DM@LHC 2014, Oxford

September 26th 2014

# Testing light Neutralino Dark Matter at the LHC

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UNIVERSITÉ LIBRE DE BRUXELLES

based on collaborations with J. Lindert, T. Ota, Y. Takanishi

# The main idea

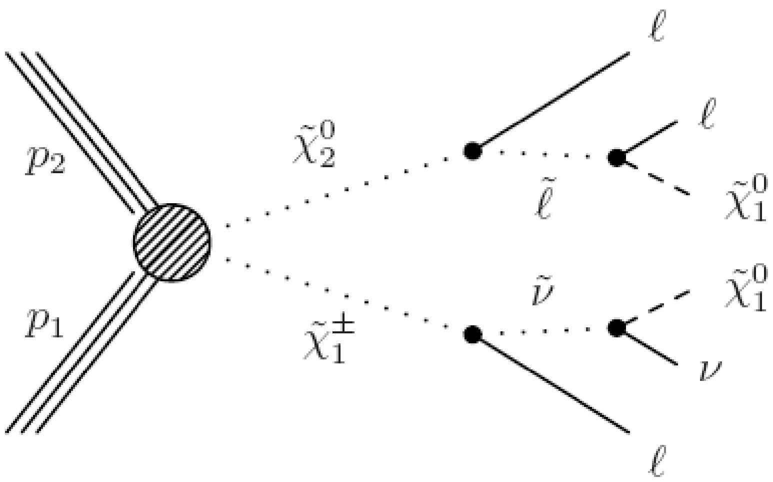
Assuming the supersymmetric Neutralino accounts for observed Dark Matter

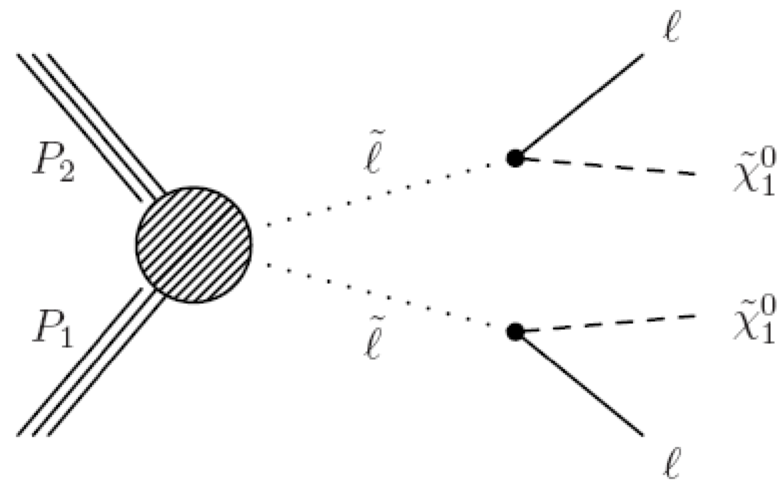
Relic density constraints set non-trivial requirements on the SUSY spectrum

Few parameters/particles involved in the relic density calculation
→simplified models can be defined

LHC experiments can indirectly test Neutralino Dark Matter!

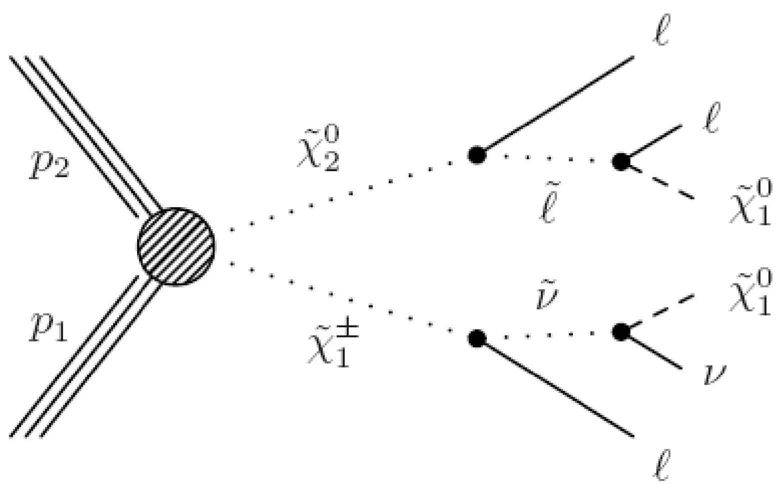
# Motivation

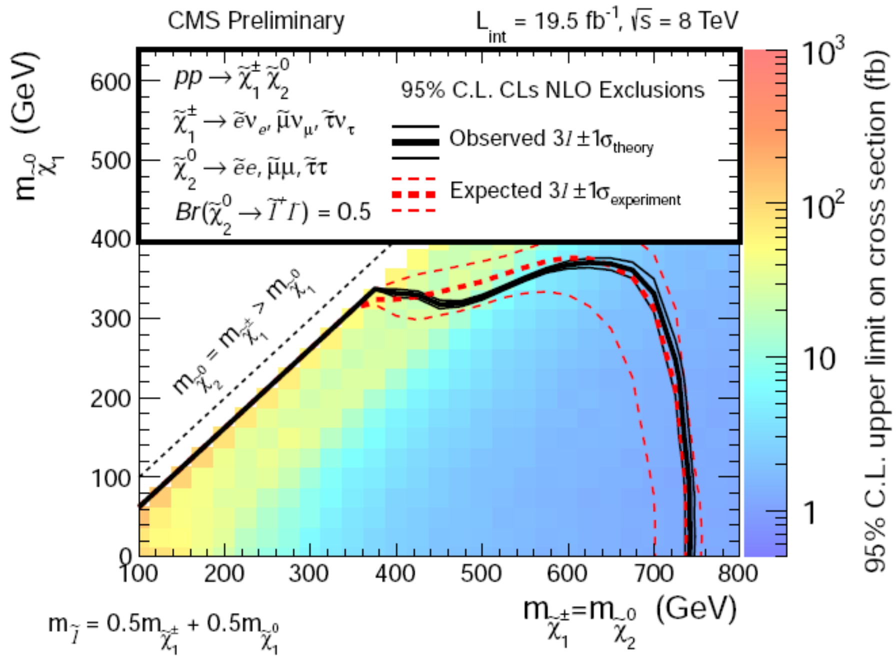



Direct bounds on EW-iteracting particles relatively weaker than those on coloured ones

But EW-searches at the LHC started to go considerably beyond the limits set by LEP!

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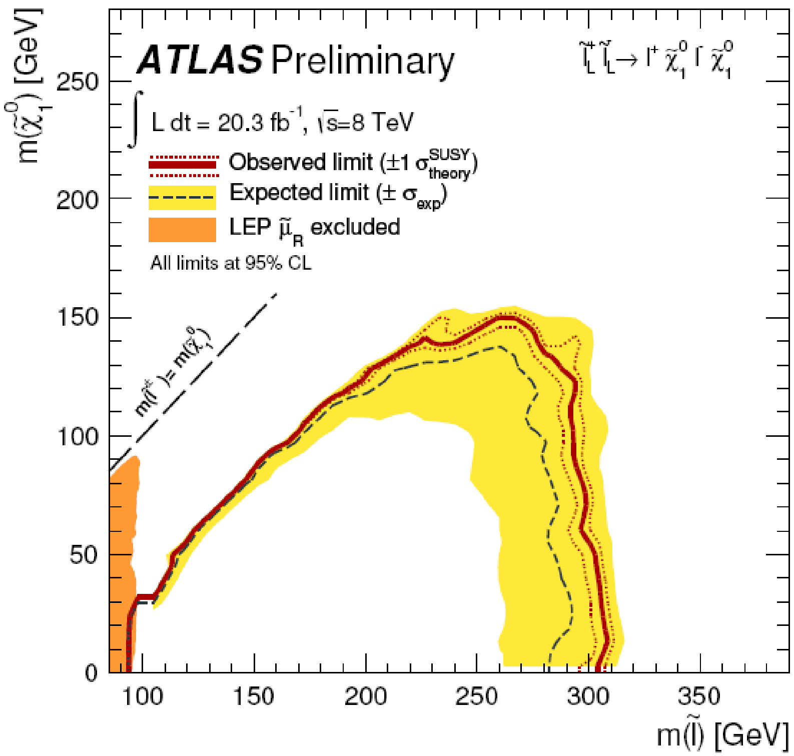
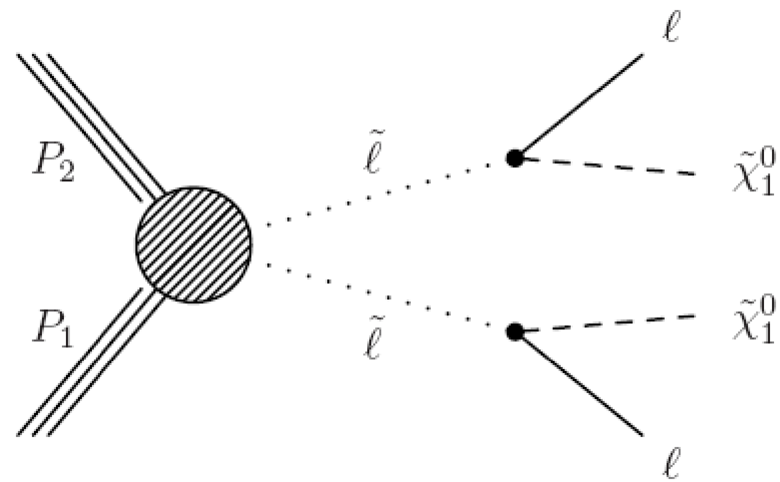


Direct bounds on EW-iteracting particles relatively weaker than those on coloured ones

But EW-searches at the LHC started to go considerably beyond the limits set by LEP!

The EW SUSY sector might be lighter than the strong sector but LHC can test it!

We discuss an example of the potential of EW searches at the LHC:

probing light Neutralino Dark Matter

Assumptions:

- Only MSSM superfields
- R-parity
- Dark Matter thermal relic, standard history of the universe
- Neutralino DM candidate, $\Omega_{\rm DM} h^2 \leq 0.124$

How light the neutralino is allowed to be after LHC searches at 8 TeV?

# Light Neutralino Dark Matter in the MSSM

MSSM neutralinos: $\left(\tilde{B}, \tilde{W}_3, \tilde{H}_d^0, \tilde{H}_u^0\right)$ MSSM charginos: $(\tilde{W}^{\pm}, \tilde{H}_u^{+}, \tilde{H}_d^{+})$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix} \qquad \mathcal{M}_{\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

Mass eigenstates: LEP chargino searches: $m_{\tilde{\chi}^{\pm}} > 103.5$ GeV

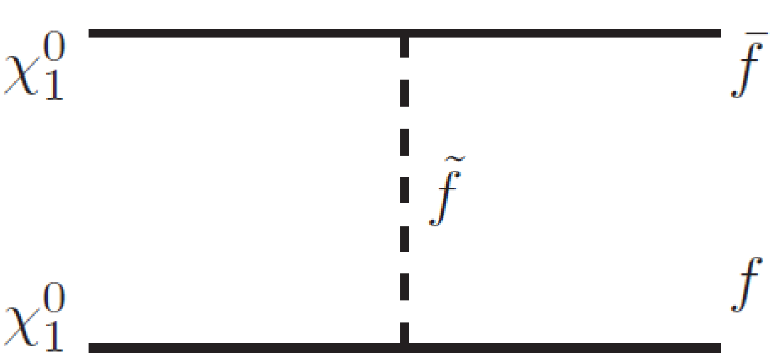
$$\widetilde{\chi}_i^0 = N_{i1}\widetilde{B} + N_{i2}\widetilde{W} + N_{i3}\widetilde{H}_d + N_{i4}\widetilde{H}_u \qquad \Downarrow \quad M_2,\ \mu \gtrsim 100 \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} \lesssim 30 \text{ GeV} \Rightarrow M_1 \ll M_2,\, \mu \iff \tilde{\chi}_1^0 \approx \tilde{B}$$

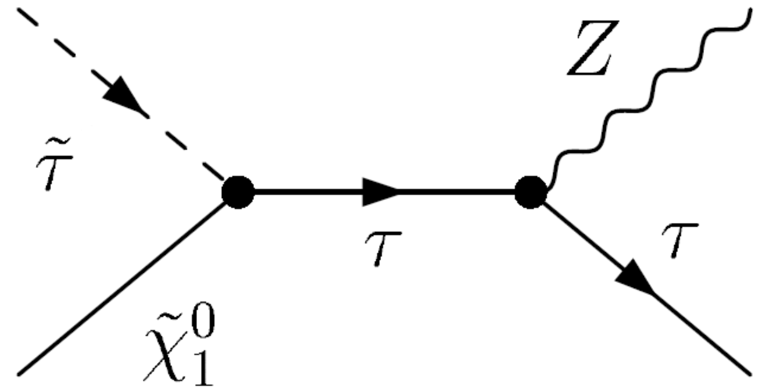
Relic density (WMAP, Planck): $\Omega_\chi h^2 \sim 0.1$

Efficient annihilation required

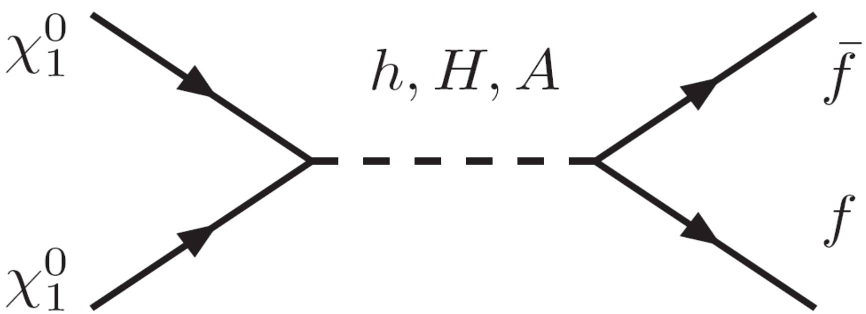
t-channel exchange (e.g. sfermions):



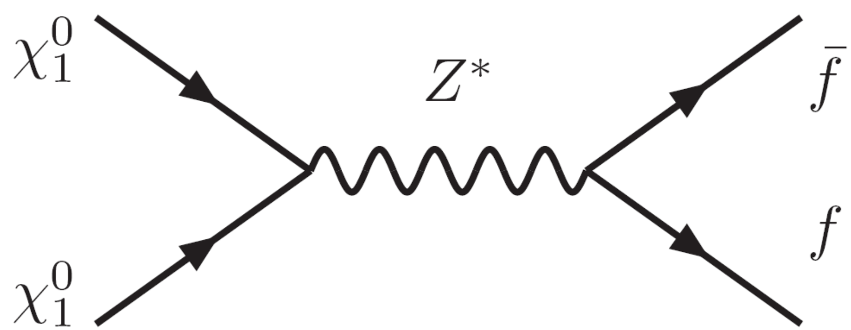

Coannihilations (e.g. stau):




Higgs mediation:

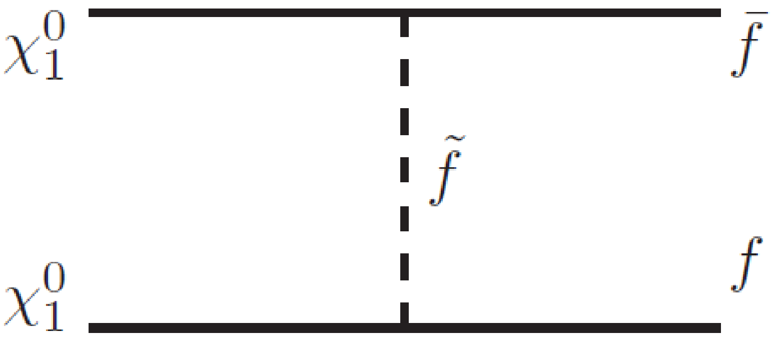



Z mediation:




⇒ different regions of the SUSY parameter space are selected

Sfermion mediated annihilation:




$$\propto \frac{m_{\tilde{\chi}_1^0} m_f}{m^2_{\tilde{f}}}$$

LEP limits: $e^+e^- \to \tilde{f}\tilde{f}^* \to f\bar{f}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

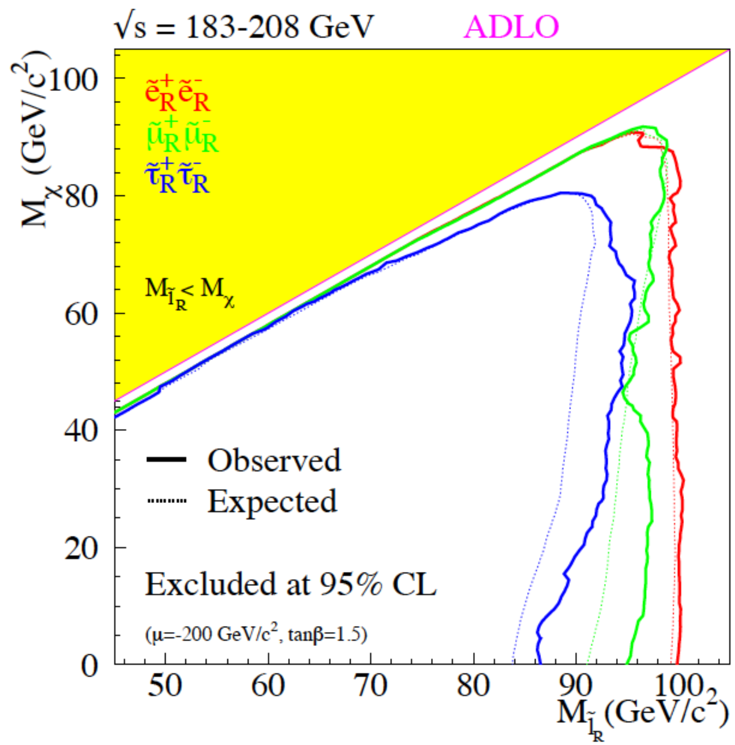
Can one evade it with compressed spectra?

If $m_{\tilde{\chi}_1^0} \lesssim 30$ GeV this is not possible because Z width bounds:

$$Z \to \tilde{f}\tilde{f}^* \Longrightarrow m_{\tilde{f}} \gtrsim 40\ \text{GeV}$$

Exception: light sbottom with tuned LR mixing Arbey Battaglia Mahmoudi ‘13

Challenged by LEP bounds, e.g.:

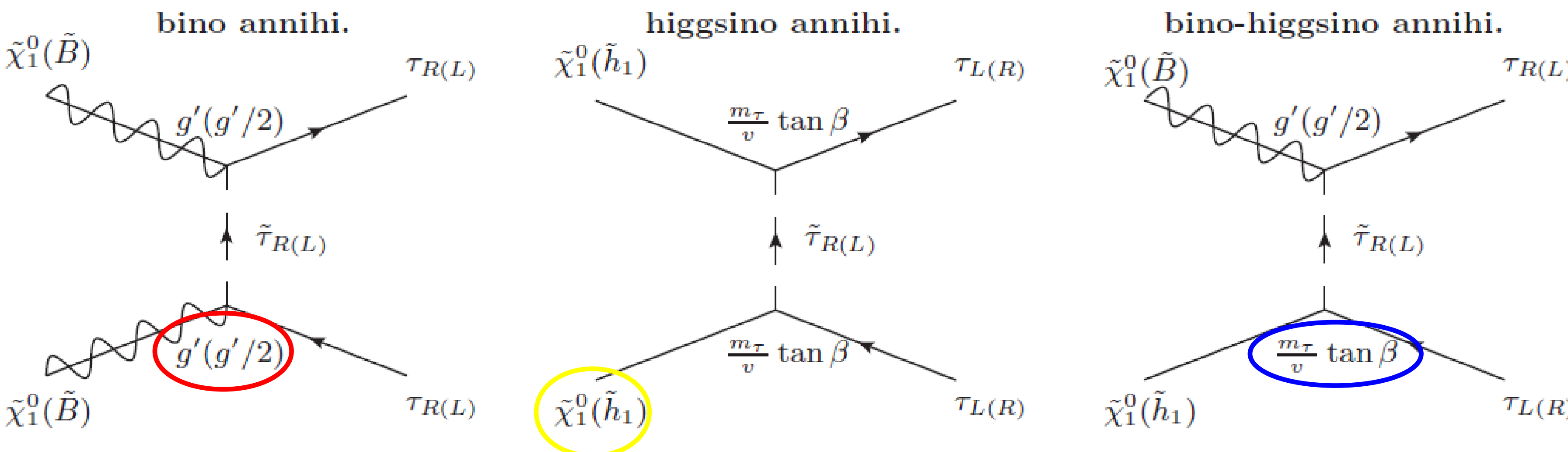


# Stau-mediated annihilation

Light neutralino DM possible in presence of a light stau

Albornoz Bélanger Boehm '11

Grothaus Lindner Takanishi '12




- RH stau much more efficient (cross-section 16x larger than LH one)
- Sizeable higgsino component: small μ
- Yukawa interactions: large tanβ

Relic density essentially controlled by 4 parameters only:

$$M_1,\ m_{\tilde{\tau}_R},\ \mu,\ \tan\beta$$

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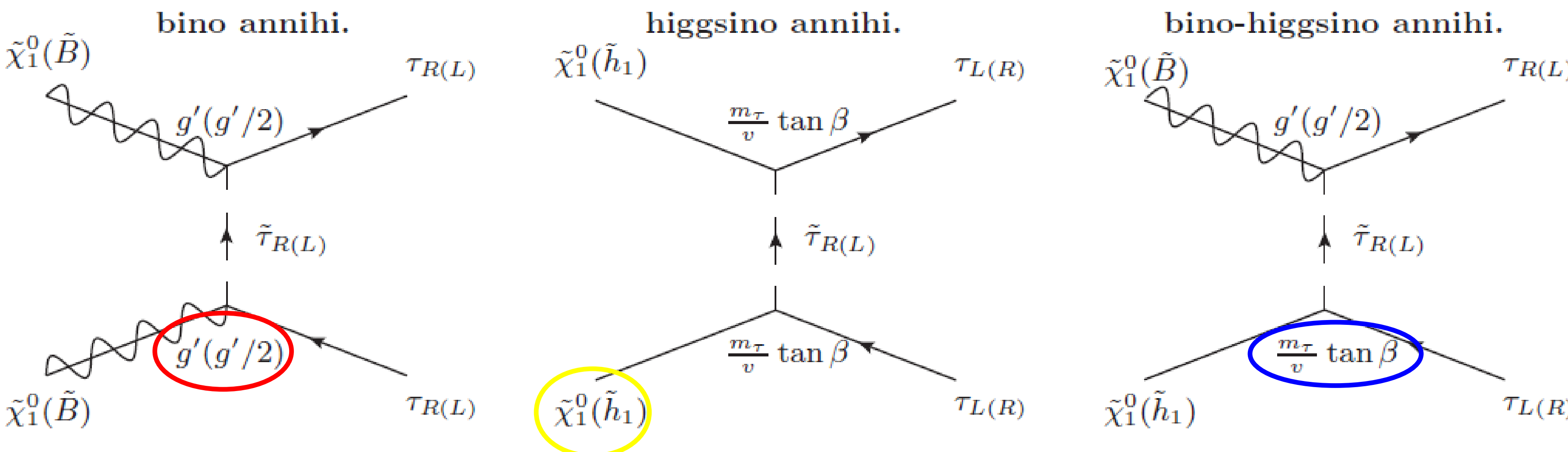



- RH stau much more efficient (cross-section 16x larger than LH one)
- Sizeable higgsino component: small μ
- Yukawa interactions: large tanβ

Light neutralino DM necessarily implies:

light stau, light higgsino-like neutralinos and charginos

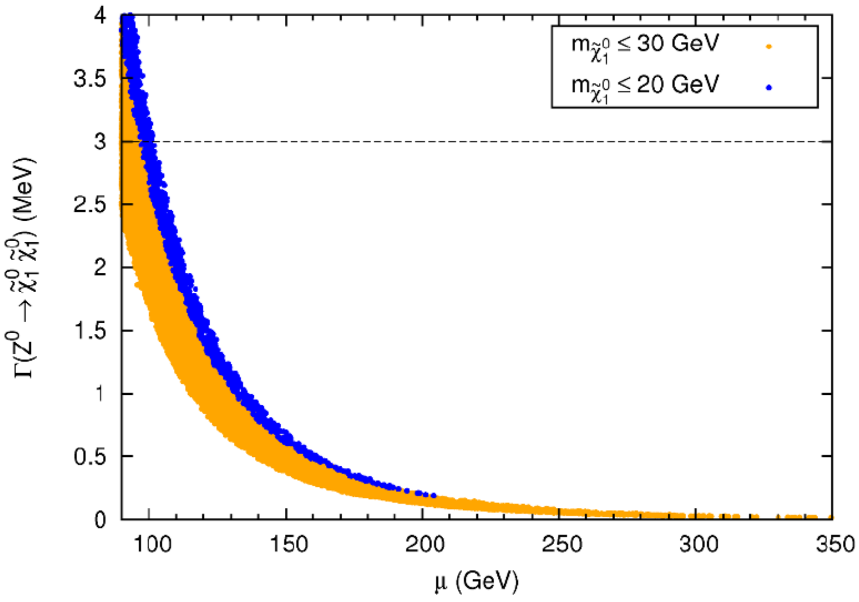
# Parameters scan and constraints

$$10\ \text{GeV} \le M_1 \le 45\ \text{GeV}, \quad 65\ \text{GeV} \le m_{\tilde{\tau}_R} \le 200\ \text{GeV},$$
$$90\ \text{GeV} \le \mu \le 400\ \text{GeV}, \quad 5 \le \tan\beta \le 60.$$
$$m_{\tilde{f}} = M_3 = m_A = 2\ \text{TeV}, \ M_2 = 500\ \text{GeV}, \ A_t = 1.5 \times m_{\tilde{f}}.$$

SuSpect, micrOMEGAs
Djouadi et al. '02
Belanger et al. '06

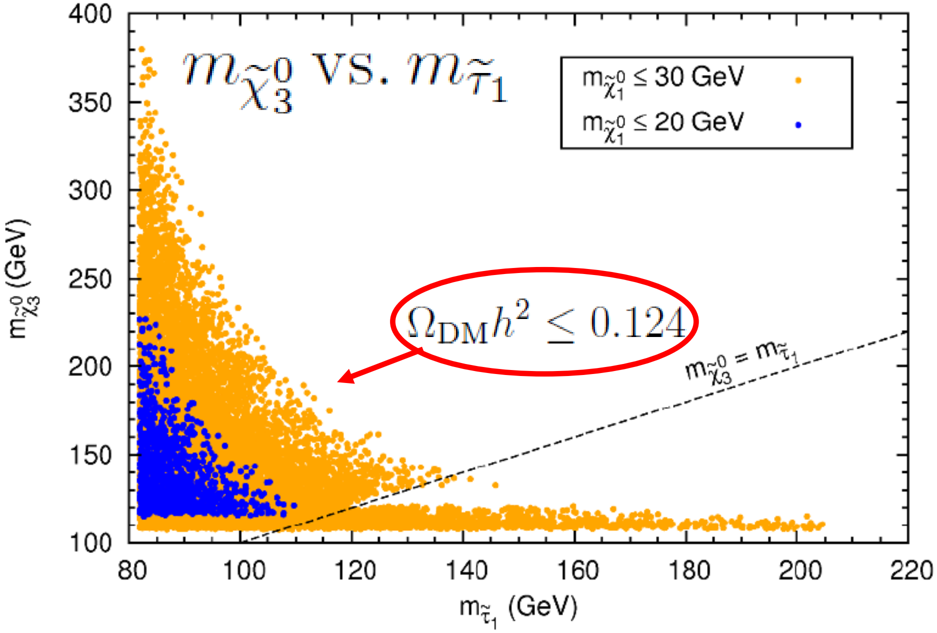
- $m_{\tilde{\chi}_1^0} \le 30\ \text{GeV}$
- **CMB**, Planck (3σ): $\Omega_{\rm DM} h^2 \le 0.124$
- **LEP2**: $m_{\tilde{\tau}_R} \ge 81.9\,\text{GeV}, \quad m_{\tilde{\chi}_1^\pm} \ge 103.5\,\text{GeV}$
- **LHC**: limits on charginos depend on smuon/selectron masses and can be evaded
- **Flavour**: $\Omega_{\rm DM}$ does not depend on heavy Higgs/squark masses, flavour observables do not constrain the DM parameter space
- **Z invisible width**, LEP: $\Delta\Gamma_Z^{\rm inv} < 3\ \text{MeV}$

LC Lindert Ota Takanishi '13




$$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = \frac{G_F}{\sqrt{2}} \frac{M_Z^3}{12\pi} \left(1 - \frac{4M_{\tilde{\chi}_1^0}^2}{M_Z^2}\right)^{\frac{3}{2}} \left|N_{13}^2 - N_{14}^2\right|^2$$

# Parameter space



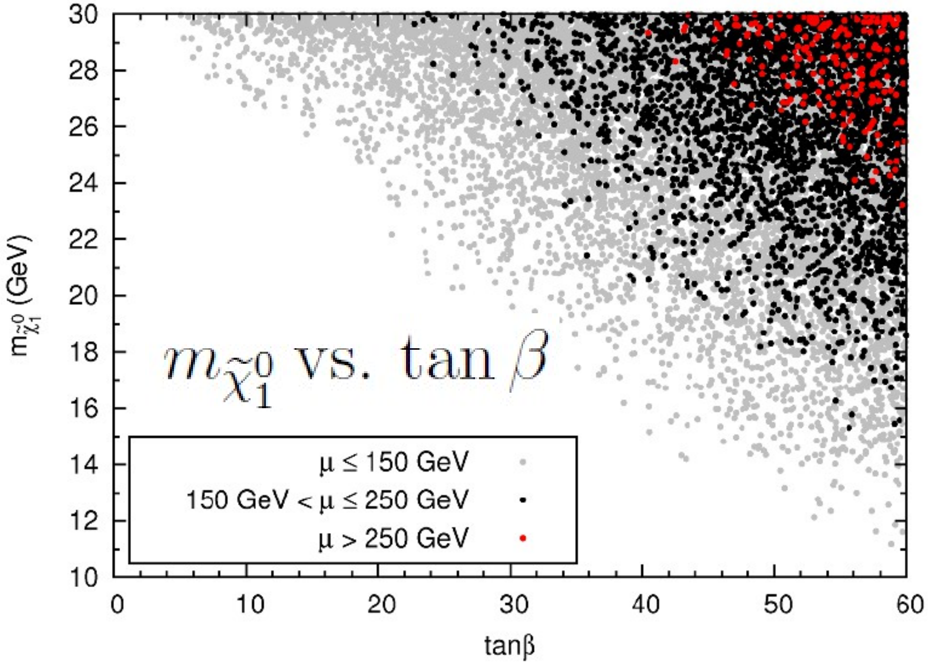

LC Lindert Ota Takanishi '13

$$m_{\tilde{\chi}^0_1} \gtrsim 11 \text{ GeV}$$

$$(\tan\beta \leq 60)$$

$$m_{\tilde{\tau}_1} \lesssim 210 \text{ GeV}$$

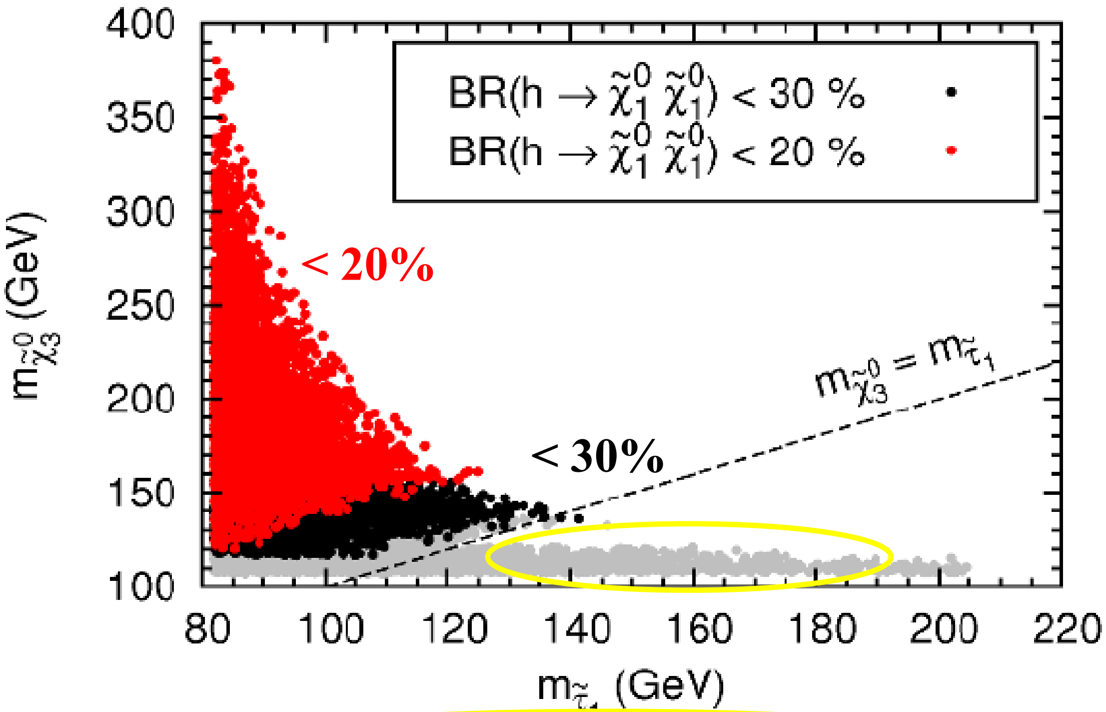
$$m_{\tilde{\chi}^\pm_1} \approx m_{\tilde{\chi}^0_2} \approx m_{\tilde{\chi}^0_3} \lesssim 380 \text{ GeV}$$



# Invisible Higgs decay

$$\Gamma(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = \frac{G_F M_W^2 m_h}{2\sqrt{2}\pi} \left(1 - 4m_{\tilde{\chi}_1^0}^2/m_h^2\right)^{3/2} \left|C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}\right|^2$$

$$C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = \left(N_{12} - \tan\theta_W\, N_{11}\right)\left(\sin\beta\, N_{14} - \cos\beta\, N_{13}\right)$$




$$m_{\tilde{\tau}_1} > m_{\tilde{\chi}_3^0} \;\Rightarrow\; \mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \gtrsim 30\%$$

Fits to Higgs data:

$$\mathrm{BR}_h^{\mathrm{inv}} < 16\% \quad (95\%\ \mathrm{CL})$$

Falkowski et al. '13

$$\mathrm{BR}_h^{\mathrm{inv}} < 19\% \quad (95\%\ \mathrm{CL})$$

Giardino et al. '13

$$\mathrm{BR}_{h^0}^{\mathrm{inv}} < 26\% \quad (95\%\ \mathrm{C.L.})$$

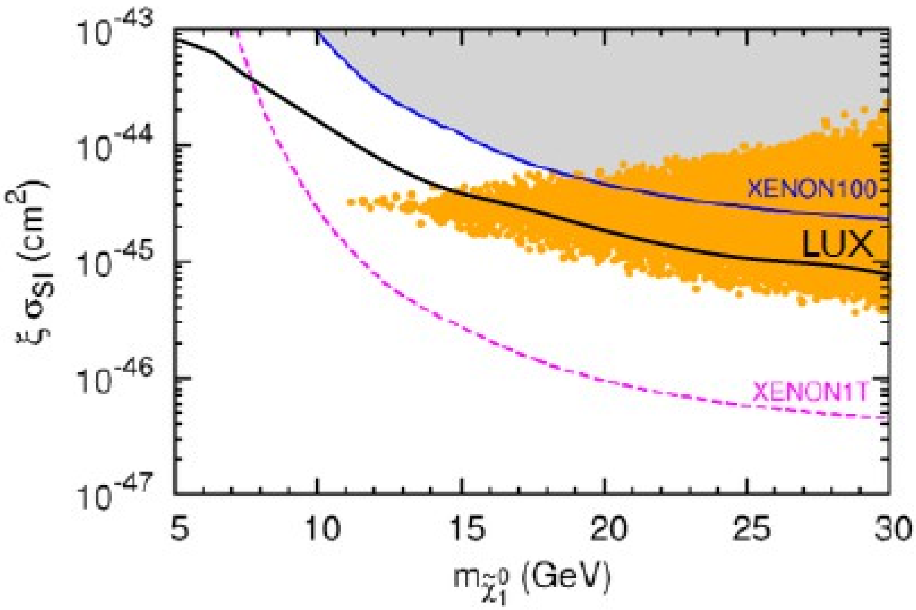
Bechtle et al. '13

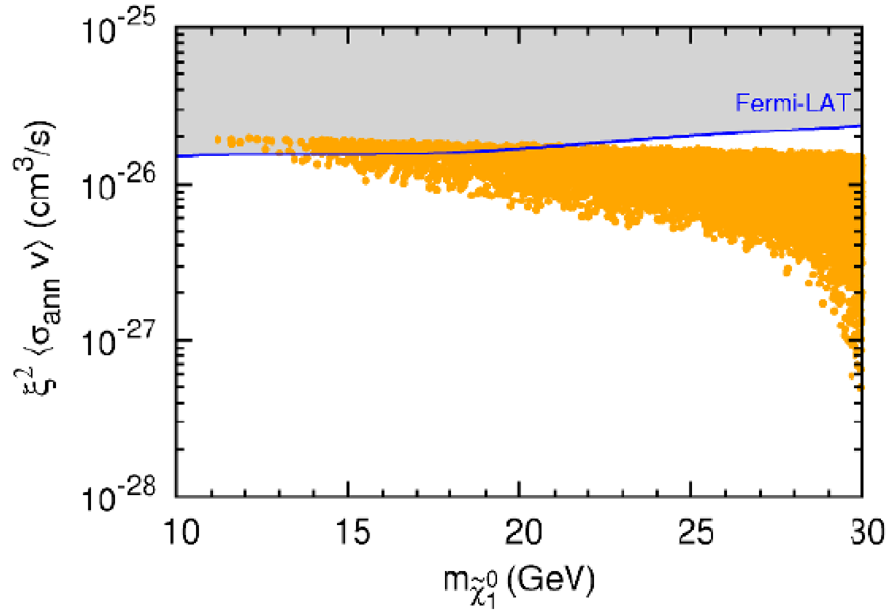
$$m_{\tilde{\tau}_1} > m_{\tilde{\chi}_{2,3}^0} > m_{\tilde{\chi}_1^0}$$

disfavoured!

Spin-independent scattering cross section

Annihilation cross-section




Th. prediction can be lowered by 2x by uncert. in light quark masses/form factors

Gamma rays from satellite galaxies

Heavy Higgs slow decoupling (possible additional ~3x suppression)

Relic density constr. imply that we have *at least* 4 states at O(100) GeV:

$$\widetilde{\tau}_1,\ \widetilde{\chi}_2^0,\ \widetilde{\chi}_3^0,\ \widetilde{\chi}_1^\pm$$

The rest of the spectrum *can* be decoupled. Still sizeable EW production:

$$pp \to \widetilde{\tau}_1^+\,\widetilde{\tau}_1^- + X, \quad pp \to \widetilde{\chi}_i^0\,\widetilde{\chi}_j^0 + X, \quad pp \to \widetilde{\chi}_i^0\,\widetilde{\chi}_1^\pm + X, \quad pp \to \widetilde{\chi}_1^+\,\widetilde{\chi}_1^- + X$$

Drell-Yan, up to O(1) pb at LHC8

Decays:

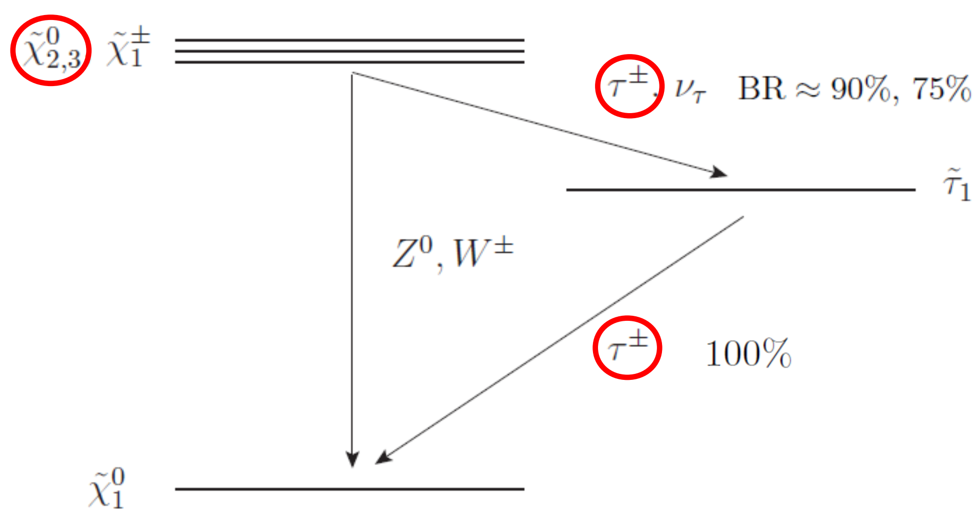
$$m_{\tilde\chi_1^\pm} \simeq m_{\tilde\chi_{2,3}^0} > m_{\tilde\tau_1} > m_{\tilde\chi_1^0}$$

⇩

$$pp \to \widetilde{\chi}_{2,3}^0\,\widetilde{\chi}_{2,3}^0 \to 4\tau + \not{E}_T$$

$$pp \to \widetilde{\chi}_{2,3}^0\,\widetilde{\chi}_1^\pm \to 3\tau + \not{E}_T$$

multi-tau signals!



**ATLAS NOTE**

ATLAS-CONF-2013-028

March 10, 2013

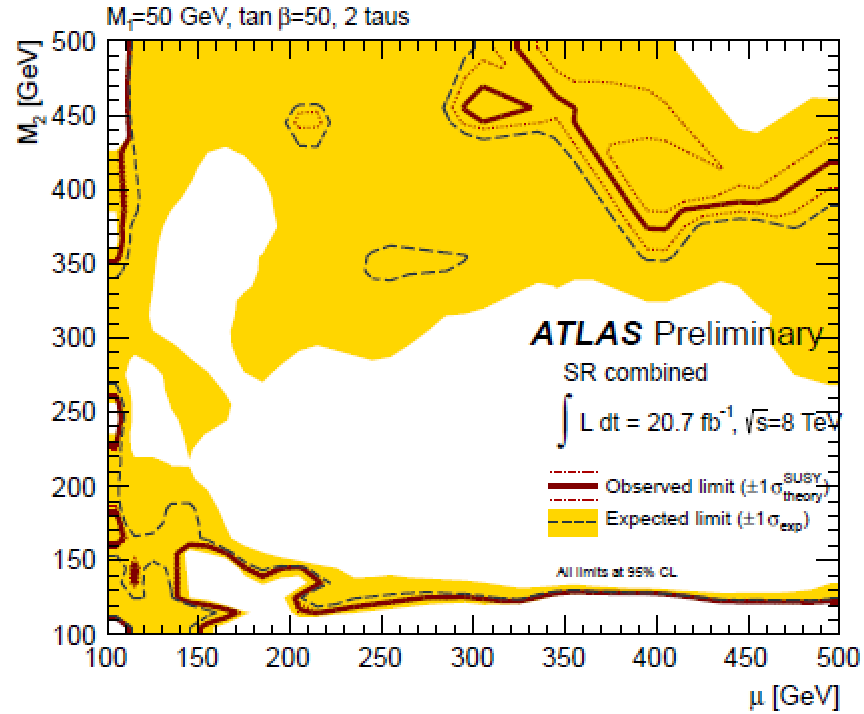
**Search for electroweak production of supersymmetric particles in final states with at least two hadronically decaying taus and missing transverse momentum with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV**

The ATLAS Collaboration

ATLAS-CONF-2013-028

| Signal region | requirements |
|---|---|
| OS $m_{T2}$ | at least 1 OS tau pair<br>jet veto<br>$Z$-veto<br>$E_T^{miss} > 40$ GeV<br>$m_{T2} > 90$ GeV |
| OS $m_{T2}$-nobjet | at least 1 OS tau pair<br>b-jet veto<br>$Z$-veto<br>$E_T^{miss} > 40$ GeV<br>$m_{T2} > 100$ GeV |

Table 1: Definition of the signal regions.




| SM process | SR OS $m_{T2}$ | SR OS $m_{T2}$ -nobjet |
|---|---|---|
| top | $0.2 \pm 0.5 \pm 0.1$ | $1.6 \pm 0.8 \pm 1.2$ |
| $Z$+jets | $0.28 \pm 0.26 \pm 0.23$ | $0.4 \pm 0.3 \pm 0.3$ |
| diboson | $2.2 \pm 0.5 \pm 0.5$ | $2.5 \pm 0.5 \pm 0.9$ |
| multi-jet & $W$+jets | $8.4 \pm 2.6 \pm 1.4$ | $12 \pm 3 \pm 3$ |
| SM total | $11.0 \pm 2.7 \pm 1.5$ | $17 \pm 4 \pm 3$ |
| data | 6 | 14 |

$$m_{\tilde{\tau}_1} = 95\,\text{GeV}, \quad m_{\tilde{\chi}_1^0} = 50\,\text{GeV}$$

$\Rightarrow$ $S^{95}_{\rm SR1} < 5.6 \quad S^{95}_{\rm SR2} < 10.4$

# Simulation and recasting

Herwig++ (event samples)

Prospino 2 (NLO K-factors)

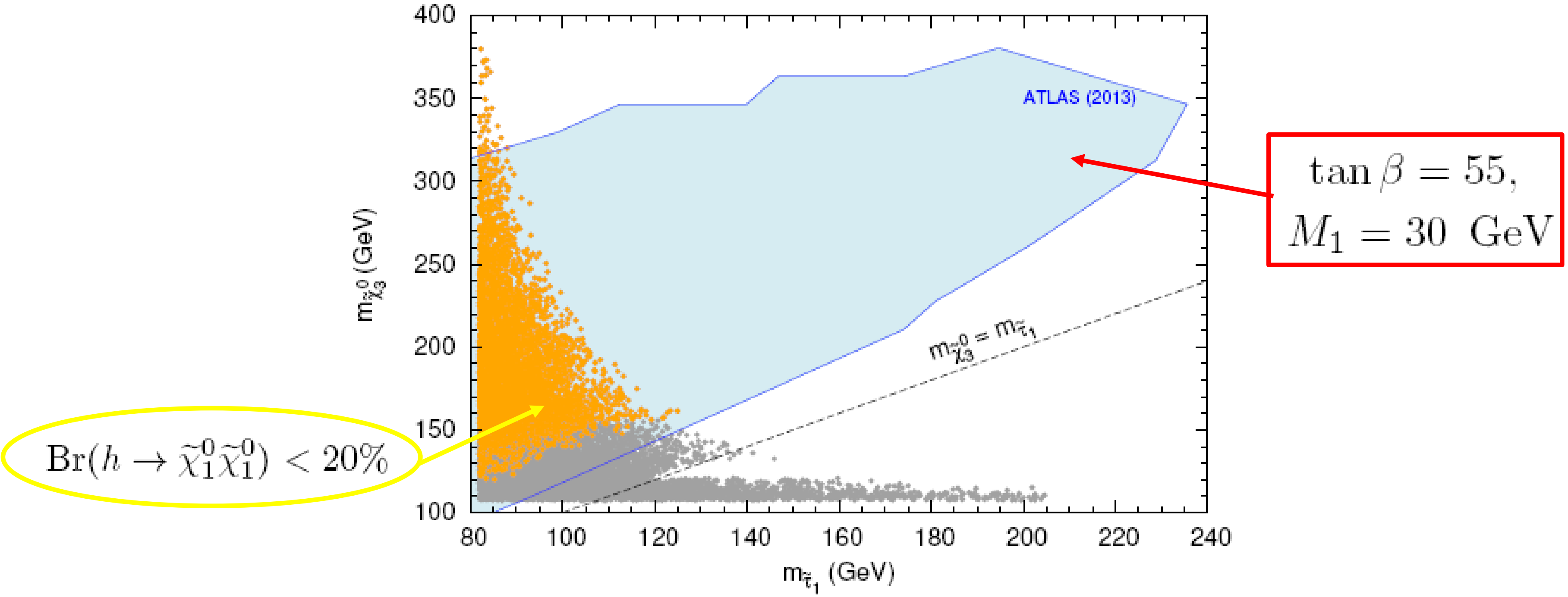
Delphes 3 (fast detector simul.)

Cuts of two Atlas SR applied

95% CL limits on the number of events:

$$S^{95}_{\rm SR1} < 5.6 \quad S^{95}_{\rm SR2} < 10.4$$

Interpretation on our parameter space: LC Lindert Ota Takanishi '13



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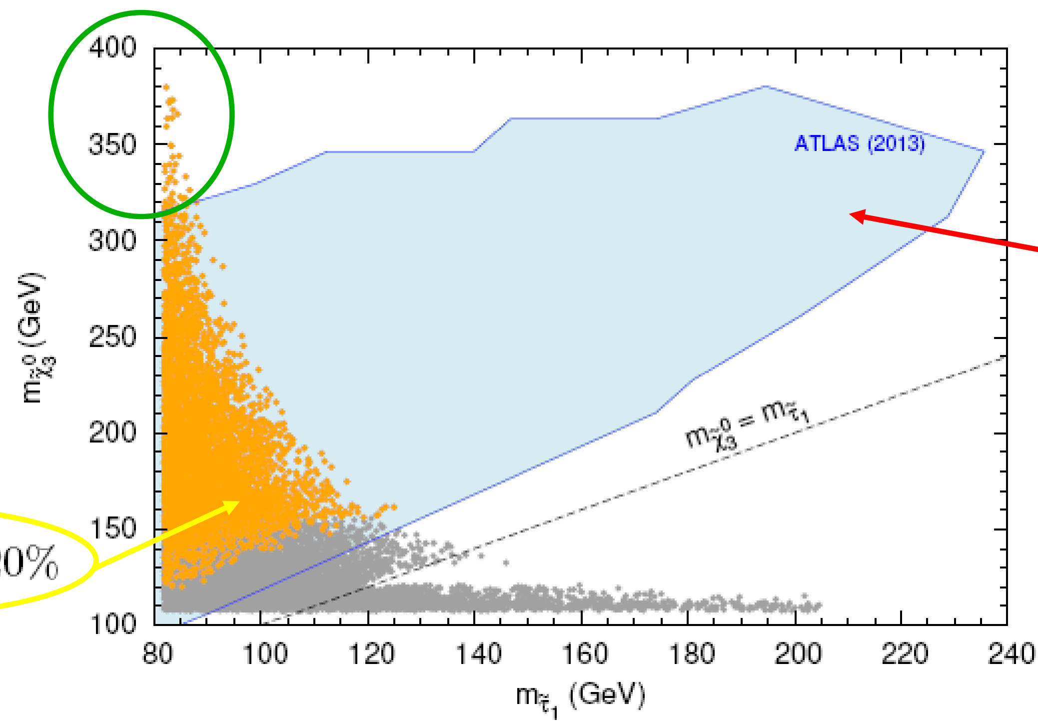


$\tan\beta = 55,$
$M_1 = 30\ \text{GeV}$

$\text{Br}(h \to \tilde\chi^0_1 \tilde\chi^0_1) < 20\%$

# Results

Herwig++ (event samples)

Prospino 2 (NLO K-factors)

Delphes 3 (fast detector simul.)

Cuts of two Atlas SR applied

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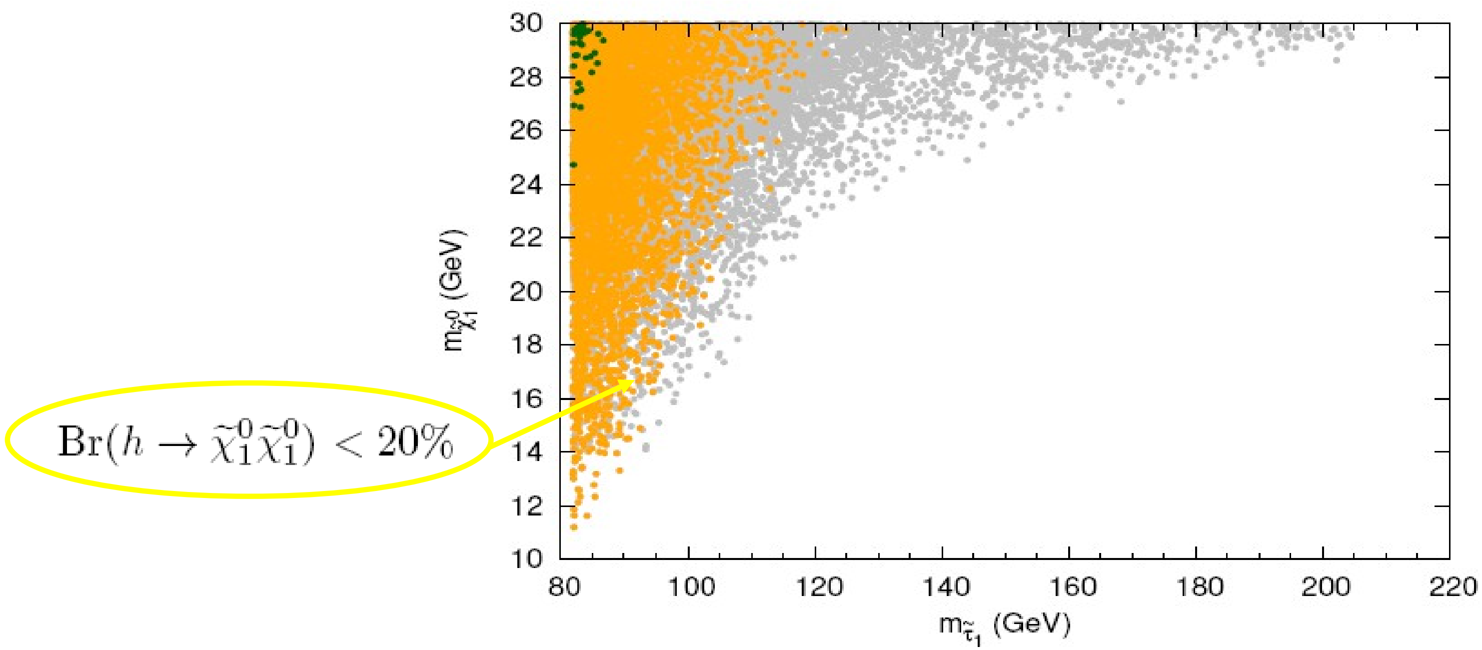
Interpretation on the stau-neutralino mass plane:



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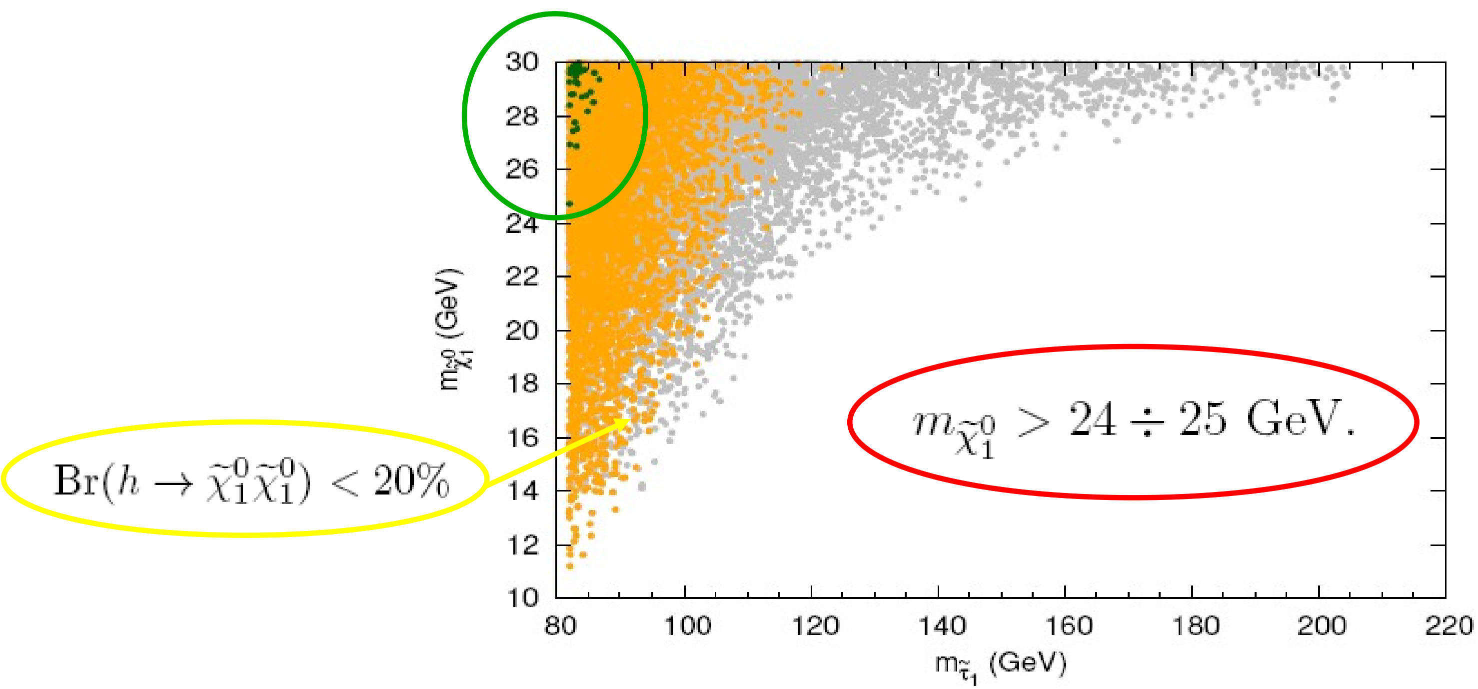
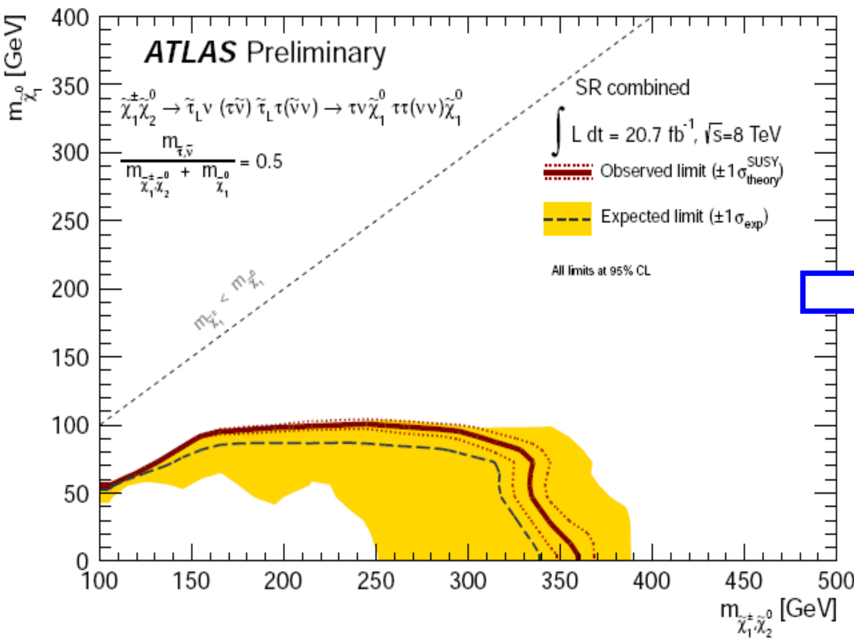


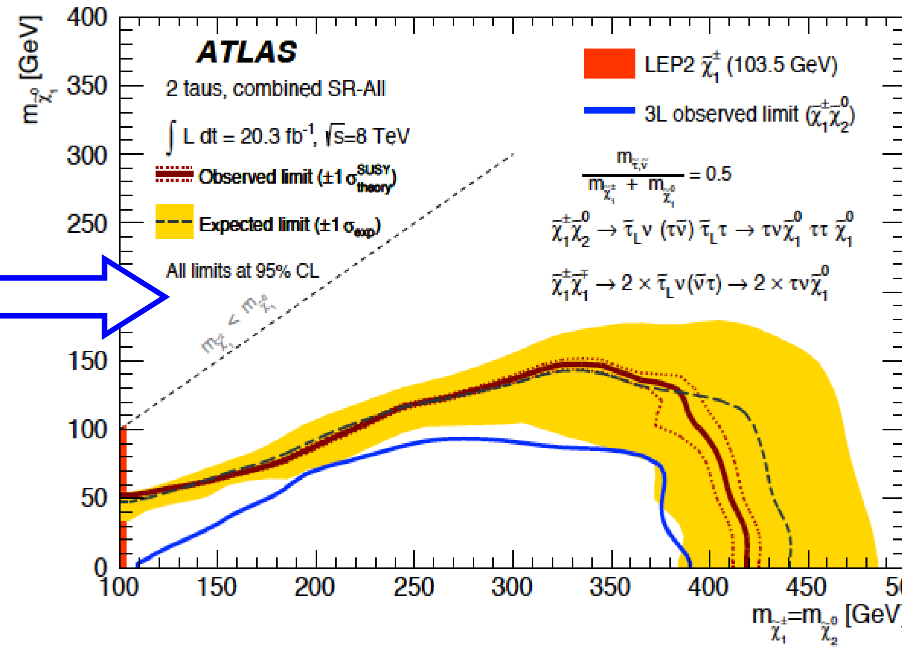
# Published analysis: arXiv:1407.0350

**Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in $pp$ collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector**

ATLAS-CONF-2013-028



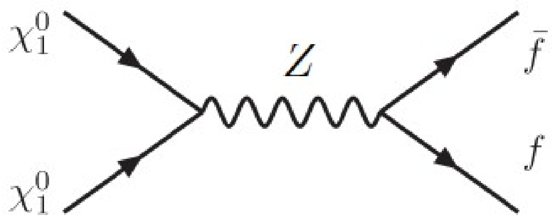

arXiv:1407.0350

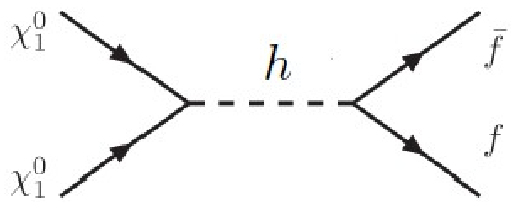


 LC Lindert Ota Takanishi, to appear

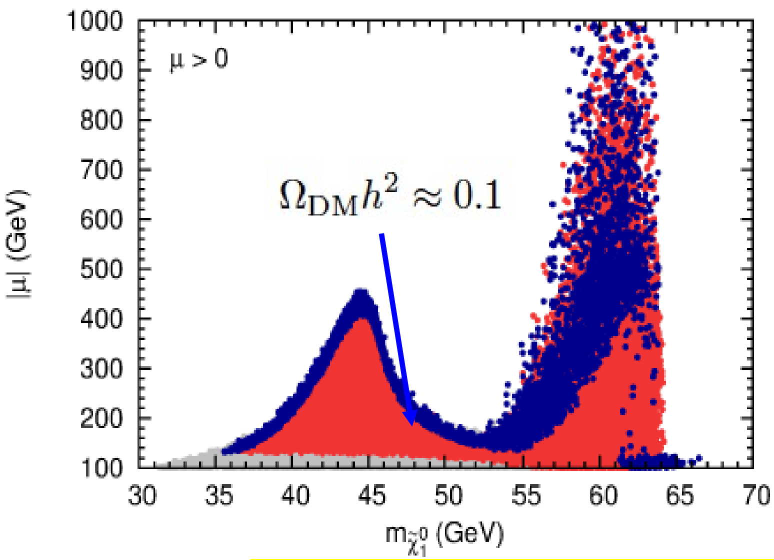
What if there are no scalars below few hundreds GeV?

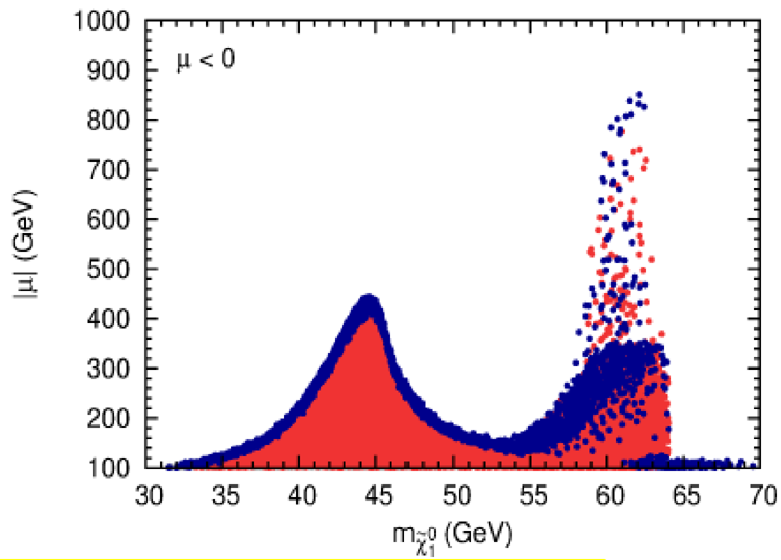
Dark Matter might hide close to the Z or h “resonances”




Only higgsino/gaugino parameters are involved: $M_1$, $M_2$, $\mu$, $\tan\beta$

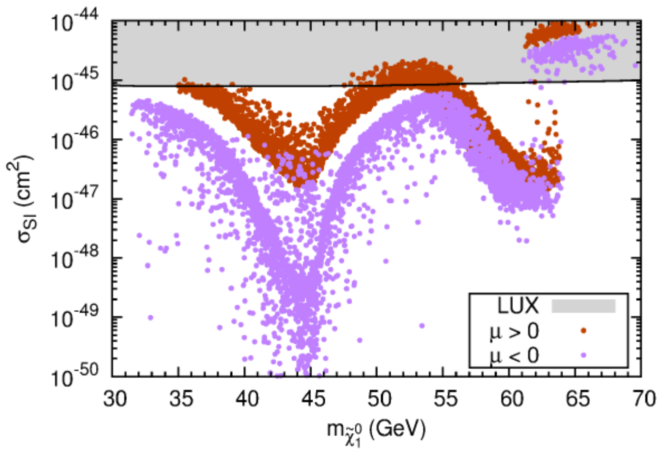


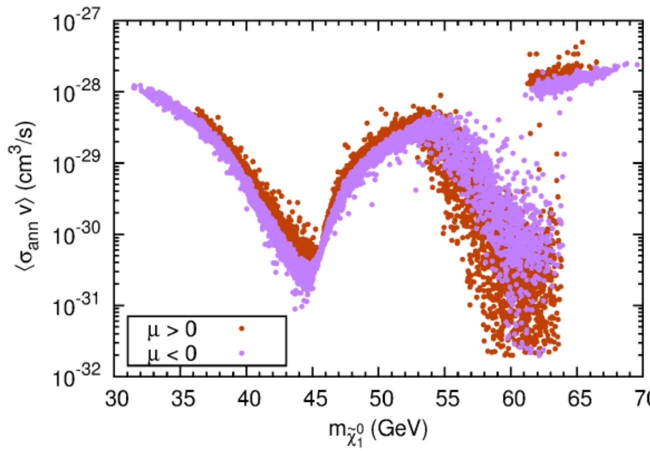




⇨ Relic density gives an upper bound on the Higgsino mass

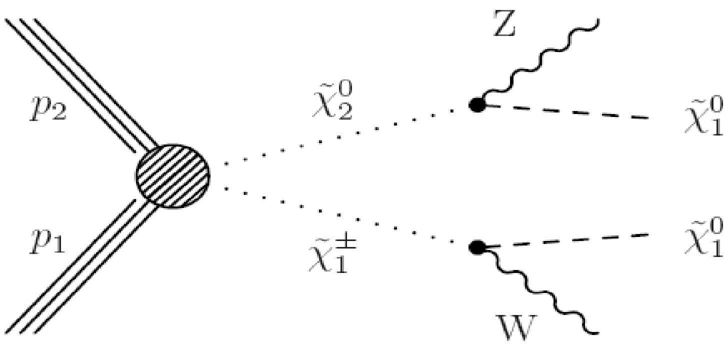
LC Lindert Ota Takanishi, to appear

Close to the resonances, the scenario might be problematic for direct/indirect DM searches:

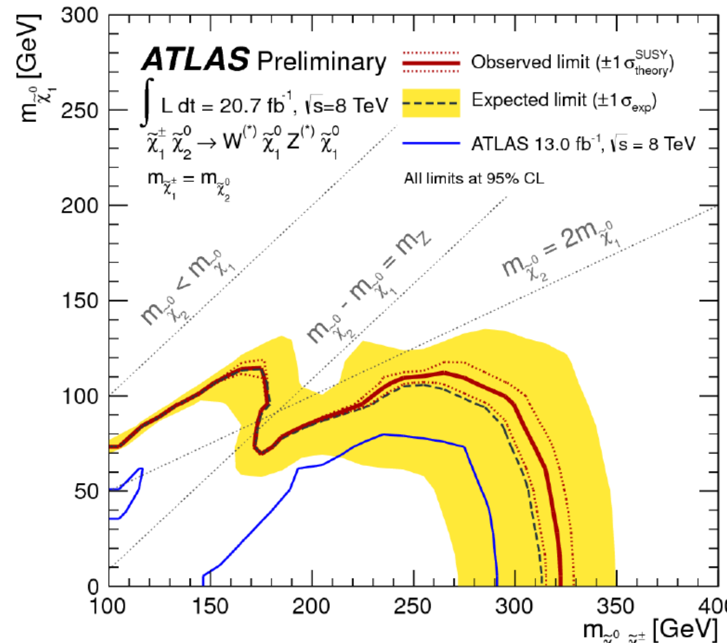



Again, LHC searches can test it!

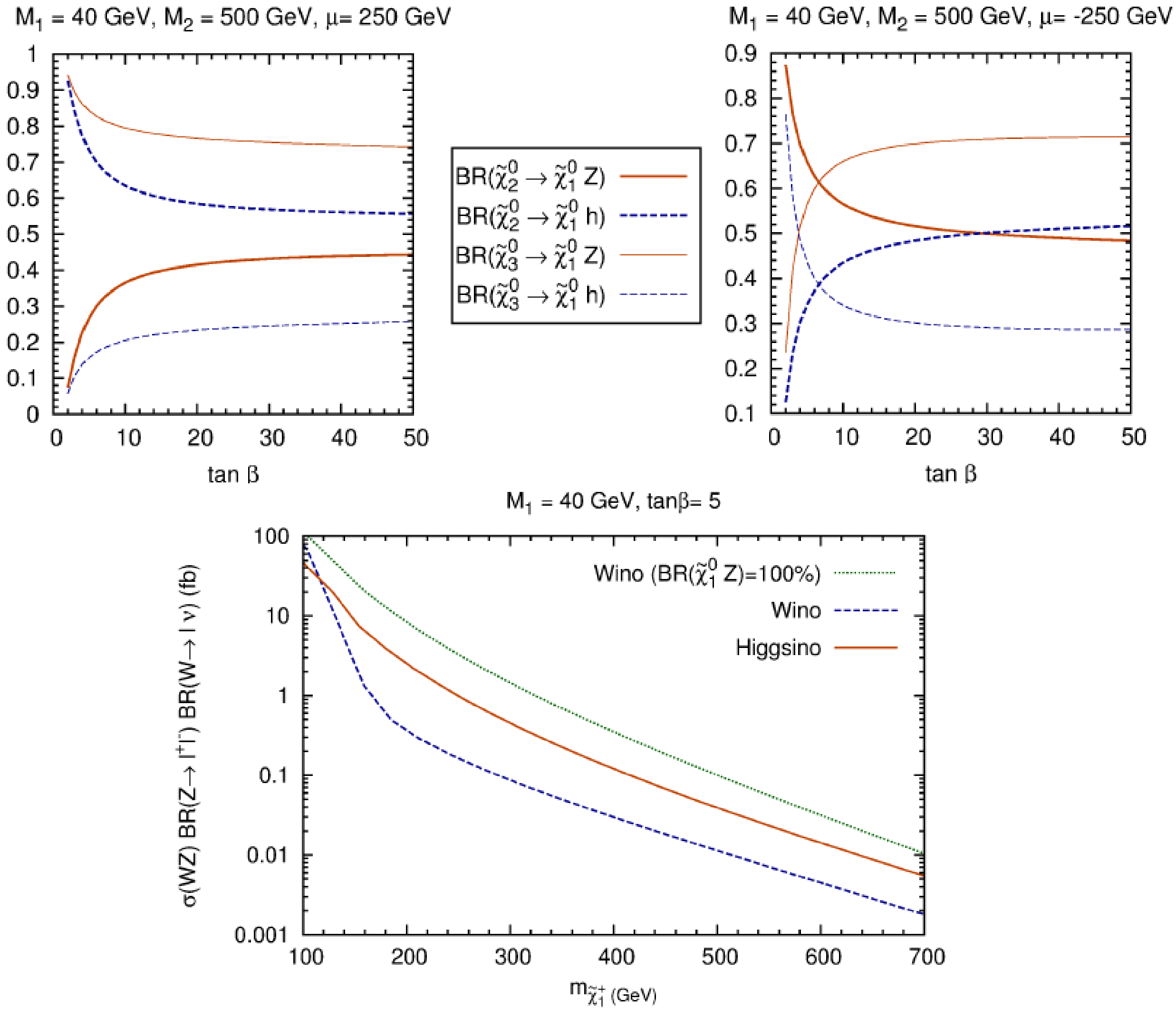



3 leptons + missing $E_T$



LC Lindert Ota Takanishi, to appear

Experiments interpret the search in terms of Wino production and $\mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)=100\%$



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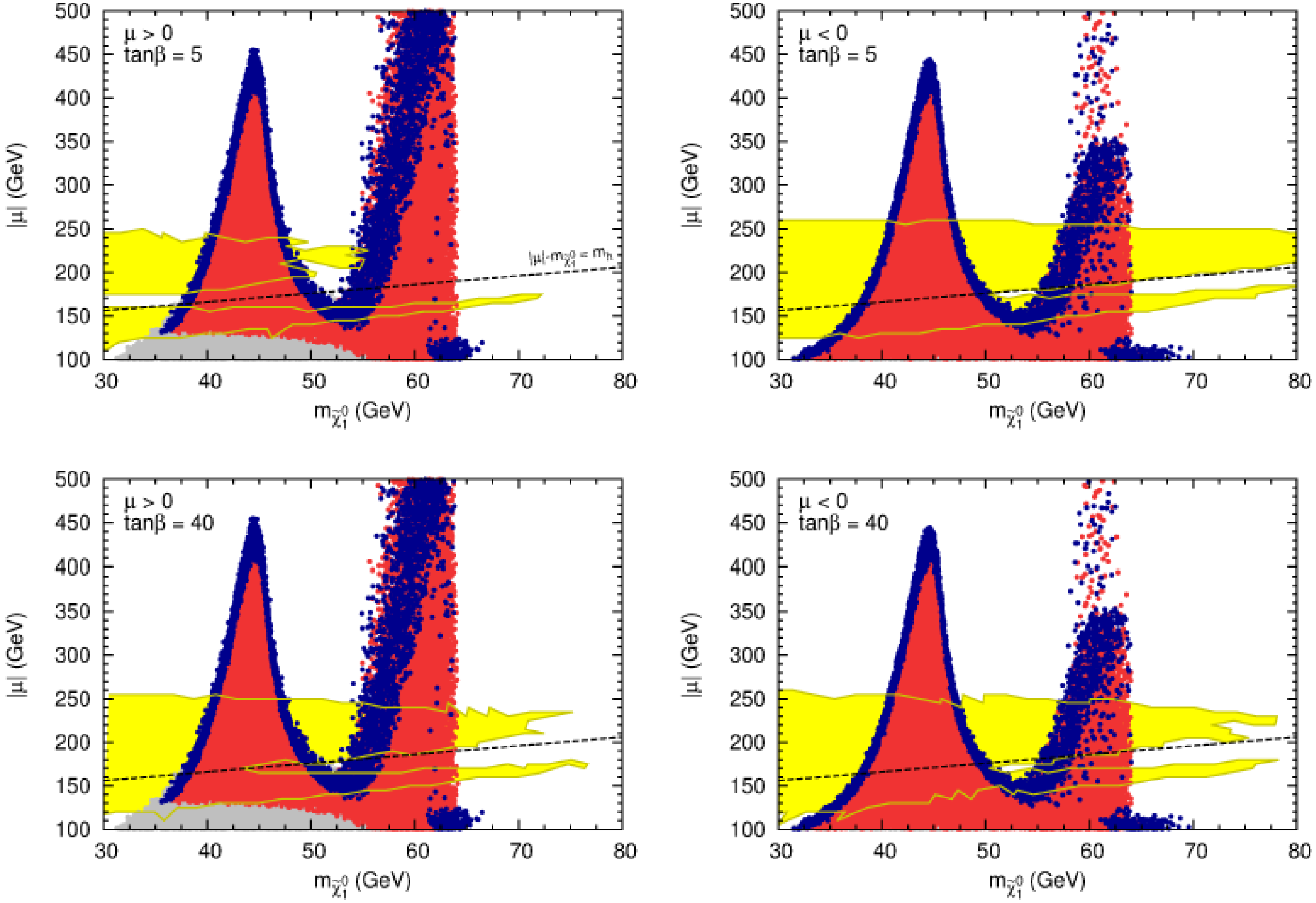
Experiments interpret the search in terms of Wino production and $BR(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)=100\%$

Again, we have to recast the exclusion. Preliminary results (using Checkmate):

Drees et al. '13



# Conclusions

Neutralino Dark Matter lighter than ~ 30 GeV typically requires light staus and higgsinos (relic density constraints)

Few parameters involved: manageable simplified model

Generic prediction: multi-tau + missing energy signal at the LHC

Reinterpretation of an ATLAS search sets strong constraint on light Neutralino Dark Matter (in combination with Higgs -> invisible)

Limit stronger than direct/indirect DM searches

(even in the case only neutralinos and charginos are light)

# Negative μ

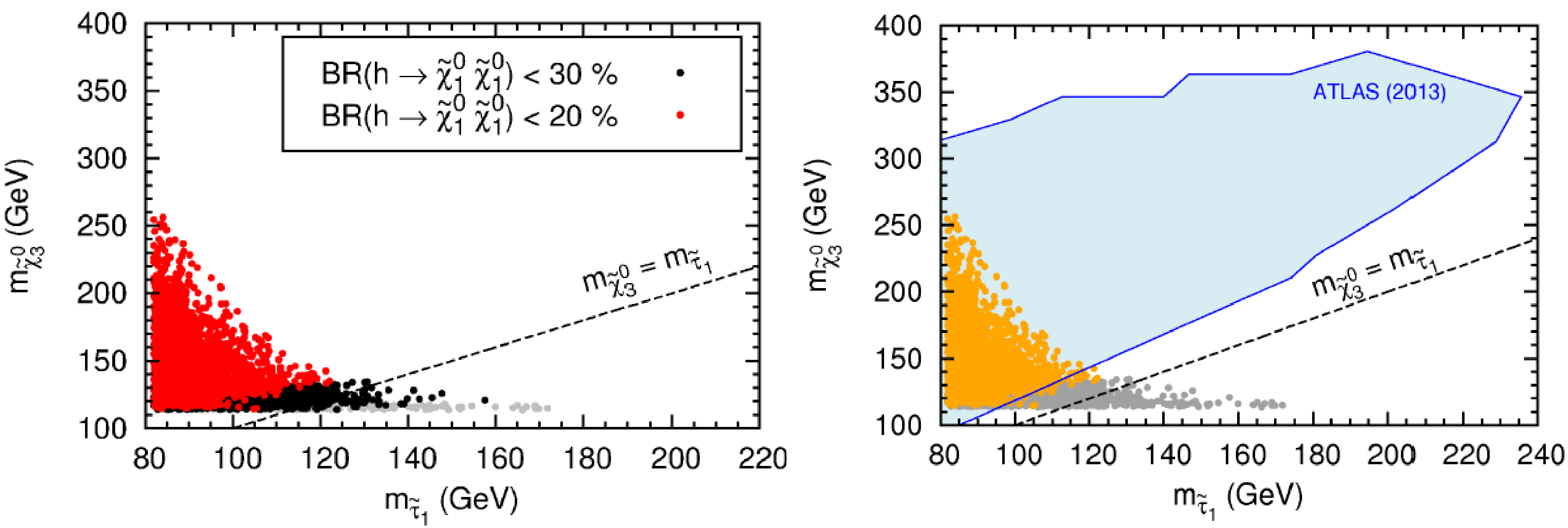
Flipping the sign of μ:

LC Lindert Ota Takanishi '14

Destructive interference between two annihilation modes: $\tilde{B}\tilde{B}$ and $\tilde{B}\tilde{H}_d$

Partial cancellation in $\tilde{\chi}_1^0\tilde{\chi}_1^0 h \implies$ lower $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$

$$N_{14} = -\frac{M_Z s_W}{\mu}\left[c_\beta + s_\beta \frac{M_1}{\mu}\right]$$

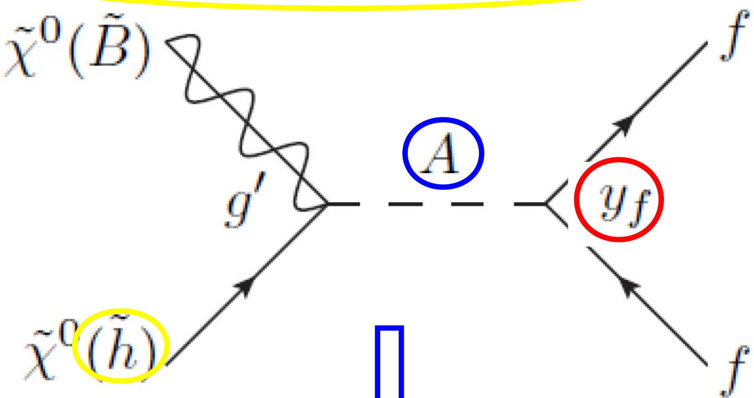



Bound from the invisible decay milder, but DM heavier because annihilation less efficient

⇒ limit on the neutralino mass similar to the case μ>0

# Annihilation mechanisms: Higgs exchange

- Higgs mediated annihilation:




$$\propto \frac{m^2_{\tilde{\chi}^0_1}}{m^2_A} \frac{m_f}{v} (N_{11} N_{13,14}) \tan\beta$$

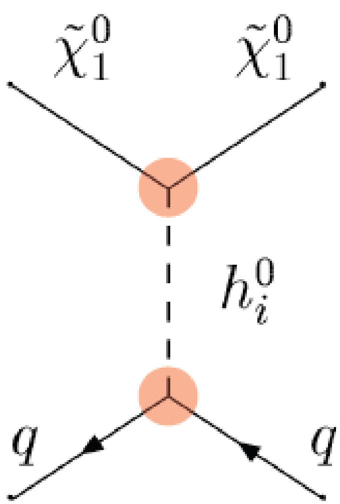
Drees Nojiri '92

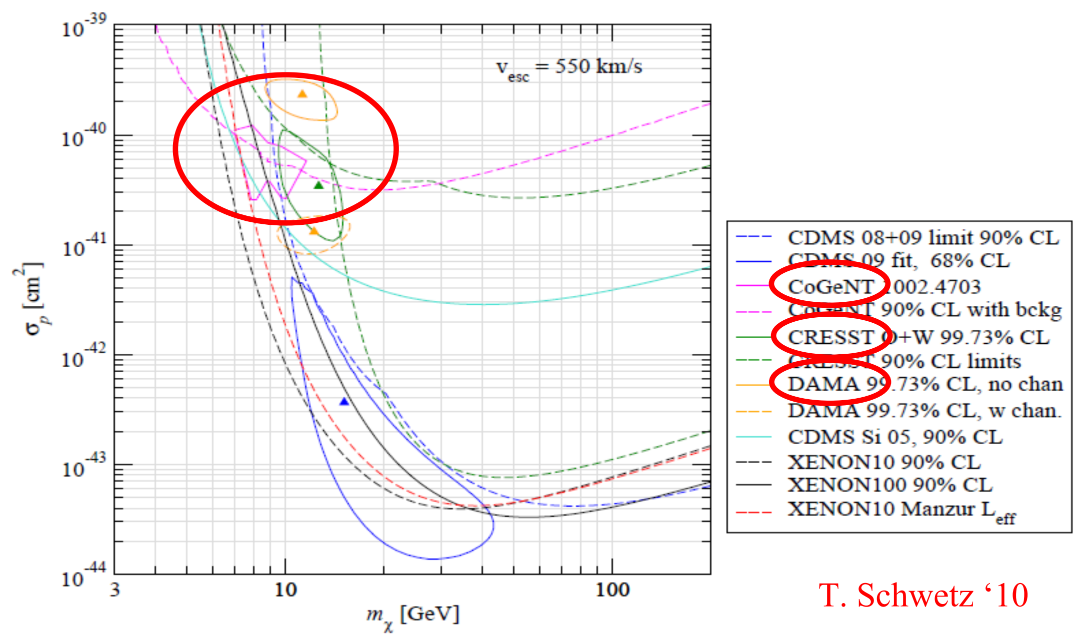
$$\text{Small } m_{\tilde{\chi}^0_1} \Longleftrightarrow \text{large } \tan\beta, \text{ small } m_A \text{ (and } \mu)$$

$$m_A \approx 100 \div 120\,\text{GeV}$$

Bottino et al. '02- '10

Large scattering cross-section with nuclei:

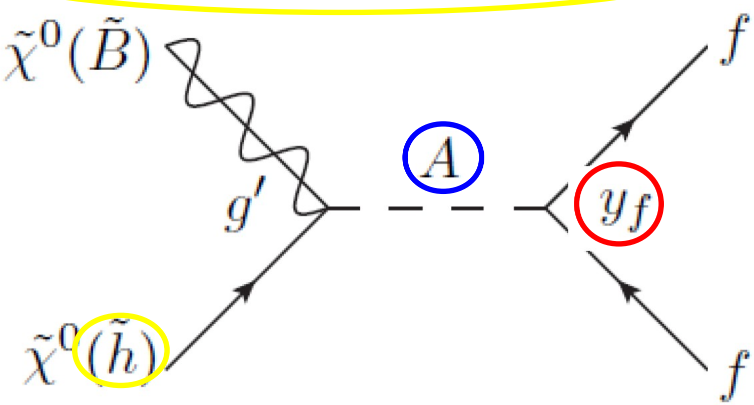



T. Schwetz '10

# Annihilation mechanisms: Higgs exchange

- Higgs mediated annihilation:




$$\propto \frac{m^2_{\tilde{\chi}^0_1}}{m^2_A} \frac{m_f}{v} (N_{11} N_{13,14}) \tan\beta$$

Drees Nojiri '92

$$\text{Small } m_{\tilde{\chi}^0_1} \Longleftrightarrow \text{large } \tan\beta, \text{ small } m_A \text{ (and } \mu)$$

$m_A \approx 100 \div 120\,\text{GeV}$ Bottino et al. '02- '10

This parameter space for light neutralinos is now excluded by:

$B_s \to \mu^+\mu^-$

Searches for extra Higgses at the LHC,

$pp \to X\,\Phi \to \tau\tau$

Higgs mass and couplings

⇨ MSSM incompatible with DAMA, CoGeNT

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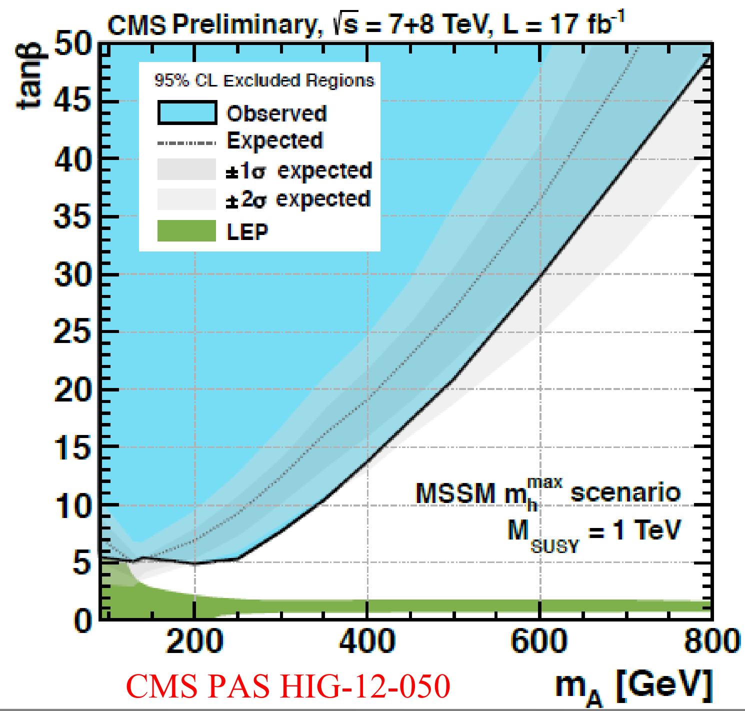


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