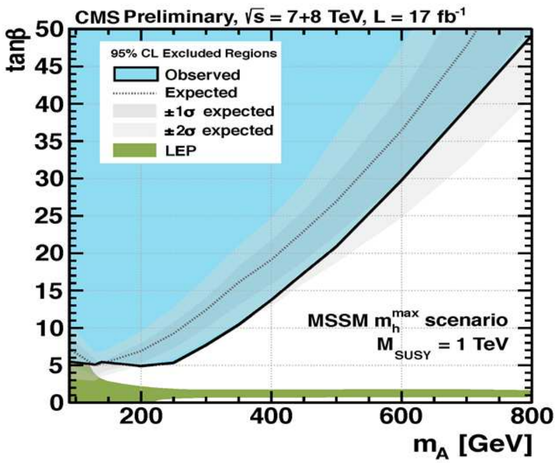


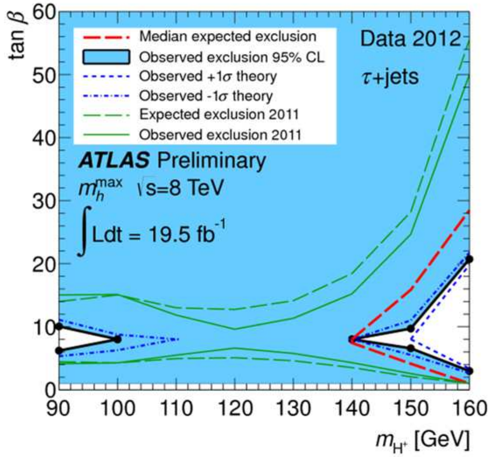


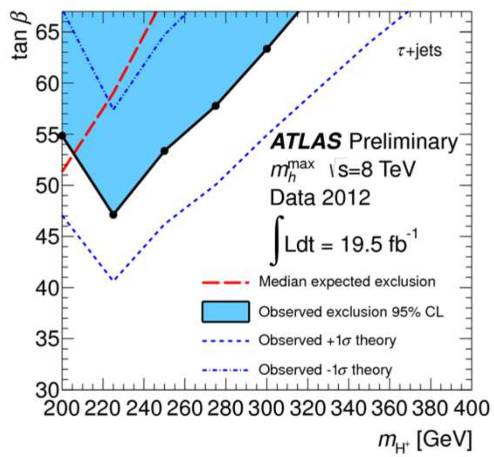
SUSY Higgses (10)

❑ Conclusions

- h^0 could still be the boson discovered (even if some tension within MSSM)
- Limits are pushing SUSY Higgses to higher masses, typically $m(H^{+/-},A^0)>130$ GeV







- In the following, I assume $A^0/H^0/H^{+/-}$ decoupled
  - ✓ It is conservative: If they happen to be lighter EWKinos cross-section will increase.

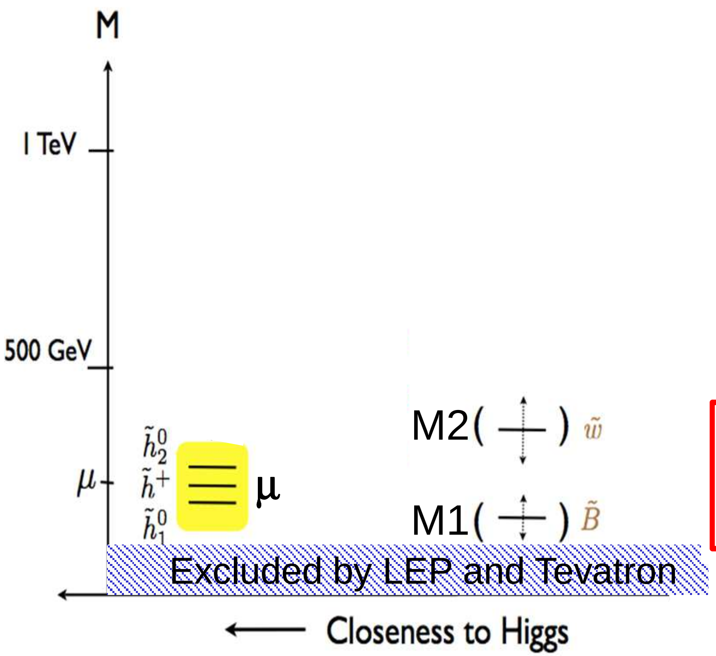
EWKinos (R_P=-1)

Theory Unknowns:

1- SUSY Breaking (**SUGRA**, GMSB, **AMSB**)

2- RPC (**here**) vs RPV (Lecture IIc)

3- **Open** or **compressed** spectra



~SUGRA
Bino-Wino case
Open Spectra

~Natural
Higgsino case
Compressed spectra

~ AMSB
Wino case
Degenerate spectra

Will mainly focus on lightest states ($\tilde{C}1$, $\tilde{N}1$, $\tilde{N}2$)

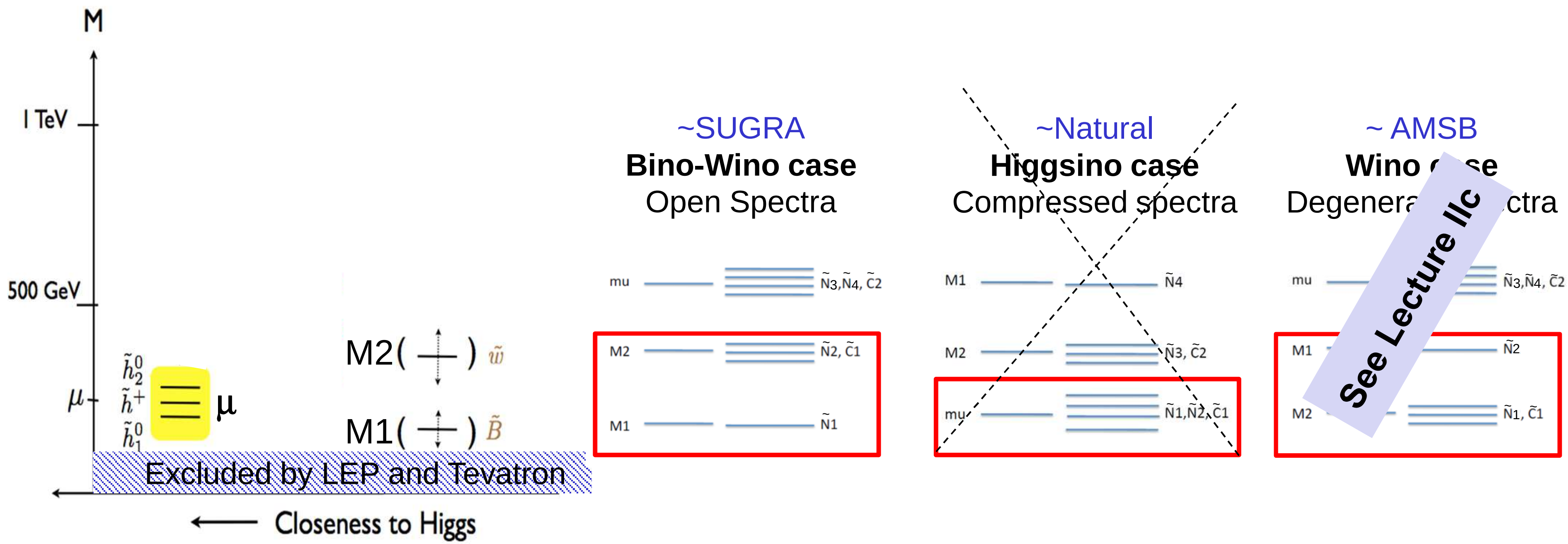
EWKinos (R_P=-1)

Theory Unknowns:

1- SUSY Breaking (**SUGRA**, GMSB, **AMSB**)

2- RPC (**here**) vs RPV (Lecture IIc)

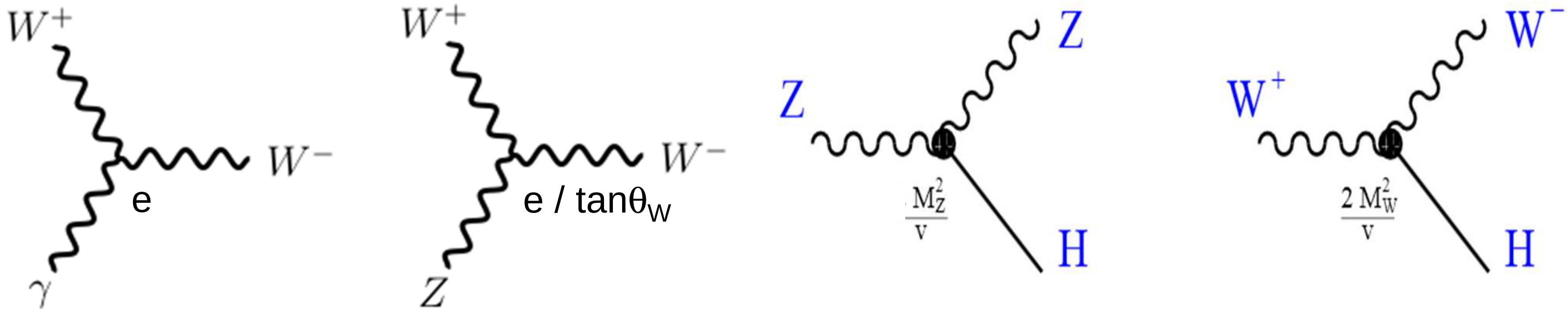
3- **Open** or **compressed** spectra



Will mainly focus on lightest states (C̃1, Ñ1, Ñ2)

EWKinos (0)

❑ Reminder : Triple Gauge coupling in the SM EWK sector



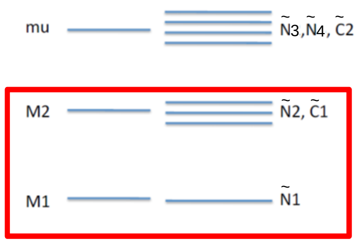
- $\lambda_{WW\gamma} \sim 0.6\ \lambda_{WWZ}$
- Neutral gauge coupling forbidden at tree level

- $\lambda_{ZZH} \sim 0.5\ \lambda_{WWH}$
- $H\gamma\gamma$ forbidden at tree level

With W↔ $\tilde{C}1$, γ (H) ↔ $\tilde{N}1$, Z (H)↔ $\tilde{N}2$ can get a feel for SUSY couplings

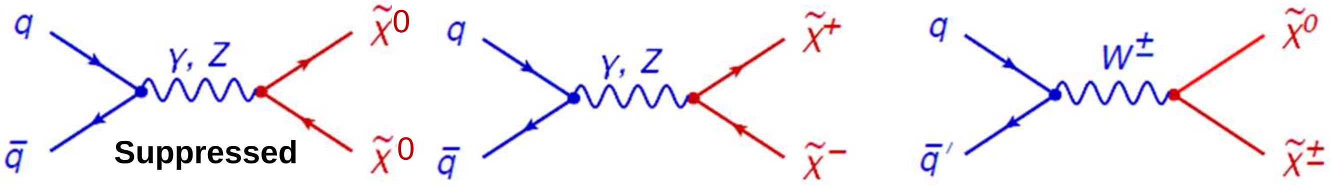
EWKinos (1)

~SUGRA
Bino-Wino case
Open Spectra



❑ How to produce them ?

- Gauginos mediated by γ, Z, W (marginally via $h^0/H^0/A^0/H^{+/-}$)



Note: coupling (W-Bino, Z/γ-Wino)~0, (W/Z/γ-Higgsino)~small, (W-Wino, Z/γ-Bino)~large

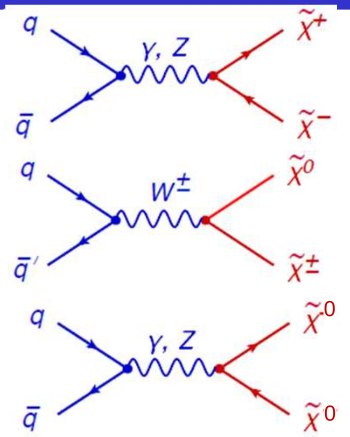
❑ How they decay (and assumptions) ?

- Most natural is via Gauge bosons and Higgses → **1- Only decay via W/Z**
- On shell or off-shell depends ΔM=M(N2,C1)-M(N1) → **2- On-shell W/Z ΔM>M(Z,W)**
- LHC = hadronic collider → **3- W/Z leptonic decays (l=e,μ)**

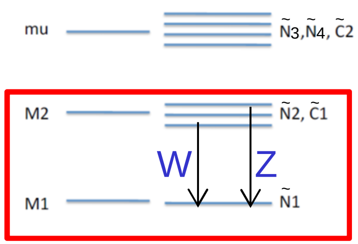
	N1	N2	C1
N1	N1N1		
N2	ZN1N1	ZZN1N1	
C1	WN1N1	WZN1N1	WWN1N1

	N1	N2	C1
N1	**ISR-jet**		
N2	**2l+MET**	**4l+MET**	
C1	**1l+MET**	**3l+MET**	**2l+MET**

EWKinos (2)



~SUGRA
Bino-Wino case
Open Spectra

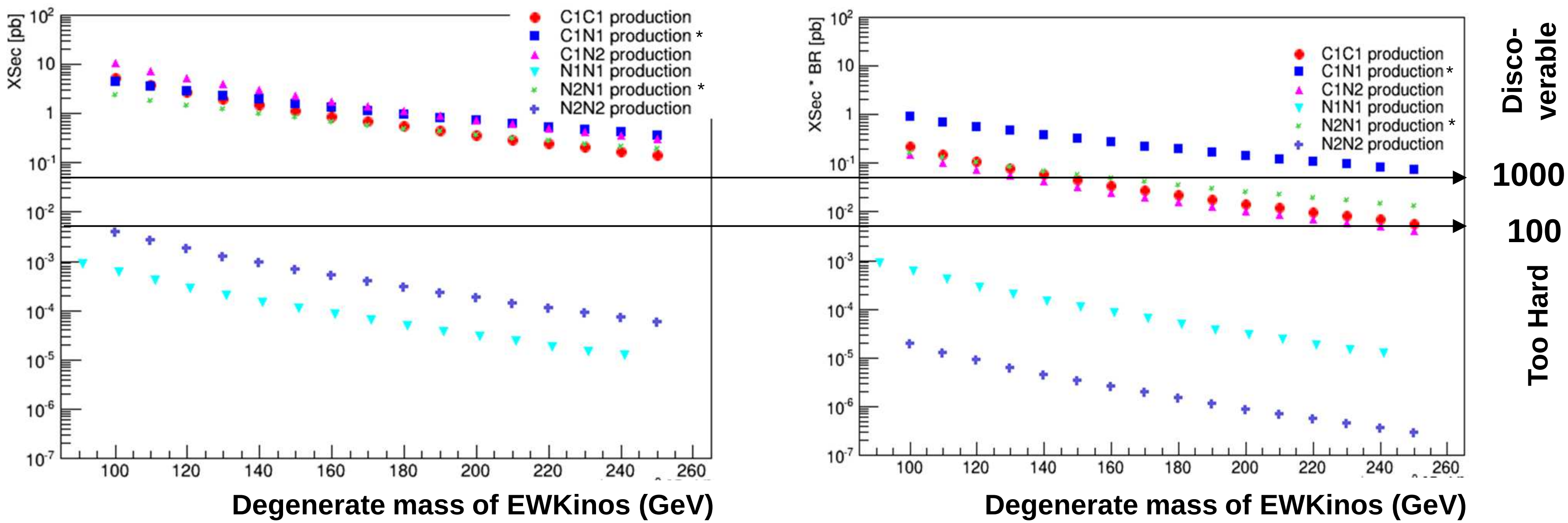


Decay via Leptonic on-shell W and Z

BR (W→lν)=0.21
BR (Z→ll)=0.07

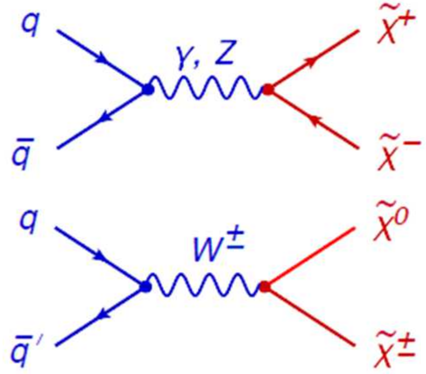
	N1	N2	C1
N1	~~ISR-jet~~ ▼		
N2	2l+MET★	~~4l+MET~~ ✚	
C1	1l+MET ■	3l+MET ▲	2l+MET ●

N(evt) 2012

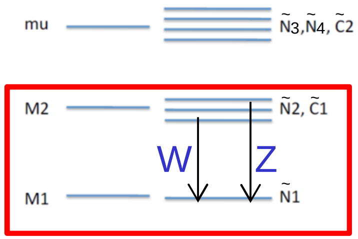


* Assume m(N1)=1 GeV

EWKinos (3)



~SUGRA
Bino-Wino case
Open Spectra

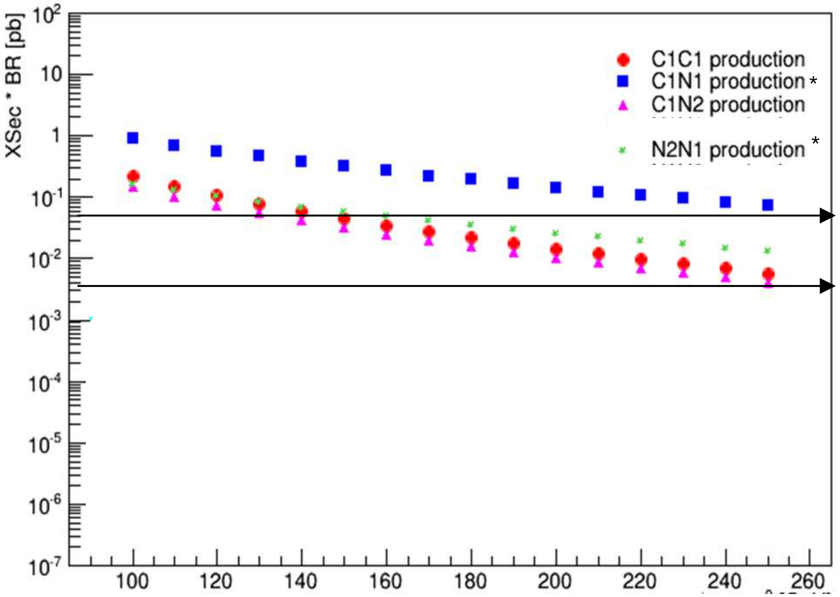


Decay via Leptonic on-shell W and Z

BR (W→lv)=0.21
BR (Z→ll)=0.07

	N1	N2	C1
N1	~~ISR-jet~~ ▼		
N2	~~2l+MET~~ ☆	~~4l+MET~~ ✚	
C1	~~1l+MET~~ ■	3l+MET ▲	2l+MET ●

N(evt) 2012



* Assume m(N1)=1 GeV

	Main EW Background		
	Type	**σ xBR (pb)**	**σ/σ_{SUSY}@100 GeV**
C1C1	**WW→lvlv**	**2.6**	2.6/0.25 ~ **10**
C1N1*	**W→lv**	**25000**	25000/1 ~ **25000**
C1N2	**WZ→lvll**	**0.3**	0.3/0.12 ~ **2.5**
N2N1*	**Z→ll**	**2200**	2200/0.17 ~ **13000**

Only C1N1 and C1N2 can be probed at LHC-8 (20 fb^{-1})

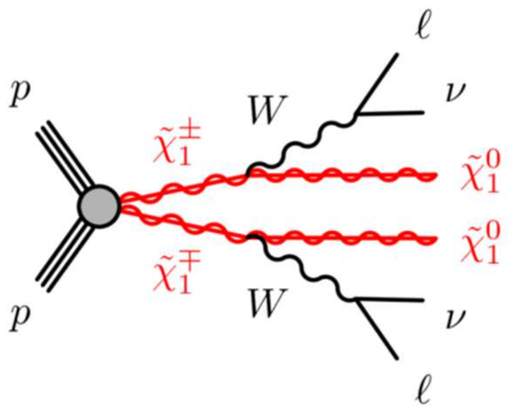
EWKinos (4)

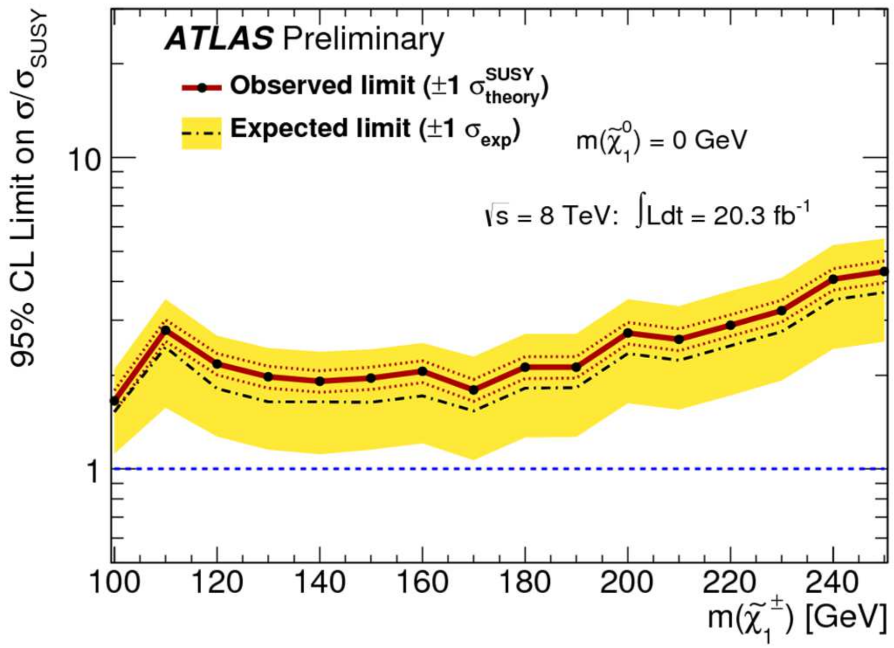
ATLAS-CONF-2013-049

~SUGRA
Bino-Wino case
Open Spectra

❑ Search for Direct Chargino (C1C1)

- Extensively discussed in Exercise 1 … only comment the result here
- Presently only consider eμ channel



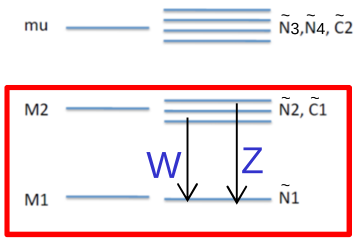


Can not exclude (yet) any SUSY models

EWKinos (5)

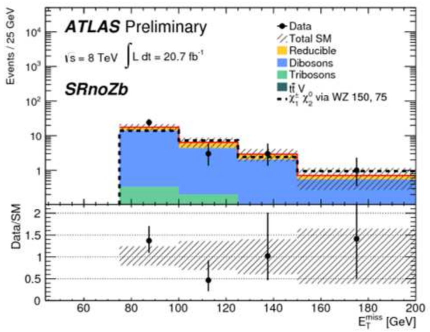
ATLAS-CONF-2013-035

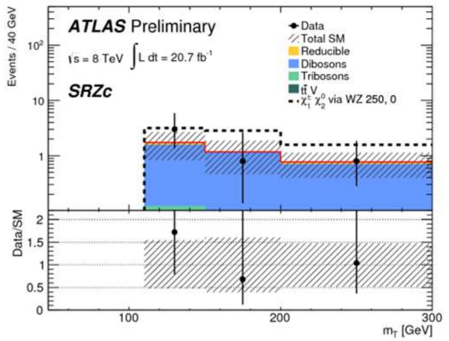
~SUGRA
Bino-Wino case
Open Spectra



❑ Search for associate production (C1N2)

- Similar experimental challenge, but dominant background is now WZ !
- Consider 3-lepton signal regions (w/wo Z veto or w/wo W veto)





Selection (SRnoZb)

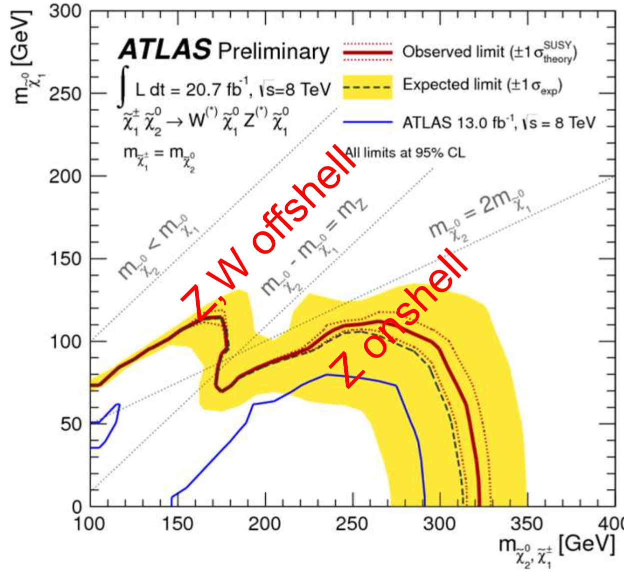
- Trigger : Single Lepton OR Dilepton
- Pt (lepton) >25/15,10,10 GeV
- Jet veto, bjet veto, Z veto
- Discriminant: MET>75 GeV

Background

N_B=29±6
Syst dominated. Mainly from WZ theo uncertainties.

Signal

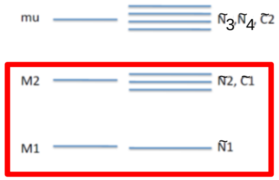
Errors are 10-20% dominated by theo. signal uncertainty



➔ Exclude $m(\chi_1^{\pm})=m(\chi_2^0)$<320 GeV for m(LSP)<80 GeV

EWKinos (6)

~SUGRA
Bino-Wino case
Open Spectra



❑ How they decay (and assumptions) ?

- Most natural is via Gauge bosons and Higgses → **1- Only decay via W/Z**
- On shell or off-shell depends ΔM=M(N2,C1)-M(N1) → **2- O~~n~~ff-shell W/Z ΔM~~>~~<M(Z,W)**
- LHC = hadronic collider → **3- W/Z leptonic decays (l=e,μ)**

	N1	N2	C1
N1	N1N1		
N2	ZN1N1	ZZN1N1	
C1	WN1N1	WZN1N1	WWN1N1

	N1	N2	C1
N1	ISR-jet		
N2	2l+MET	4l+MET	
C1	1l+MET	**3l+MET**	**2l+MET**
		Previous slide	Leptons too soft

❑ How they decay (and assumptions) ?

- Most natural is via Gauge bosons and Higgses → **1- Only decay via W/Z**
- On shell or off-shell depends ΔM=M(N2,C1)-M(N1) → **2- On-shell W/Z ΔM>M(Z,W)**
- LHC = hadronic collider → **3- W/Z ~~leptonic~~ hadronic decays**

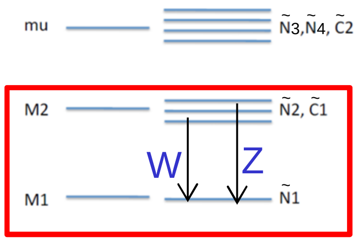
	N1	N2	C1
N1	N1N1		
N2	ZN1N1	ZZN1N1	
C1	WN1N1	WZN1N1	WWN1N1

	N1	N2	C1
N1	ISR-jet		
N2	2j+MET	2l2j/4j+MET	
C1	2j+MET	1l2j/**2l2j**/4j**+MET**	1l2j/4j+MET

ATLAS-CONF-2013-035, CMS-PAS-SUSY-13-006

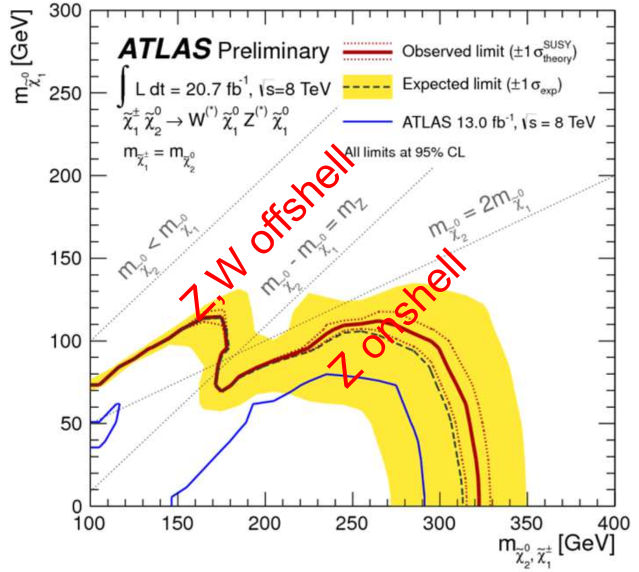
EWKinos (7)

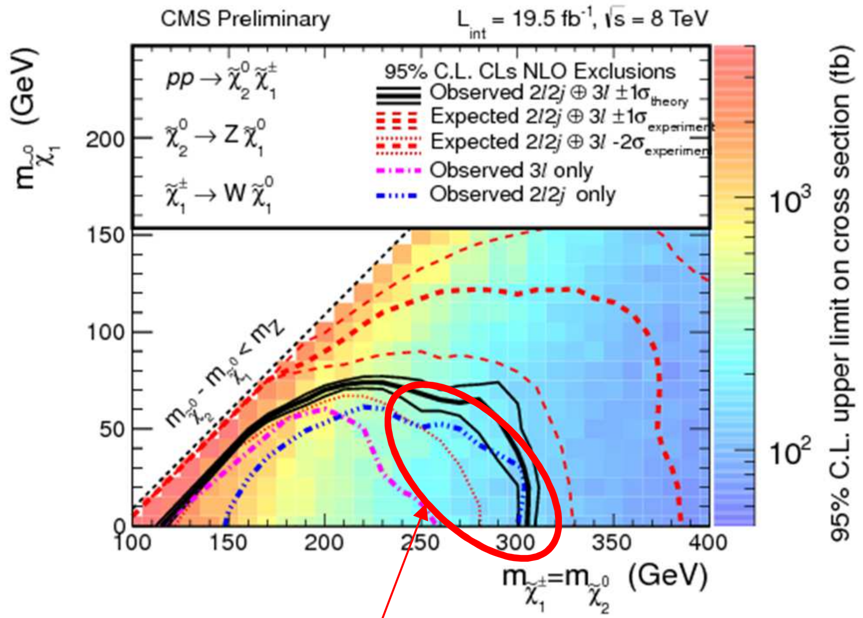
~SUGRA
Bino-Wino case
Open Spectra



❑ Search for associate production (C1N2)

- Similar experimental challenge, but dominant background is now WZ !
- All 2-lepton+2-jet to 3 signal regions (w/wo Z veto or w/wo W veto)

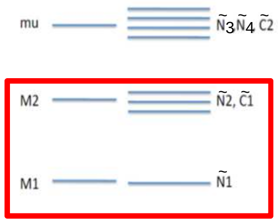




Add sensitivity to at high $m(\chi_1^{\pm})=m(\chi_2^0)$ masses for massless LSP

EWKinos (8)

~SUGRA
Bino-Wino case
Open Spectra



❑ How they decay (and assumptions) ?

- Most natural is via Gauge bosons and Higgses → **1- Only decay via ~~W/Z~~ h^0**
- On shell or off-shell depends $\Delta M=M(N2,C1)-M(N1)$ → **2- On-shell h^0 $\Delta M>M(h^0)$**
- LHC = hadronic collider → **3- All h^0 decays**

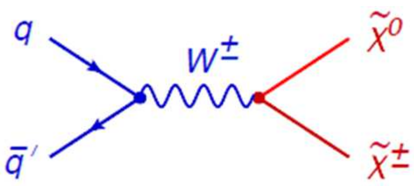
	N1	N2	C1
N1	N1N1		
N2	HN1N1	HHN1N1	
C1	WN1N1	WHN1N1	WWN1N1

→

	N1	N2	C1
N1	ISR-jet		
N2	**H+MET**	**HH+MET**	
C1	1l+MET	**WH+MET**	2l+MET

Note: in SUSY N2-wino can not decay via Higgs, however interesting for comparison purpose

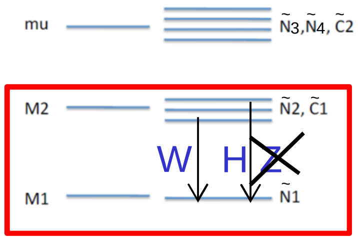
EWKinos (9)



~SUGRA

Bino-Wino case

Open Spectra

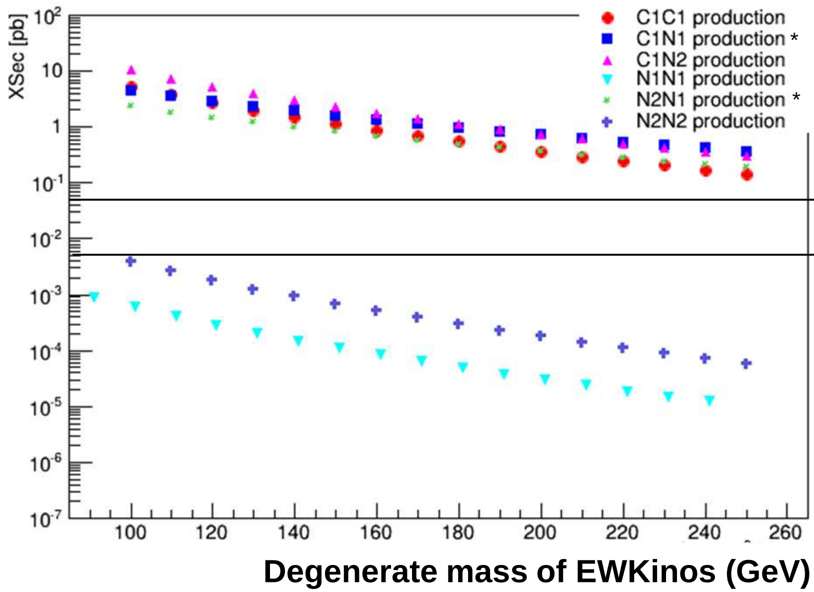


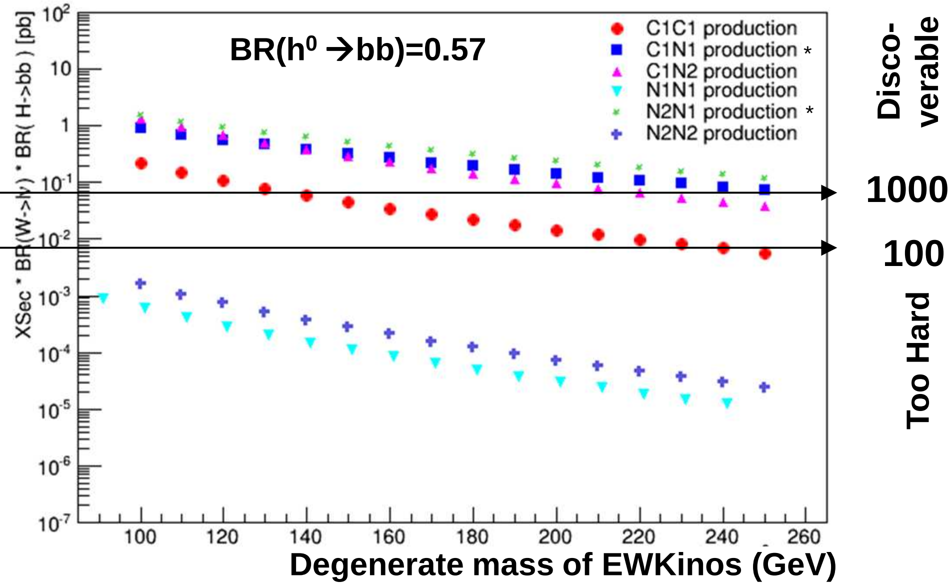
N2 Decay via SM Higgs and C1 via W

BR (W→lν)=0.21
BR (h^0→WW*→llνν)=0.008
BR (h^0 →ZZ*→llll)=0.00014
BR(h^0 →γγ)=0.0023
BR(h^0 →bb)=0.57
BR(h^0 →ττ)=0.06

Higgs decay	C1N2
H→WW*→2l2ν	3l+MET
H→ZZ*→4l	5l+MET
H→γγ	1l+γγ+MET
H→bb	1l+bb+MET
H→ττ	1l+ττ+MET

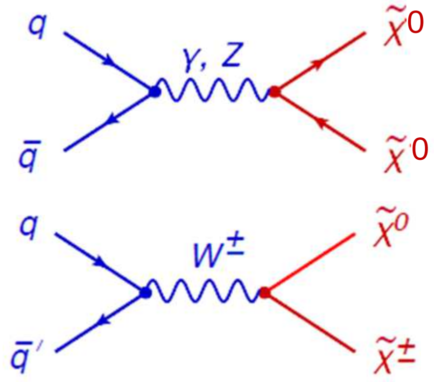
N(evt) 2012



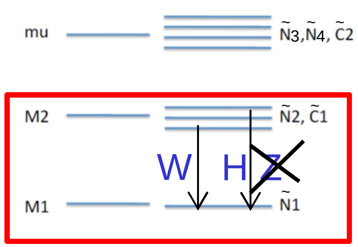


* Assume m(N1)=1 GeV

EWKinos (10)



~SUGRA
Bino-Wino case
Open Spectra



N2 Decay via SM Higgs and C1 via W

BR (W→lν)=0.21
BR (h^0→WW*→llνν)=0.008
BR (h^0 →ZZ*→llll)=0.00014
BR(h^0 →γγ)=0.0023
BR(h^0 →bb)=0.57
BR(h^0 →ττ)=0.06

	C1N2
H→WW*→2l2ν	3l+MET
H→ZZ*→4l	5l+MET
H→γγ	1l+γγ+MET
H→bb	1l+bb+MET
H→ττ	1l+ττ+MET

	Main Background		
	Type	σxBR (pb)	σ/σ_{SUSY} @100 GeV
3l+MET	WZ→3l1ν	0.3	0.3/0.02 ~**15**
5l+MET	ZZ→4l	0.5	0.5/0.0003~**1700**
1l+γγ+MET	Wγ + j ?	0.8	0.8/0.005 ~**150**
1l+bb+MET	tt→2b2l2ν	11	11/1.2 ~**9**
1l+ττ+MET	tt→2blτ2ν	6	6/0.12 ~**50**

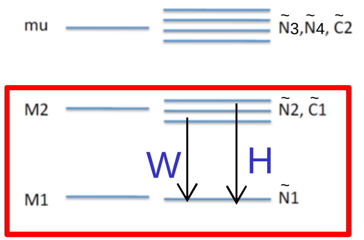
σ(Wγ + j) ?
σ(Wγ) = 40 pb
BR(W→lν) = 0.21
Jet faking γ = 0.1 ? Fab
σ(Wγ)xBR= 0.8 pb

1l+bb+MET seems the most powerfull

EWKinos (11)

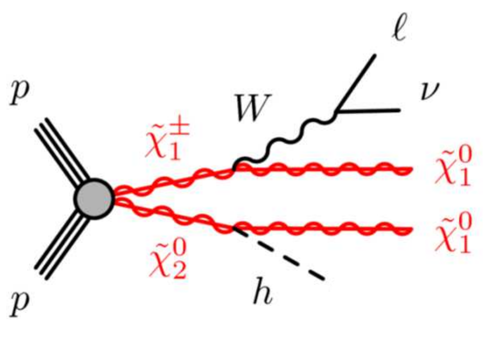
CMS-PAS-SUS-13-017

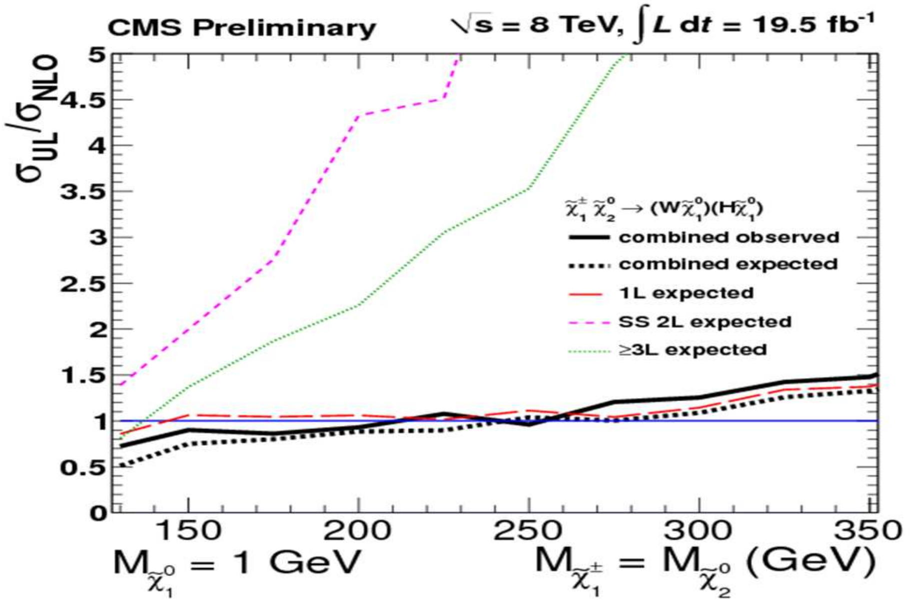
~SUGRA
Bino-Wino case
Open Spectra



❑ EWKinos production with Higgs in the cascade

- 3 different signal regions considered
- 1l +bb is stronger





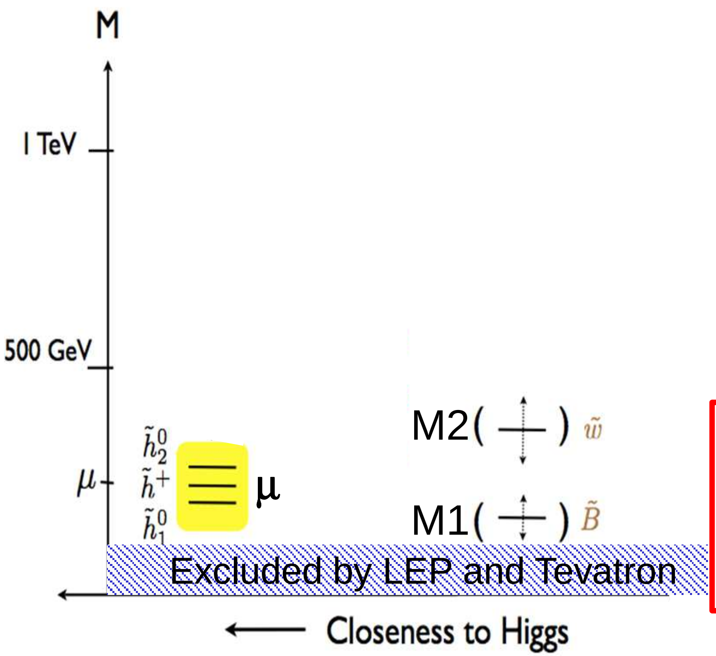
EWKinos (12)

Theory Unknowns:

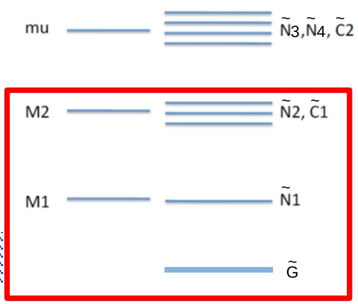
1- SUSY Breaking (SUGRA, **GMSB**, AMSB)

2- RPC (**here**) vs RPV (Lecture IIc)

3- **Open** or **compressed** spectra



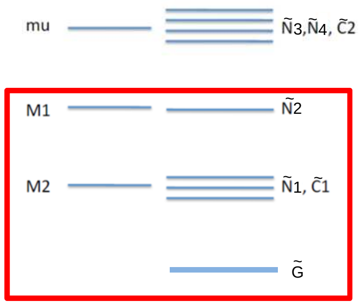
Bino-Wino case
Open Spectra



May be only way to access N1N1–at least at low mass ?

Higgsino case
Compressed spectra

Wino co-NLSP case
ΔM(C1-N1)<1GeV



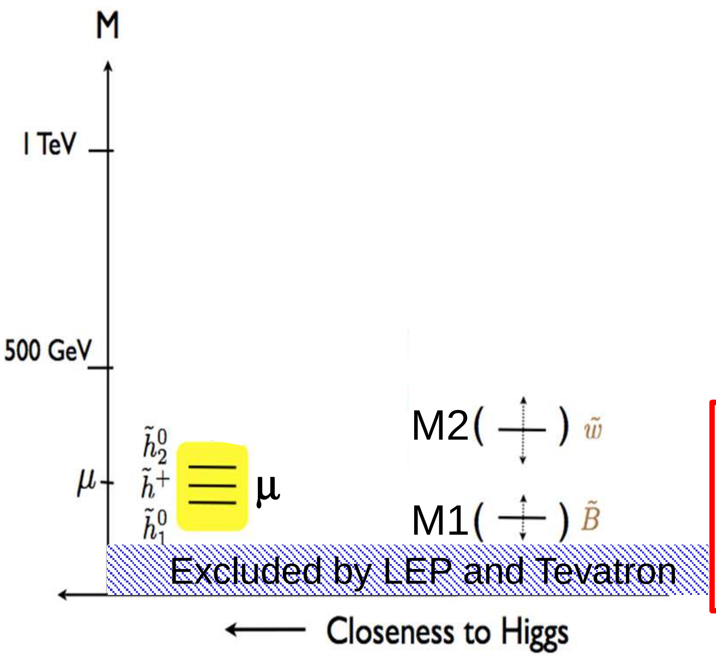
EWKinos (13)

Theory Unknowns:

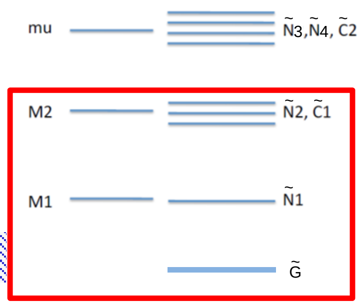
1- SUSY Breaking (SUGRA, **GMSB**, AMSB)

2- RPC (**here**) vs RPV (Lecture IIc)

3- **Open** or **compressed** spectra



Bino-Wino case
Open Spectra

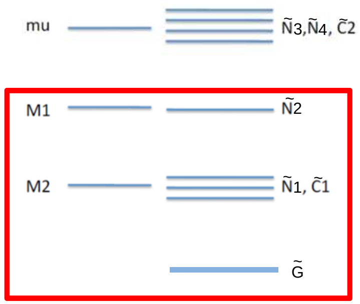


May be only way to access N1N1–at least at low mass ?

Higgsino case
Compressed spectra but now favored by ΔM(C1/N2/N1-G) !

N1→ZG for low tanβ
N1→HG for high tanβ

Wino co-NLSP case
ΔM(C1-N1)<1GeV

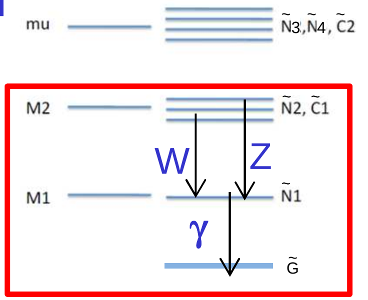


C1→WG
N1→Z/γG

EWKinos (14)

1209.0753

Bino-Wino case
Open Spectra

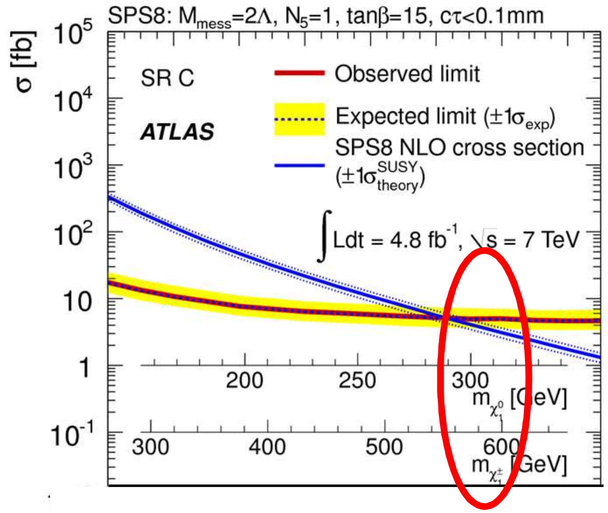


❑ A plethora of new final states for Bino-Wino case

- Remove NxNy production since too low cross-section
- σ_{SUSY} /3 because (W/Z/γ-Higgsino)~small wrt (W-Wino, Z/γ-Bino)~large
- Pure Bino NLSP → Adding 2γ in final state kill C1N1 and C1C1 background

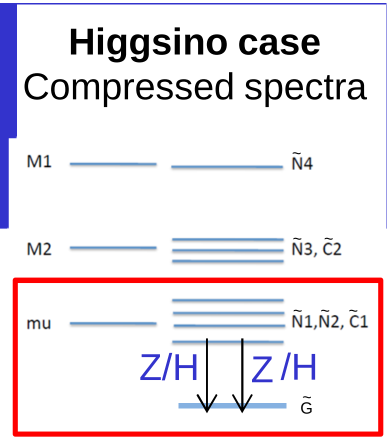
	N1	N2	C1
C1	WγγGG	WZγγGG	WWγγGG
Final states	**1l+2γ+MET**	**3l+2γ+MET**	**2l+2γ+MET**
Bkg type	**Wγ + j ?**	**Fake ?**	**Zγ + j ?**
σ xBR (pb)	**0.8**	**0.1 ??**	**0.1**
σ/σ_{SUSY}@100 GeV	**0.8/0.3 ~ 3**	**0.1/0.04~2.5**	**0.1/0.1 ~ 1**
For ~SUGRA was	2000	2.5	10

2γ+MET



No 8 TeV published results on this !

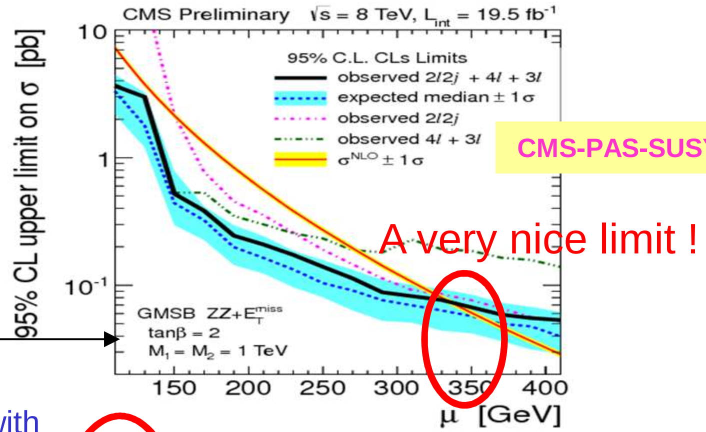
EWKinos (15)



❑ Have sensitivity to the Higgsino case !

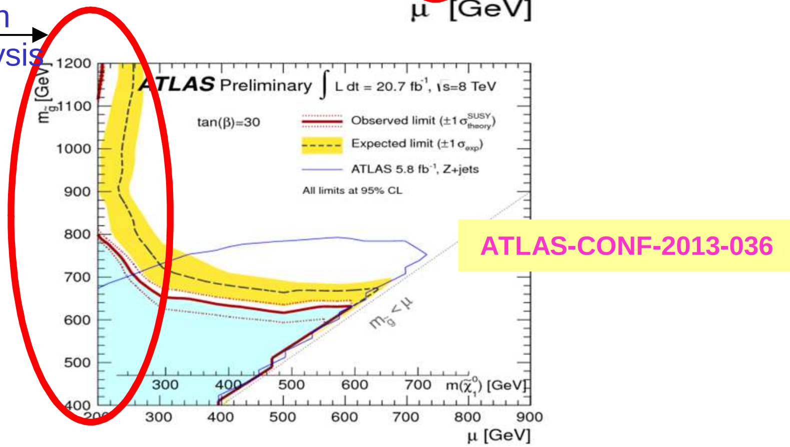
- N1,C1,N2 degenerate. Assume N1 is still the LSP (N2 similar)
- Can reuse 3lepton analysis to assess sensitivity at low tanβ

	N1	N2	C1
C1	ZZGG	ZZGG	ZZGG
Final states	**4l / 2l+2j+MET**		
Bkg type	**ZZ→llll / Z+2jets**		
σ xBR (pb)	**0.5 / 70**		
σ/σ_{SUSY}@100 GeV	0.5/(0.3+0.04+0.1) ~ **1 !!**		



- Poorer sensitivity at high tan β

Obtained with ZZ*+MET analysis

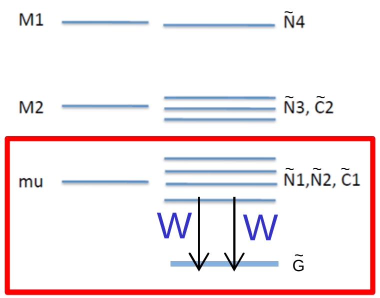


	N1	N2	C1
C1	ZHGG	ZHGG	ZHGG
Final states	**2l+bb+MET**		
Bkg type	**tt→2b2l2v**		
σ xBR (pb)	**11**		
σ/σ_{SUSY}@100 GeV	11/(0.3+0.04+0.1) ~ **25**		

EWKinos (16)

ATLAS-SUSY-2013-049

Higgsino case
Compressed spectra

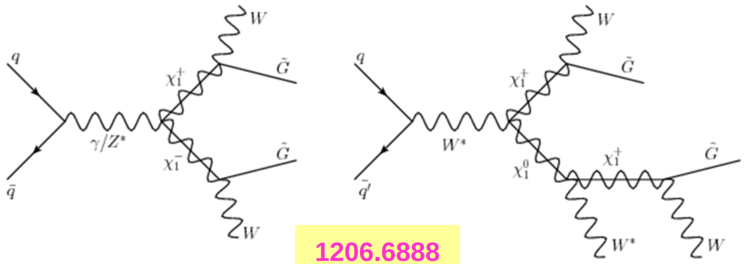


❑ Have sensitivity to the Higgsino case !

- Other interesting case: NLSP=C1 : Can add up all production …
- … and recover lower cross-section)

	N1	N2	C1
C1	WWGG	WWGG	WWGG
Final states	**2l+MET**	**2l+MET**	**2l+MET**
Bkg type	**WW→lvlv**	**WW→lvlv**	**WW→lvlv**
σ xBR (pb)	**2.6**	**2.6**	**2.6**
σ/σ_{SUSY}@100 GeV	2.6/(0.3+0.04+0.1) ~ **6**		

For ~SUGRA was 10



1206.6888

- Can reuse 2lepton analysis to assess sensitivity. For mC1=100 GeV **σ/σ_{SUSY} ~ 2.9**

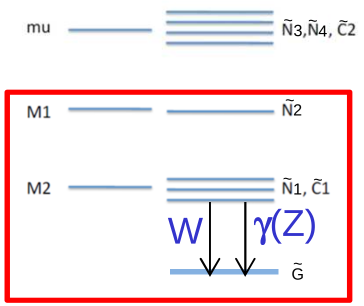
EWKinos (16)

ATLAS-SUSY-2012-144

Wino co-NLSP case
ΔM(C1-N1)<1GeV

❑ And finally the Wino co-NLSP case

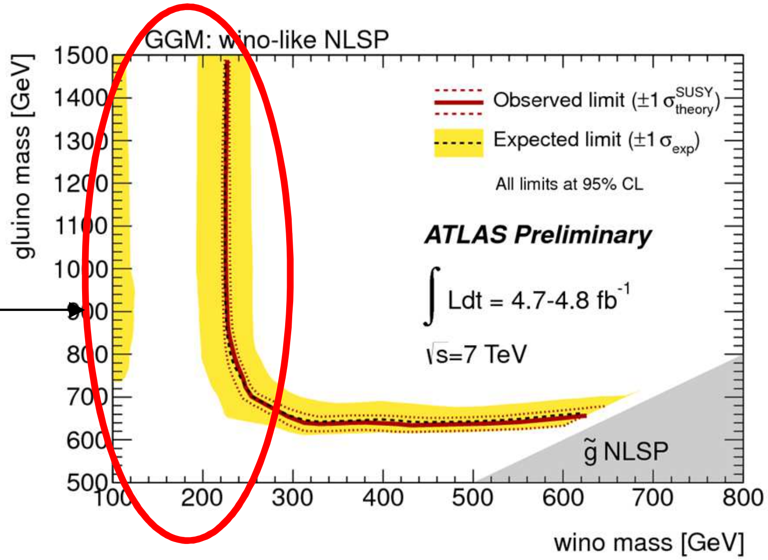
- Decay C1→W*N1 is longer than ~0.1 mm … and C1→WG dominates !
- C1N2 has very low cross-section



	N1	C1
C1	WγGG	WWGG
Final states	**1l+1γ+MET**	**2l+MET**
Bkg type	**Wγ→lνγ**	**WW→lνlν**
σ xBR (pb)	**12**	**2.6**
σ/σ$_{SUSY}$@100 GeV	12/1~**12**	2.6/0.25~**10**

For ~SUGRA was 25000 10

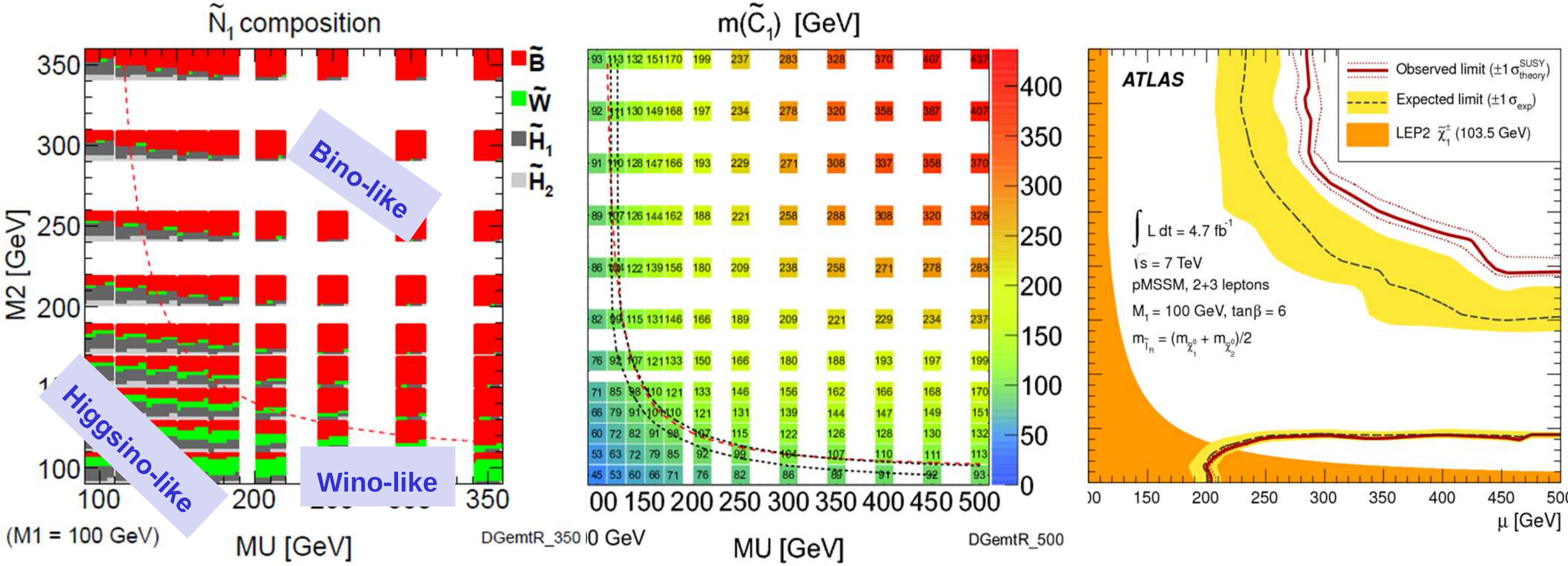
- 1l+1γ+MET can exclude mC1<220 GeV !!



EWKinos (17)

❑ pMSSM = systematic scan of 19 parameters MSSM

- We have treated 3 extreme cases Higgsino-like, Bino-Wino or pure Wino.
- Sometimes even SUSY impossible models ! *(N1 Higgs decay in Bino-Wino models)*
- Can consider SUSY-motivated case and all the intermediate cases with pMSSM



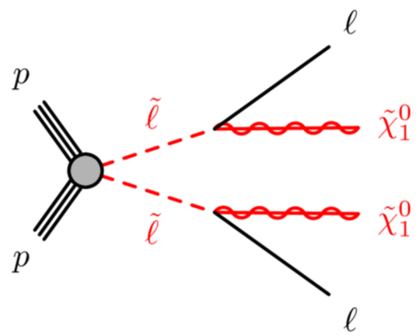
Final results recasted there will allow to be more quantitative (still to come)

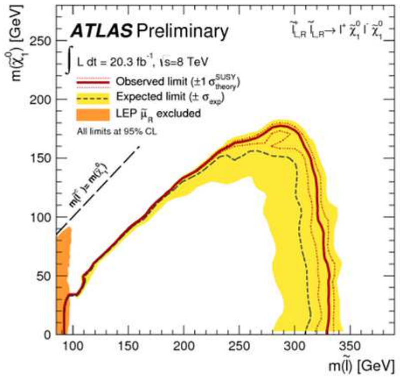
Some Left over (1)

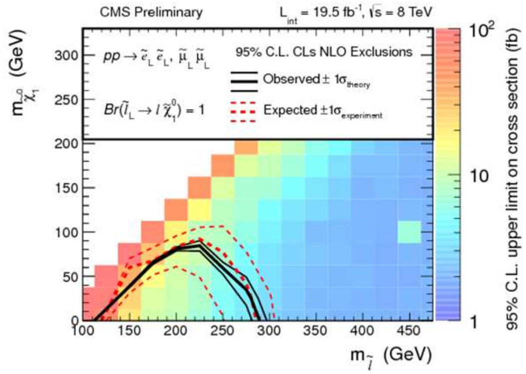
ATLAS-SUSY-2013-049
CMS-PAS-SUS-13-006
ATLAS-SUSY-2013-028

❑ Low mass slepton are not natural but …

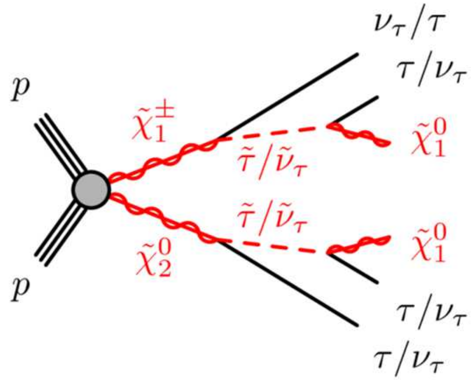
- Have same final states as C1C1→WWN1N1 so can be exclude beyond LEP

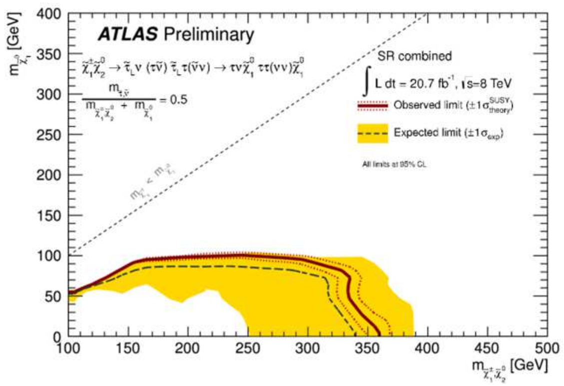






- m(tau)~1.8 GeV heavy, low mass stau can be conceived



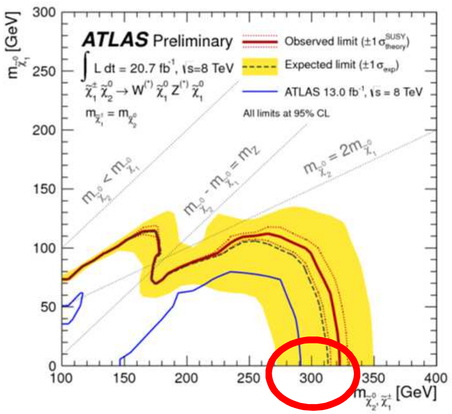


Some Left-over (2)

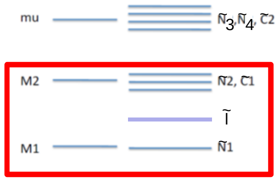
ATLAS-CONF-2013-035

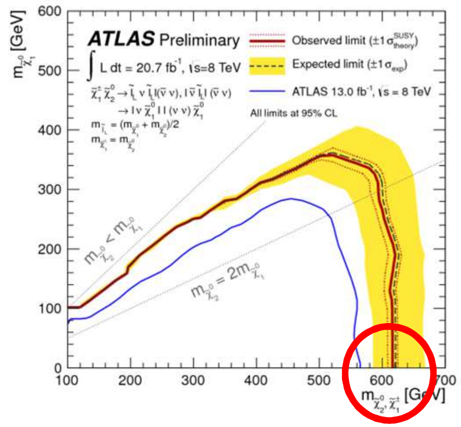
❑ Intermediate sleptons

- Not natural but if present will double the mass limits



~SUGRA
Bino-Wino case
Open Spectra

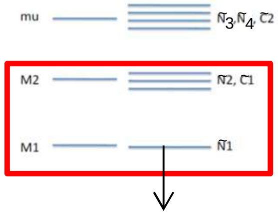




- AMSB case and RPV → Lecture 3

~ AMSB
Wino case
Degenerate spectra

~SUGRA
Bino-Wino case
Open Spectra



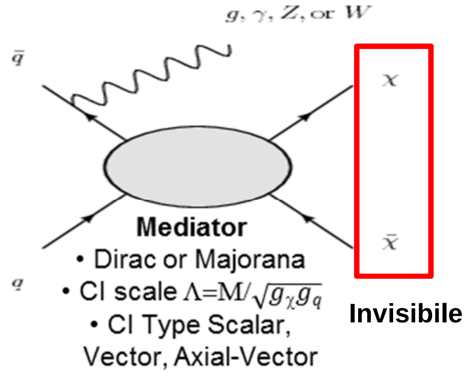
SM particles

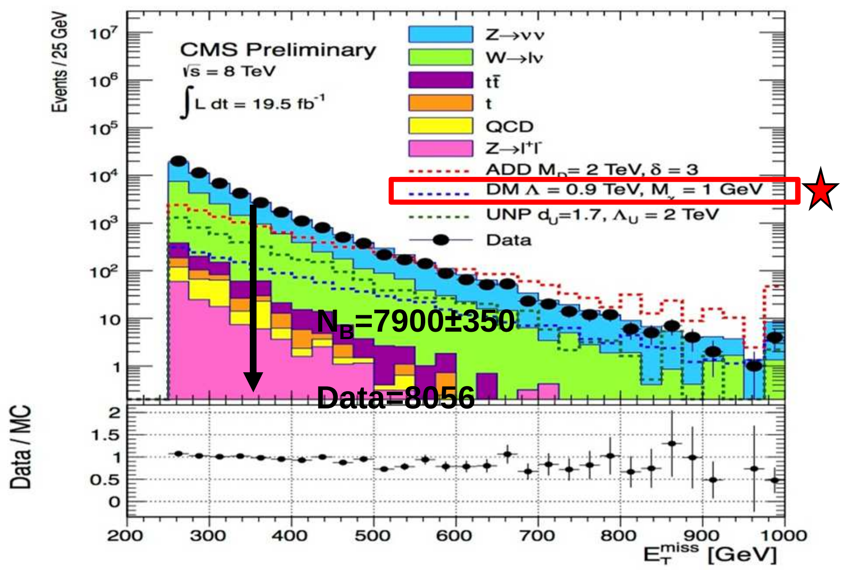
Some Left-over (3)

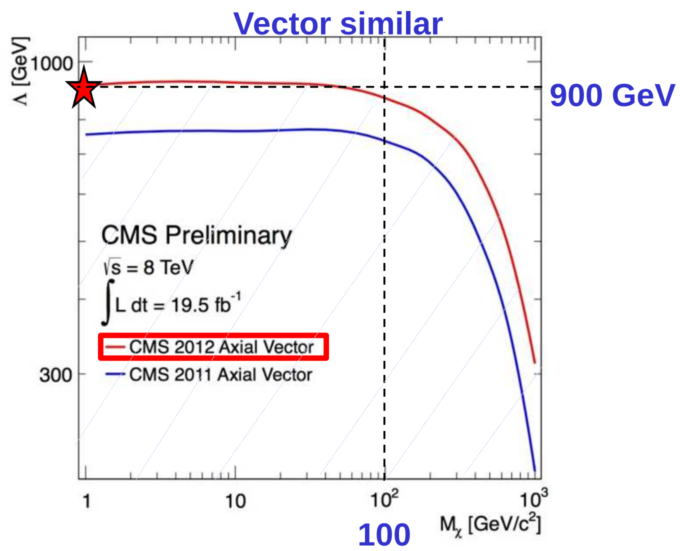
CMS-PAS-EXO-12-048

❑ Monojet : sensitivity to LSP ?

- Mono-x (x=j, g, W, Z) signature. Most powerful is x=j
  - ✓ Jet is recoiling against χ *(boosted by the heavy final state)*
  - ✓ Enhance MET at high value !
- x=j : 1high energetic jet + imbalanced event (MET ~ pTj)
  - ✓ Main background Z(→νν)+jets estimated with Z(→μμ)+jets





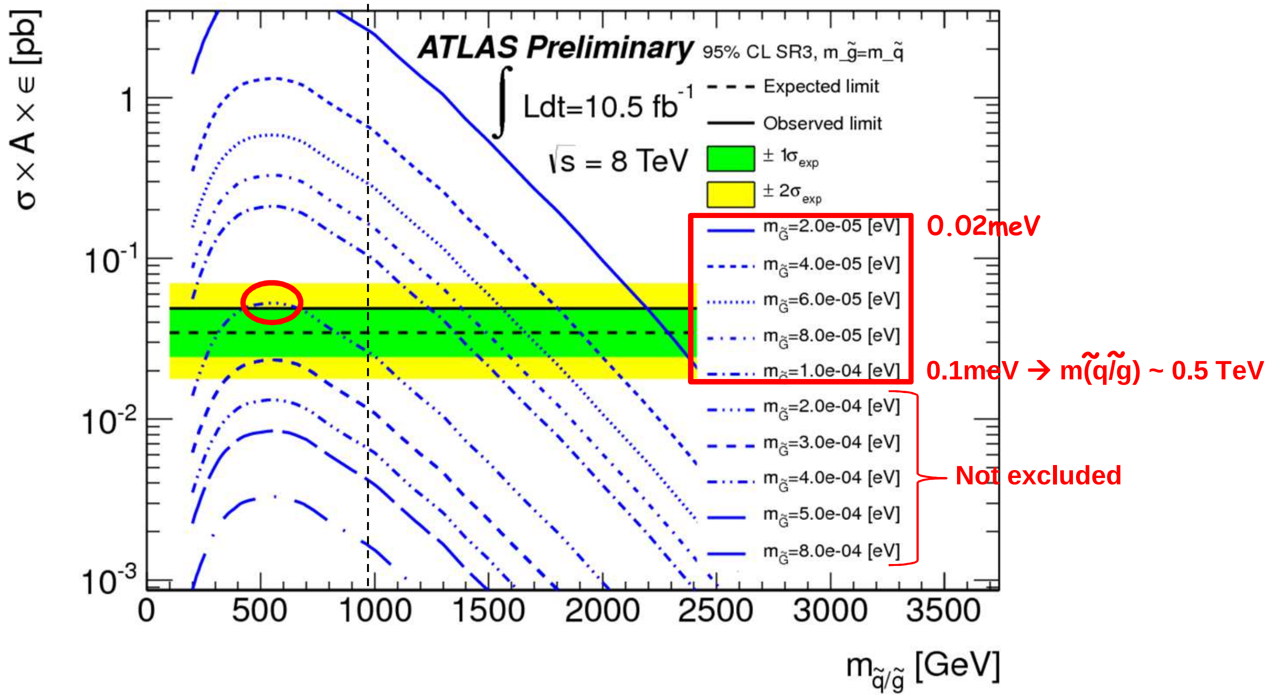


Some Left-over (4)

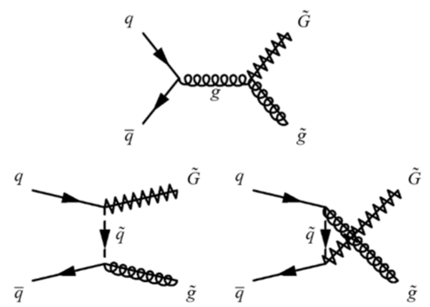
ATLAS-CONF-2012-147

❑ Monojet : sensitive to LSP ?

- In case of bino case no sensitivity (see before)
- Sensitive to gravitino mass !!!



Assume $\tilde{q} \to q\tilde{G}$, $\tilde{g} \to g\tilde{G}$ i.e. 1j+$\tilde{G}$



Summary of Part IIa

❑ Natural EWK Sector challenging

- MSSM Higgses need more attention
  - ✓ A discovery of Charged Higgs or other neutral Higgs will be a major discovery !
  - ➔ **Generally pushed neutral and charged Higgs > 130 GeV**

- EWKinos have low cross-sections → Need high luminosity ! Will be the sector that will benefit the most from HL-LHC
  - ✓ Bino N1 and Wino N2/C1 case can be covered in C1N2 (and C1C1)
  - ✓ Most natural case (Higgsinos) hard to cover apart in some GMSB models.
  - ✓ Nice by-products: slepton mass limits beyond LEP !
  - ✓ More realism can be brought by scanning M1, M2, mu (considering pMSSM)
  - ➔ **Can not really exclude (yet) natural SUSY spectrum with EWKino searches**

SPARE

Higgsino like

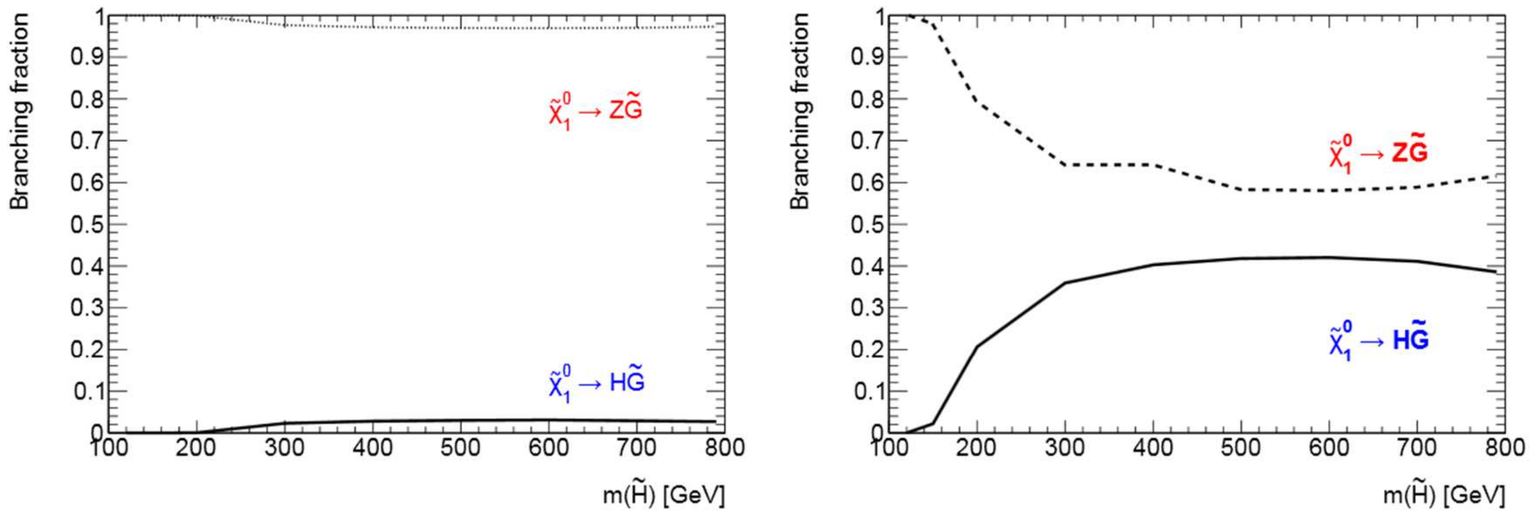


Figure 1: The branching fraction for $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ processes as function of μ for GGM grid models characterized by the following parameters: M_1 = 1 TeV, M_2 = 1 TeV, $m(\tilde{g})$ = 800 GeV, $\tan(\beta)$ = 1.5(left), $\tan(\beta)$ = 30(right).