Portoroz 2013

April 17th 2013

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

- Strongly-interacting SUSY particles (squarks and gluinos) typically excluded by the LHC above 1 TeV

ATLAS-CONF-2012-109
CMS, arXiv:1301.2175

- Direct bounds on EW-iteracting particles relatively weaker, due to the smaller production cross-section, e.g. $m_{\tilde{\ell}} \gtrsim 275\,\mathrm{GeV}$

CMS-PAS-SUS-12-022

- The EW SUSY sector might be much lighter than the strong sector

- However, with 8 TeV run data, LHC searches for EW-produced new states started to go considerably beyond the limits set by LEP

- Here, we discuss an example of the potential of EW searches at the LHC: how to test light Neutralino Dark Matter in the MSSM, i.e.

$$m_{\tilde{\chi}_1^0} \lesssim 30 \ \mathrm{GeV}$$

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: $(\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^+)$

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

Mass eigenstates:

$$\tilde{\chi}_i^0 = N_{i1}\widetilde{B} + N_{i2}\widetilde{W} + N_{i3}\widetilde{H}_d + N_{i4}\widetilde{H}_u$$

LEP chargino searches: $M_{\tilde{\chi}_1^+} > 94\,\mathrm{GeV}$

⇓

$$M_2,\ \mu \gtrsim 90\ \mathrm{GeV}$$

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

No gaugino mass unification at the GUT scale ($M_1 \simeq 0.5 \times M_2$)

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: $(\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^+)$

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

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$$\tilde{\chi}_i^0 = N_{i1}\widetilde{B} + N_{i2}\widetilde{W} + N_{i3}\widetilde{H}_d + N_{i4}\widetilde{H}_u$$

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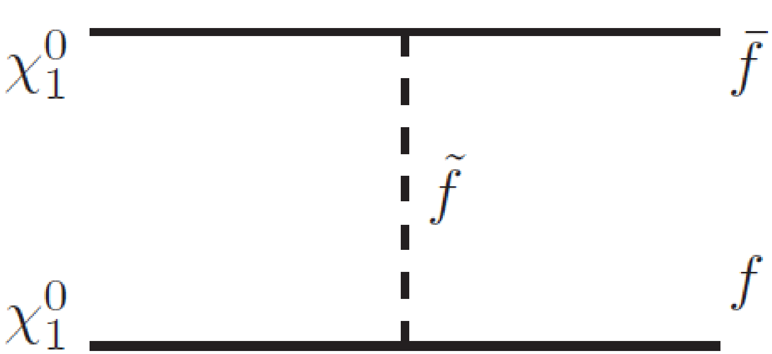
Relic density (WMAP, Planck): $\Omega_\chi h^2 \sim 0.1$

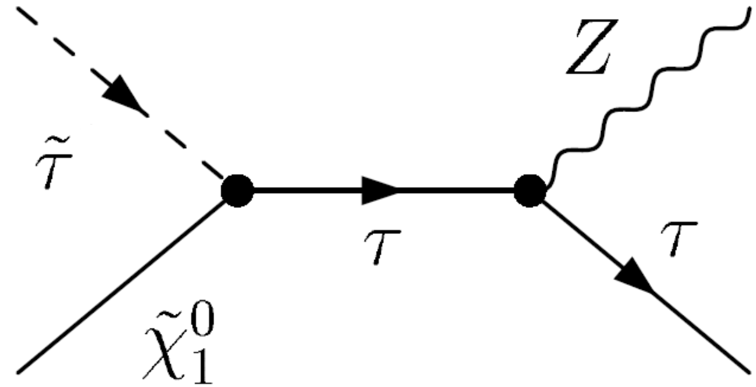
Efficient annihilation required

Annihilation processes

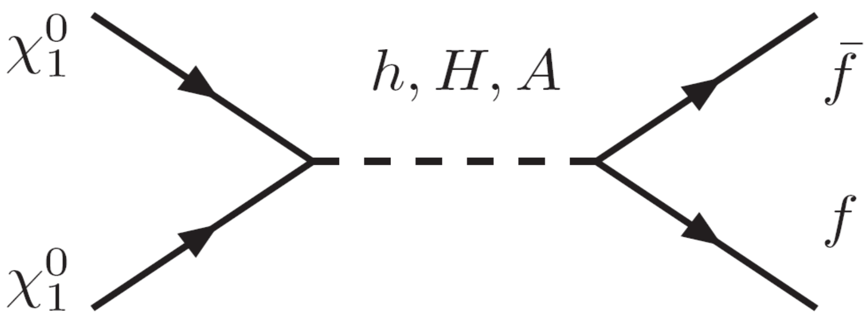
t-channel exchange (e.g. sfermions):



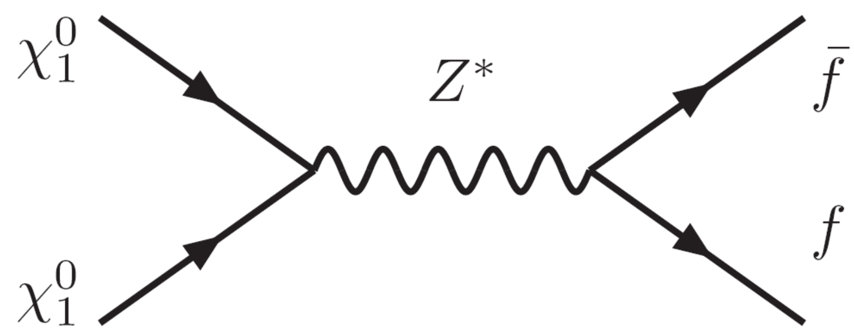
Coannihilations (e.g. stau):



Higgs mediation:



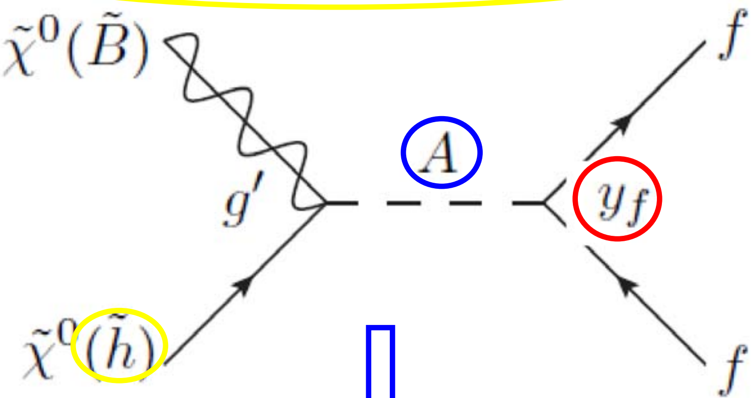
Z mediation:



⇨ different regions of the SUSY parameter space are selected

Annihilation processes: Higgs exchange

- Higgs mediated annihilation:



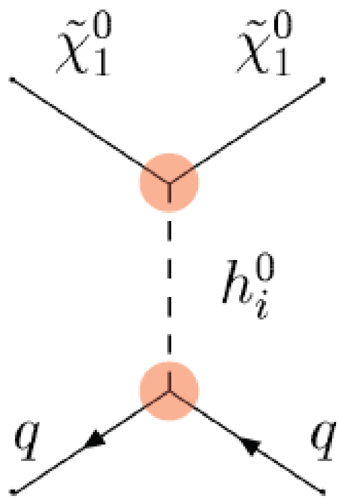
$$\propto \frac{m^2_{\tilde{\chi}^0_1}}{m^2_A} \frac{m_f}{v} \, (N_{11} N_{13,14}) \, \tan\beta$$

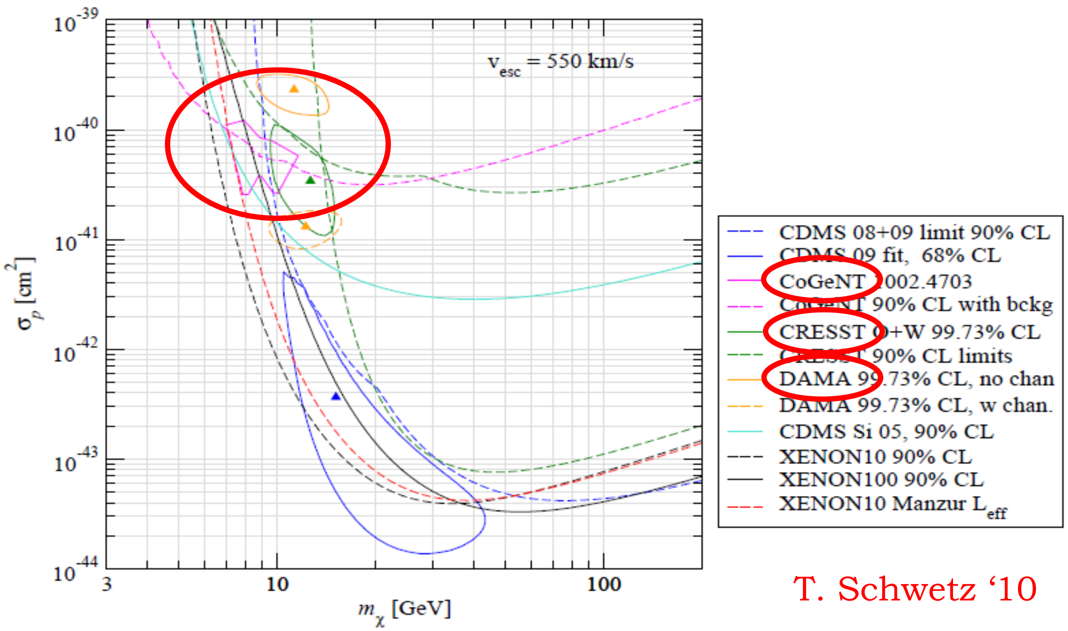
Drees Nojiri '92

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

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

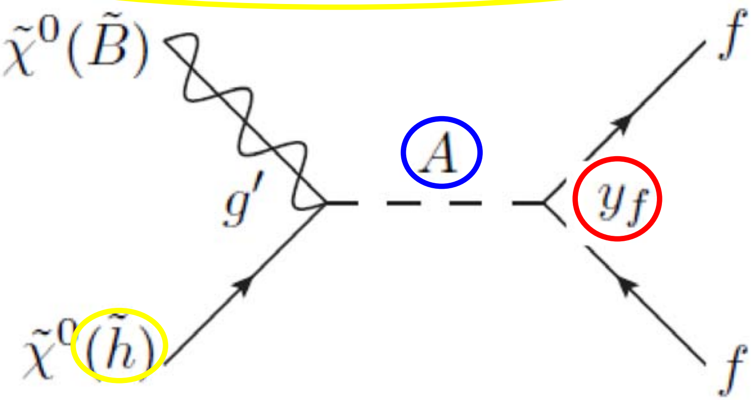
Large scattering cross-section with nuclei:





T. Schwetz '10

- Higgs mediated annihilation:



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

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

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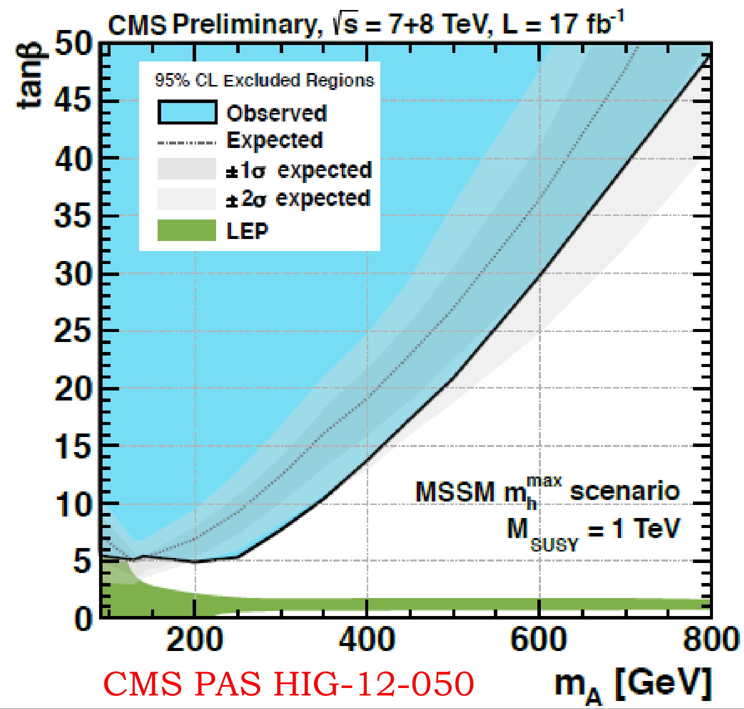
This parameter space for light neutralinos is now excluded by:

- $B_s \to \mu^+\mu^-$
- Searches for extra Higgses at the LHC, $pp \to X\,\Phi \to \tau\tau$
- Higgs mass and couplings

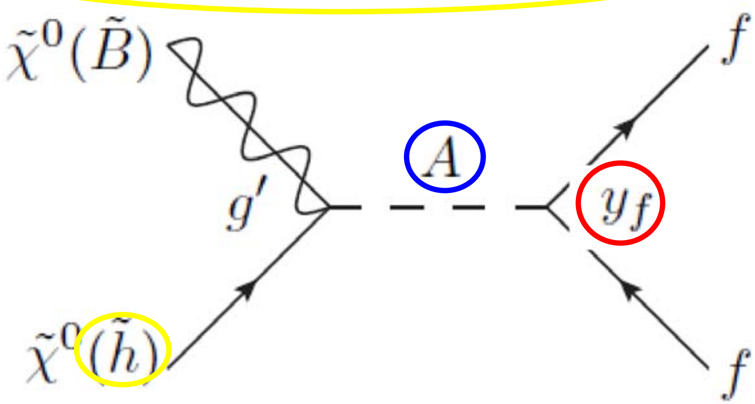
LC Ota Takanishi '11



CMS PAS HIG-12-050

⇒ MSSM not compatible with DAMA, CoGent, CRESST

- Higgs mediated annihilation:



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

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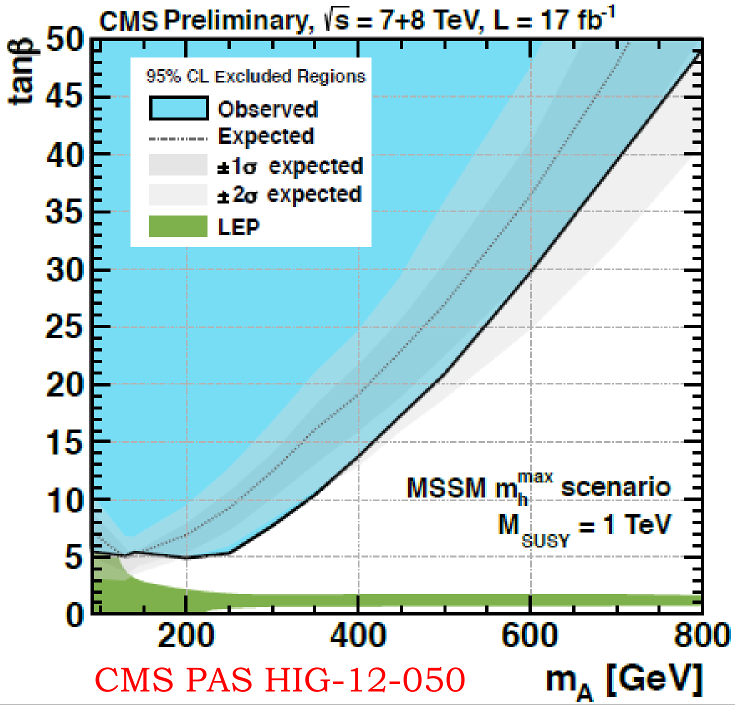
LC Ota Takanishi ’11

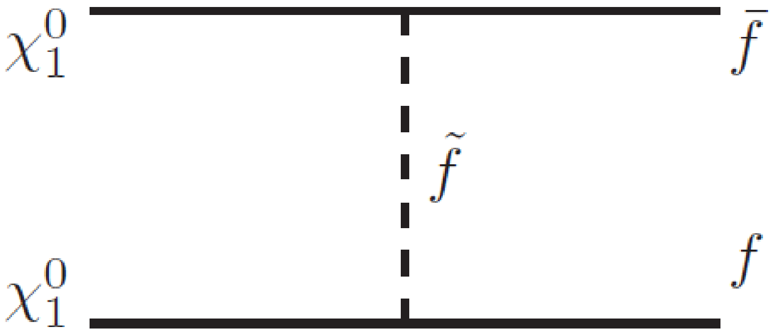
Heavier neutralinos excluded by XENON100



CMS PAS HIG-12-050

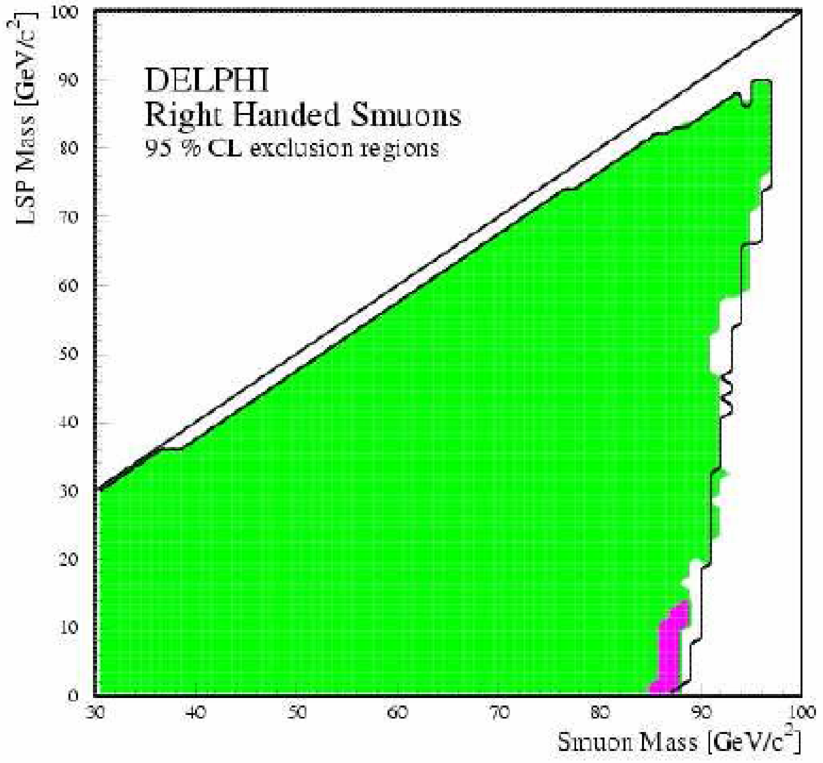
Annihilation processes: sfermion exchange

- Sfermion mediated annihilation:



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

Challenged by LEP bounds, e.g.:



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

Valid for $\Delta m \gtrsim 10$ GeV

- Can one evade it?

- Still $m_{\tilde{\chi}_1^0} \lesssim 30$ GeV not possible even for compressed spectra

Z width bounds:

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

Similarly, LEP and/or Z width bounds exclude chargino and Z exchanges as annihilation mechanisms for light neutralinos

Arbey Battaglia Mahmoudi '12

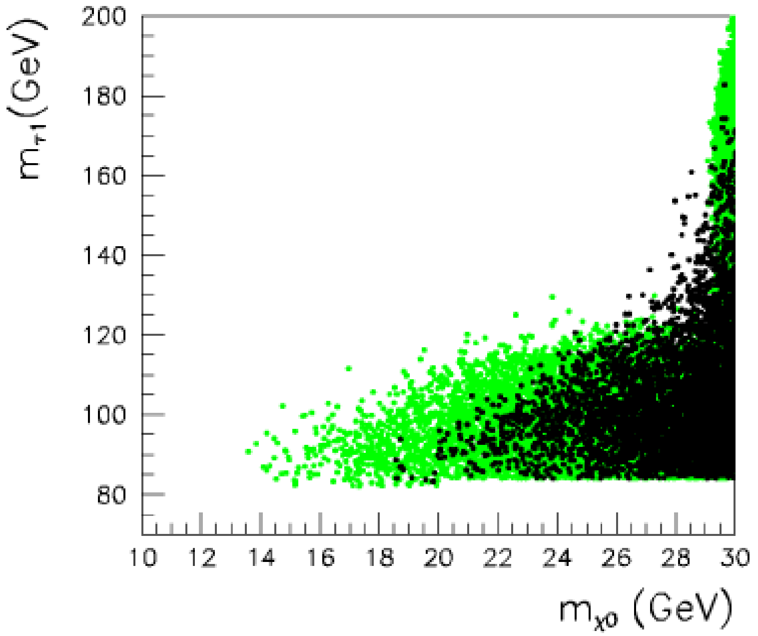
Light neutralino DM is only possible in presence of a light stau

Albornoz Bélanger Boehm '11
Grothaus Lindner Takanishi '12

because:

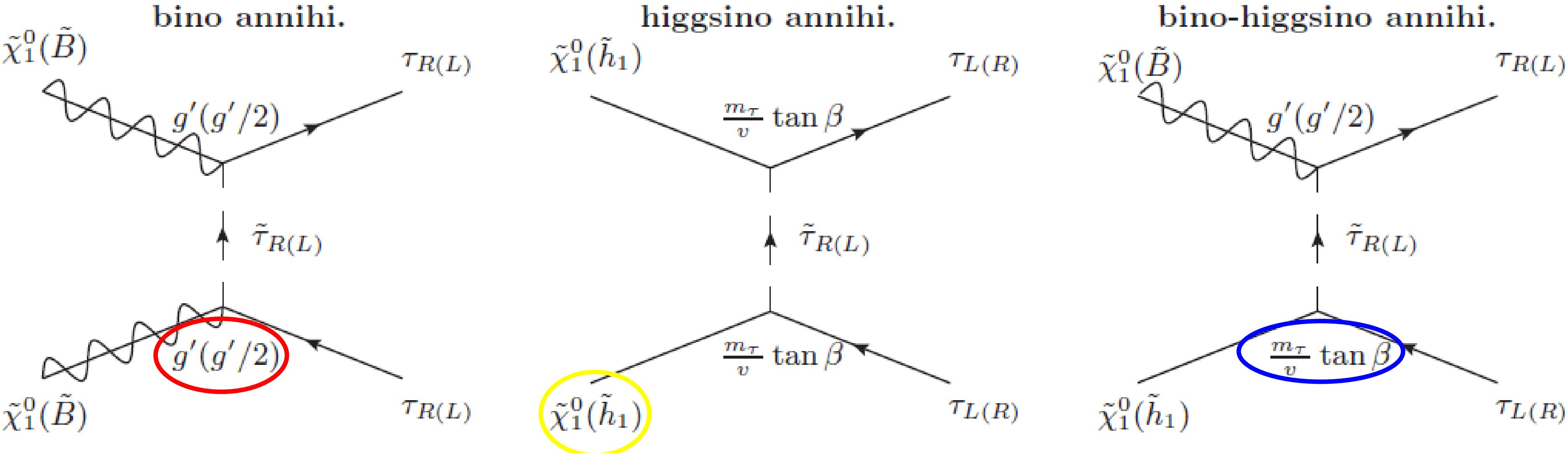
(a) efficient annihilation is achieved if Yukawa interactions contribute

(a) LEP/LHC set too severe bounds to other sfermions (e.g. $m_{\tilde{b}} \gtrsim 650\,\mathrm{GeV}$)



Albornoz Bélanger Boehm '11

Stau-mediated annihilation

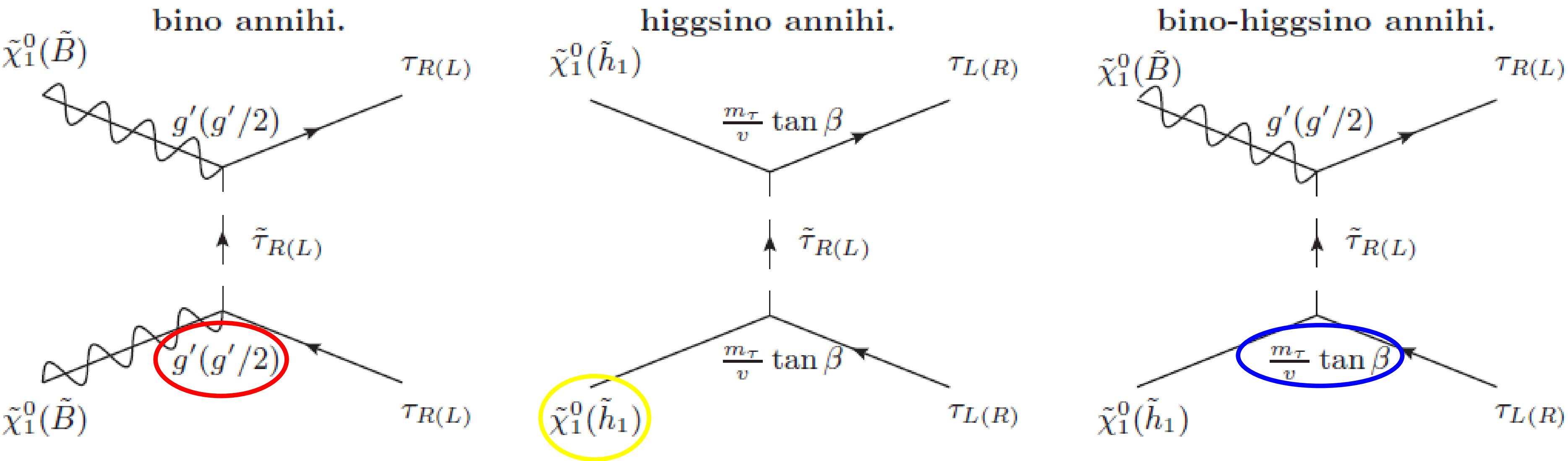


- RH stau much more efficient (cross-section 16x larger than LH one)
- Sizeable higgsino component: small μ
- Yukawa interactions: large $\tan\beta$

Relic density essentially controlled by 4 parameters only:

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

Stau-mediated annihilation



- 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

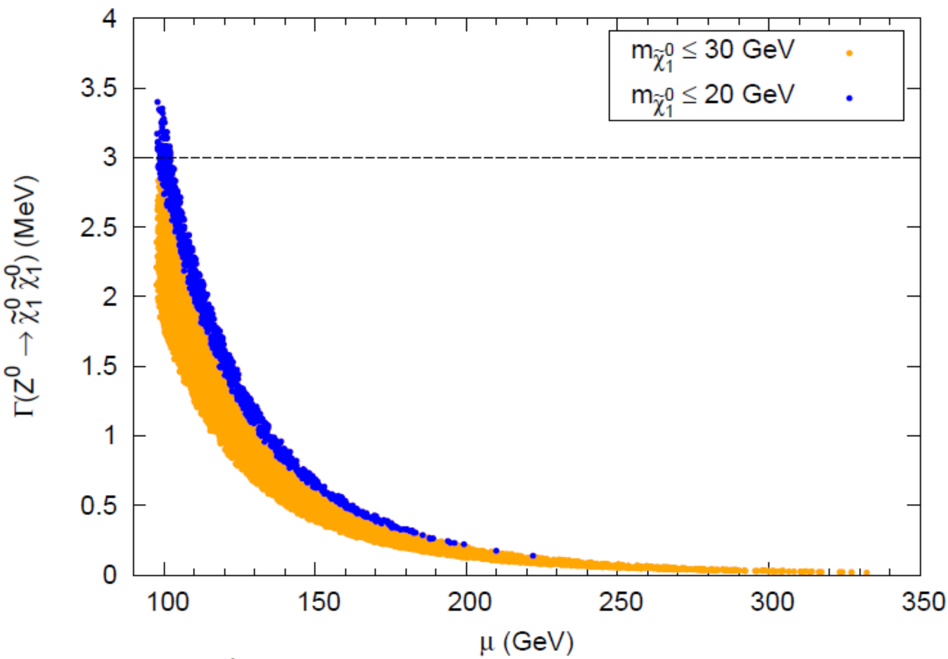
Parameters scan and constraints

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

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

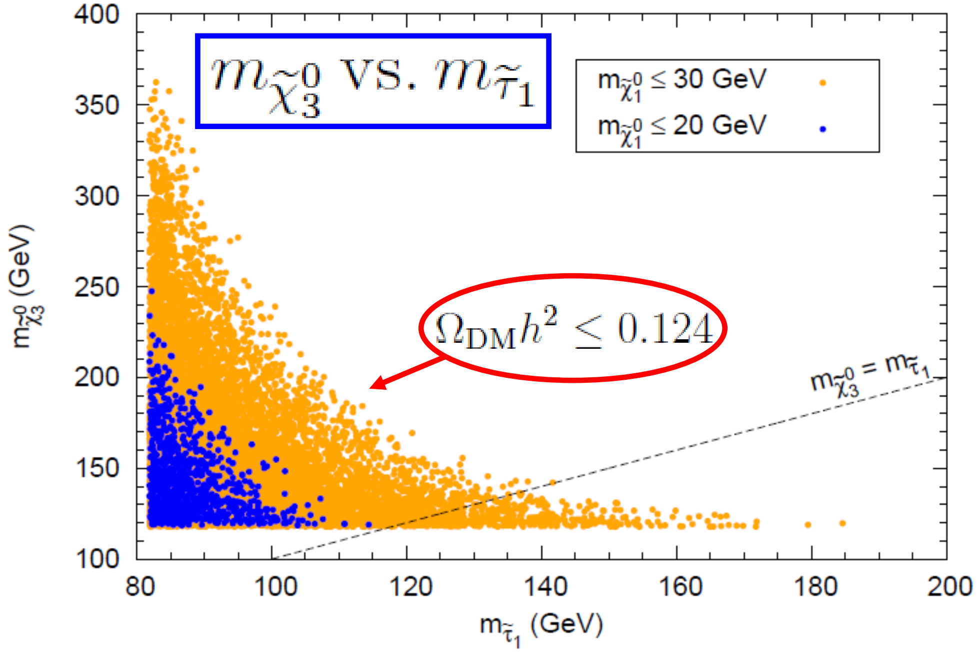
- $m_{\tilde\chi_1^0} \le 30$ GeV
- **CMB**, Planck (3σ): $\Omega_{\rm DM} h^2 \le 0.124$
- **LEP2**: $m_{\tilde\tau_R} \ge 81.9\,\text{GeV}, \quad m_{\tilde\chi_1^\pm} \ge 103.5\,\text{GeV}$
- **LHC**: limits on charginos depend on smuon/selectron masses and can be evaded
- **Flavour**: $\Omega_{\rm DM}$ does not depend on heavy Higgs/squark masses, flavour observables do not constrain the DM parameter space
- **Z invisible width**, LEP: $\Delta\Gamma_Z^{\rm inv} < 3$ MeV

LC Lindert Ota Takanishi, to appear



$$\Gamma(Z \to \tilde\chi_1^0\tilde\chi_1^0) = \frac{G_F}{\sqrt{2}}\frac{M_Z^3}{12\pi}\left(1 - \frac{4M_{\tilde\chi_1^0}^2}{M_Z^2}\right)^{\frac{3}{2}} \left|N_{13}^2 - N_{14}^2\right|^2$$

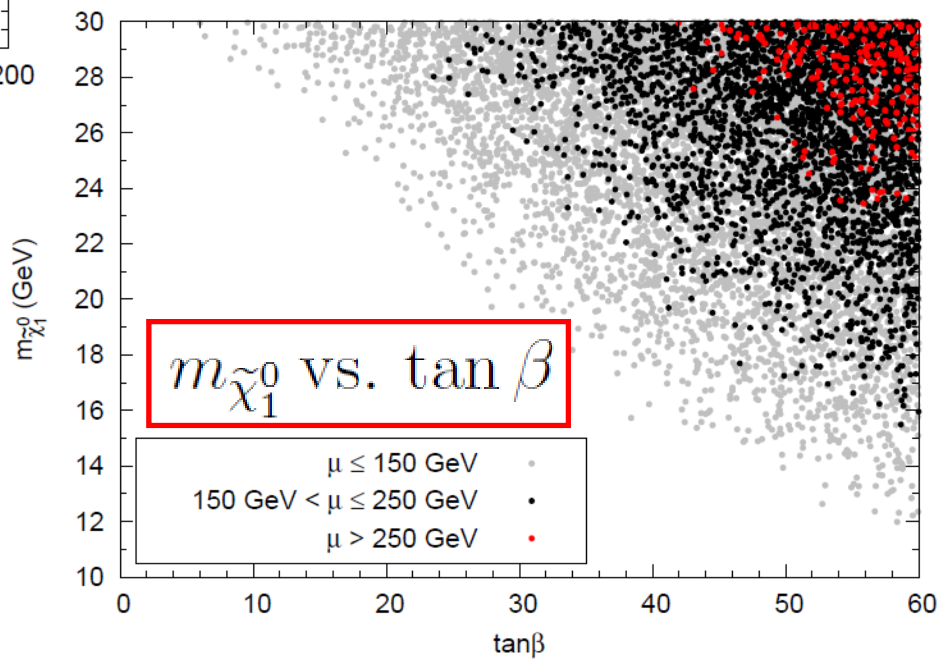
Parameter space



LC Lindert Ota Takanishi, to appear

$$m_{\tilde\chi^0_1} \gtrsim 12 \text{ GeV}$$

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



$$m_{\tilde\tau_1} \lesssim 180 \text{ GeV}$$

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

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

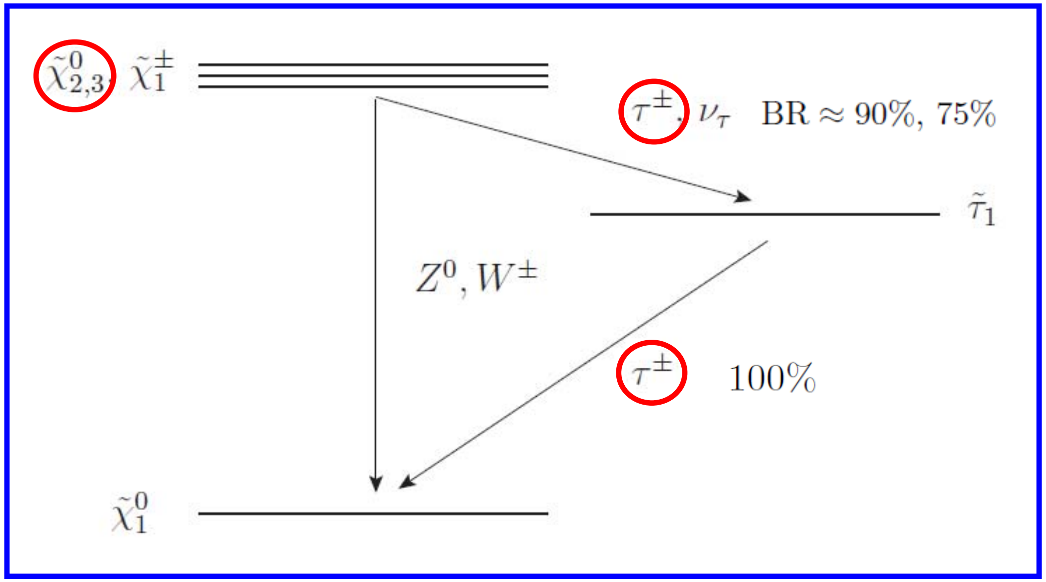
Decays:

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

⇩

$$pp \to \widetilde{\chi}_{2,3}^0\,\widetilde{\chi}_{2,3}^0 \to 4\tau + \not{E}_T$$
$$pp \to \widetilde{\chi}_{2,3}^0\,\widetilde{\chi}_1^\pm \to 3\tau + \not{E}_T$$

multi-tau signals!



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

Decays:

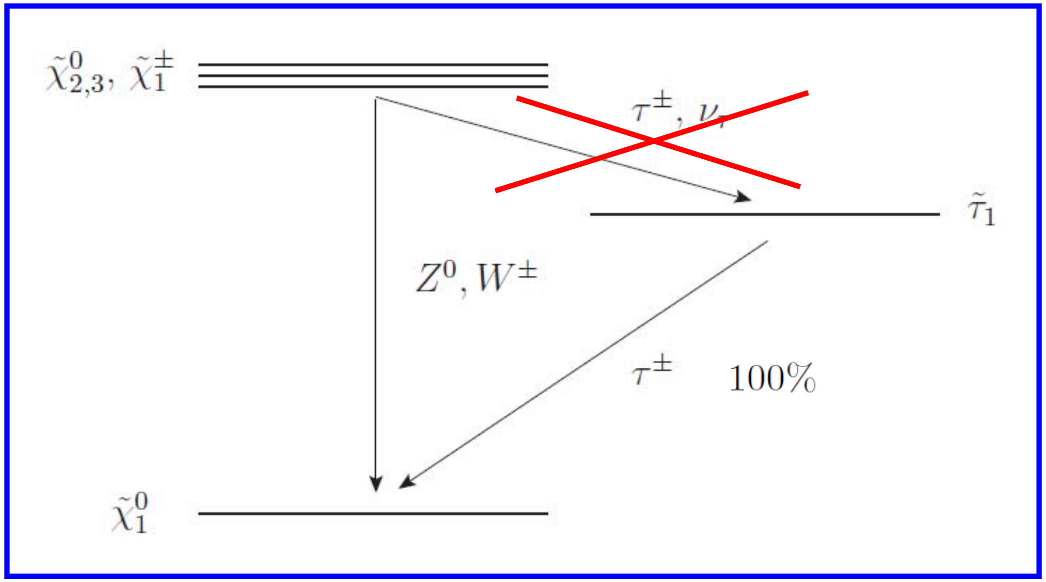
$$m_{\tilde{\tau}_1} > m_{\tilde{\chi}^0_{2,3}} > m_{\tilde{\chi}^0_1}$$

⇓

3-body decays

it might be more difficult

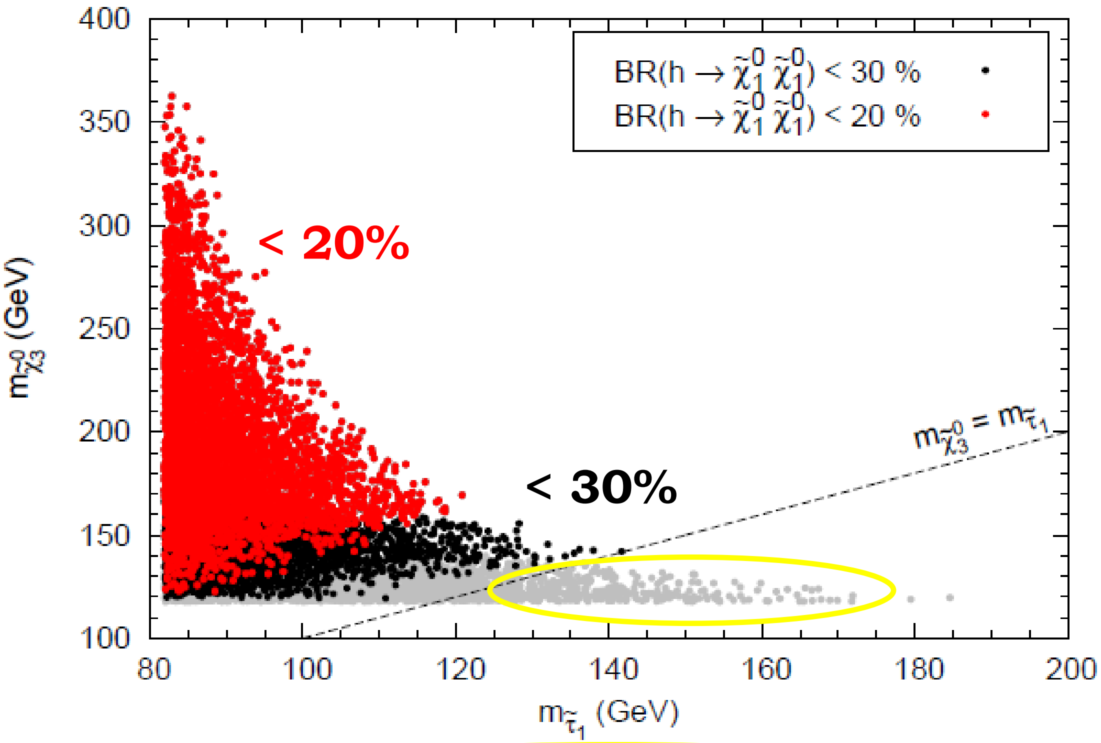
However...



LHC phenomenology: invisible Higgs decay

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

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



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

Last fits to Higgs data:

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

Falkowski et al. '13

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

Giardino et al. '13

but with 20% theo unc.:

$\text{BR}_h^{\text{inv}} < 52\% \quad (68\%\,\text{CL})$

Djouadi Moreau '13

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

strongly disfavoured!

ATLAS NOTE

ATLAS-CONF-2013-028

March 10, 2013

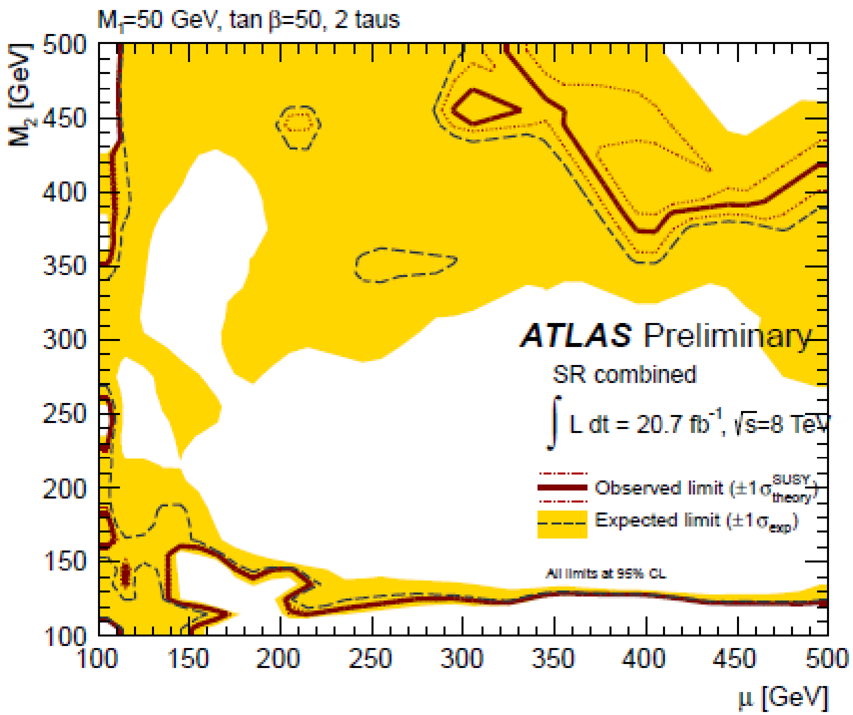
Search for electroweak production of supersymmetric particles in final states with at least two hadronically decaying taus and missing transverse momentum with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

ATLAS-CONF-2013-028

Signal region	requirements
OS m_{T2}	at least 1 OS tau pair jet veto Z-veto E_T^{miss}> 40 GeV m_{T2}> 90 GeV
OS m_{T2}-nobjet	at least 1 OS tau pair b-jet veto Z-veto E_T^{miss}> 40 GeV 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 ± 0.5 ± 0.1	1.6 ± 0.8 ± 1.2
Z+jets	0.28 ± 0.26 ± 0.23	0.4 ± 0.3 ± 0.3
diboson	2.2 ± 0.5 ± 0.5	2.5 ± 0.5 ± 0.9
multi-jet & W+jets	8.4 ± 2.6 ± 1.4	12 ± 3 ± 3
SM total	11.0 ± 2.7 ± 1.5	17 ± 4 ± 3
data	6	14

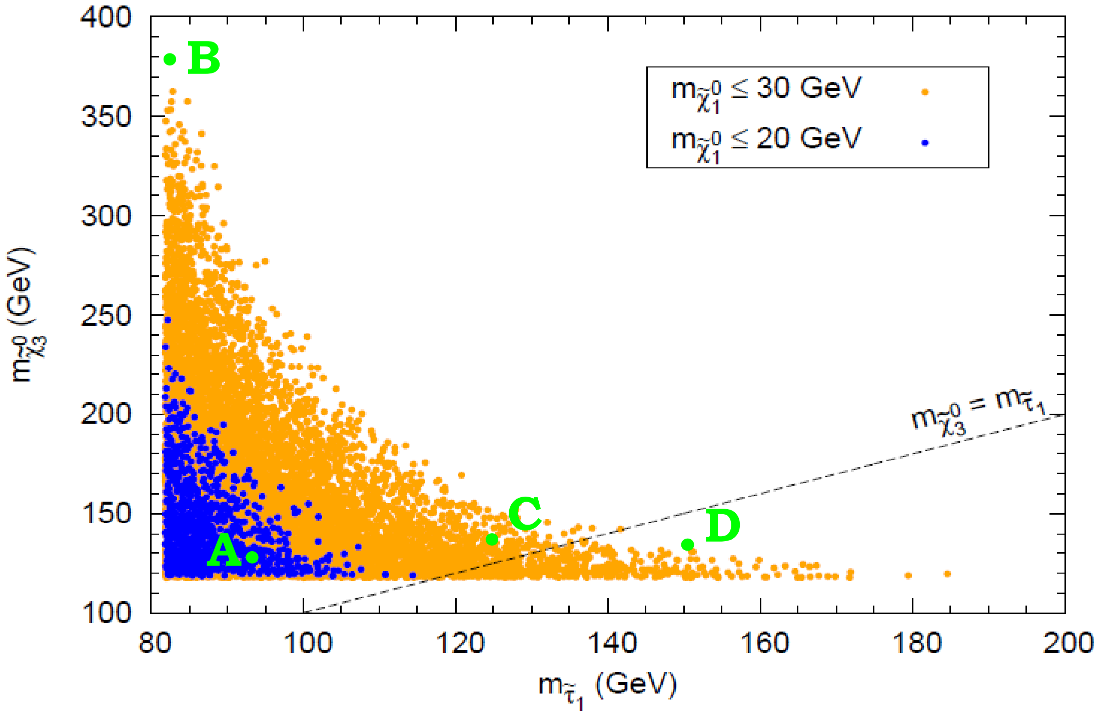
$$m_{\tilde{\tau}_1} = 95\,\text{GeV}, \quad m_{\tilde{\chi}_1^0} = 50\,\text{GeV}$$

Representative points

	A	B	C	D
M_1 (GeV)	20	29	32	34
$m_{\tilde{\tau}_R}$ (GeV)	90	72	125	150
μ (GeV)	105	350	115	100
$\tan\beta$	55	57	55	55

$\Rightarrow$

GeV	A	B	C	D
$m_{\tilde{\chi}_1^0}$	17	30	29	29
$m_{\tilde{\chi}_2^0}$	117	368	127	114
$m_{\tilde{\chi}_3^0}$	126	381	135	120
$m_{\tilde{\chi}_1^\pm}$	111	358	121	105
$m_{\tilde{\tau}_1}$	93	83	126	151



Herwig++ (event samples)

Prospino 2 (NLO K-factors)

Delphes 3 (fast detector simul.)

Cuts of two Atlas SR applied

VERY preliminary results

SM process	SR OS m_{T2}	SR OS m_{T2} -nobjet
top	$0.2 \pm 0.5 \pm 0.1$	$1.6 \pm 0.8 \pm 1.2$
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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
point A	31.2	42.4
point B	7.3	17.6
point C	1.6	6.0
point D	2.8	7.7

	A	B	C	D
$\mathrm{BR}_h^{\mathrm{inv}}$	20%	1%	26%	36%

Work in progress, but our first results indicate that multi-tau searches and Higgs fits can exclude neutralino DM up to 30 GeV already now