MORIOND ELECTROWEAK

March 18th 2014

Light Neutralino Dark Matter > 24 GeV from LHC

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ULB

UNIVERSITÉ LIBRE DE BRUXELLES

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

Searches for EW-interacting SUSY particle at the LHC started to go beyond LEP limits

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

Here an example of the potential of EW searches: 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: $(\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^+)$

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

Mass eigenstates:

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

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

⇓

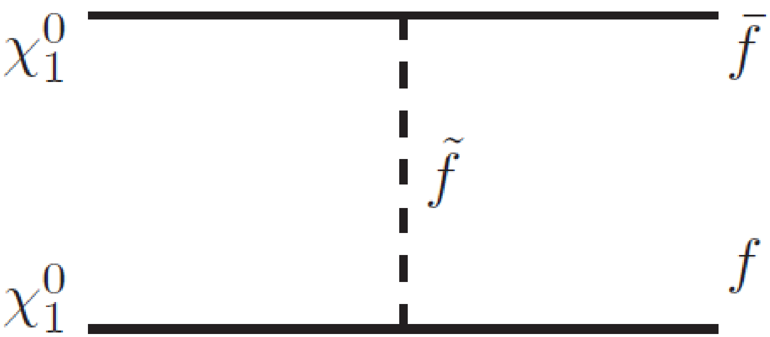
$$M_2,\ \mu \gtrsim 90 \text{ GeV}$$

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

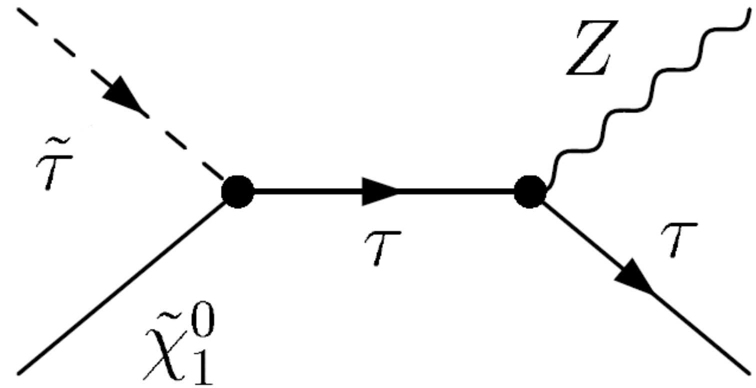
Relic density (WMAP, Planck): $\Omega_\chi h^2 \sim 0.1$

Efficient annihilation required

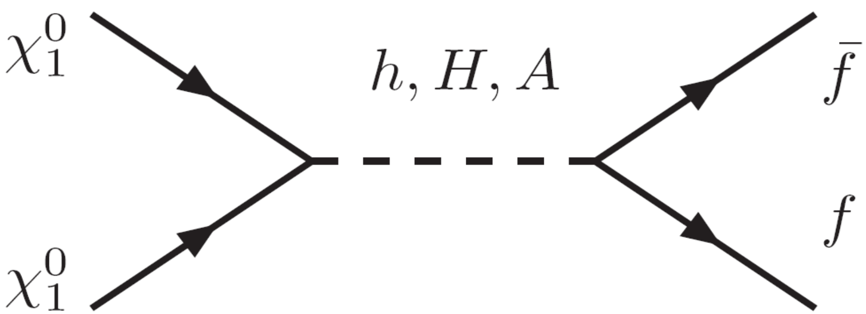
t-channel exchange (e.g. sfermions):



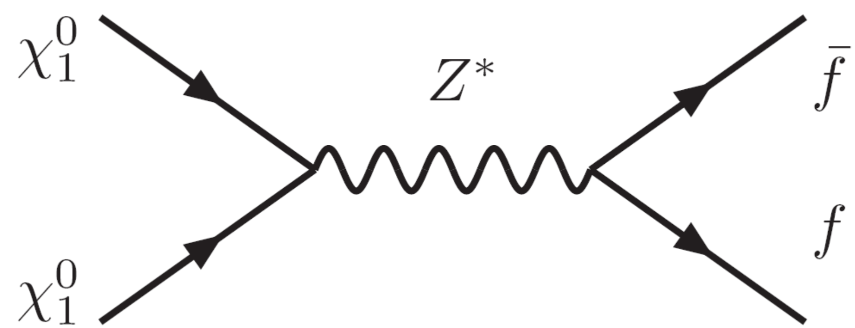
Coannihilations (e.g. stau):



Scalar mediation:

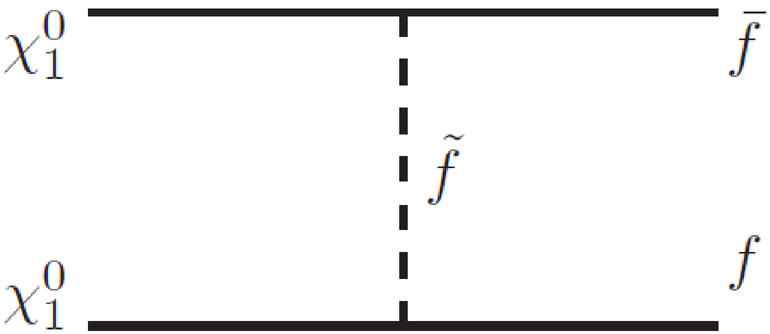


Z mediation:



different regions of the SUSY parameter space are selected

Sfermion mediated annihilation:



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

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

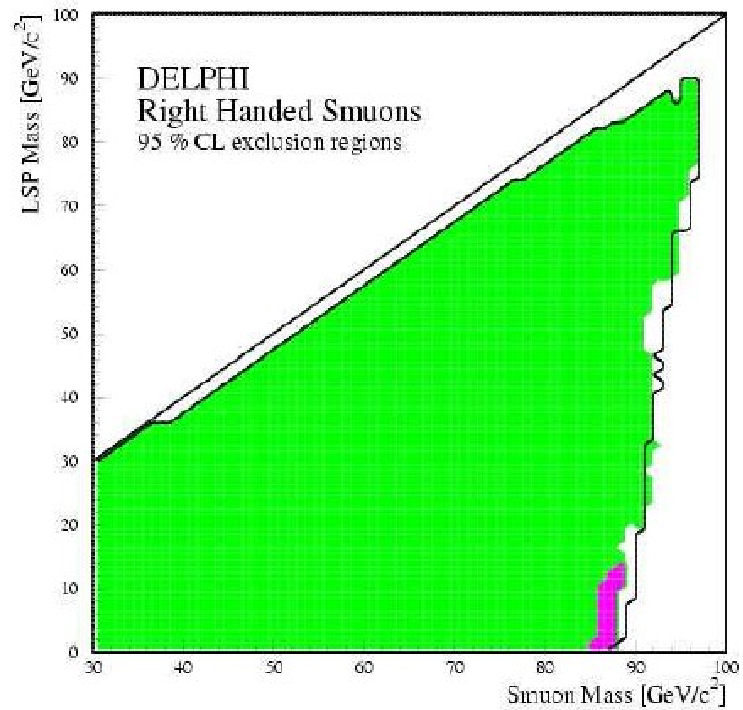
Can one evade it with compressed spectra?

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

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

(Possible exception: light sbottom with tuned LR mixing) Arbey Battaglia Mahmoudi ‘13

Challenged by LEP bounds, e.g.:

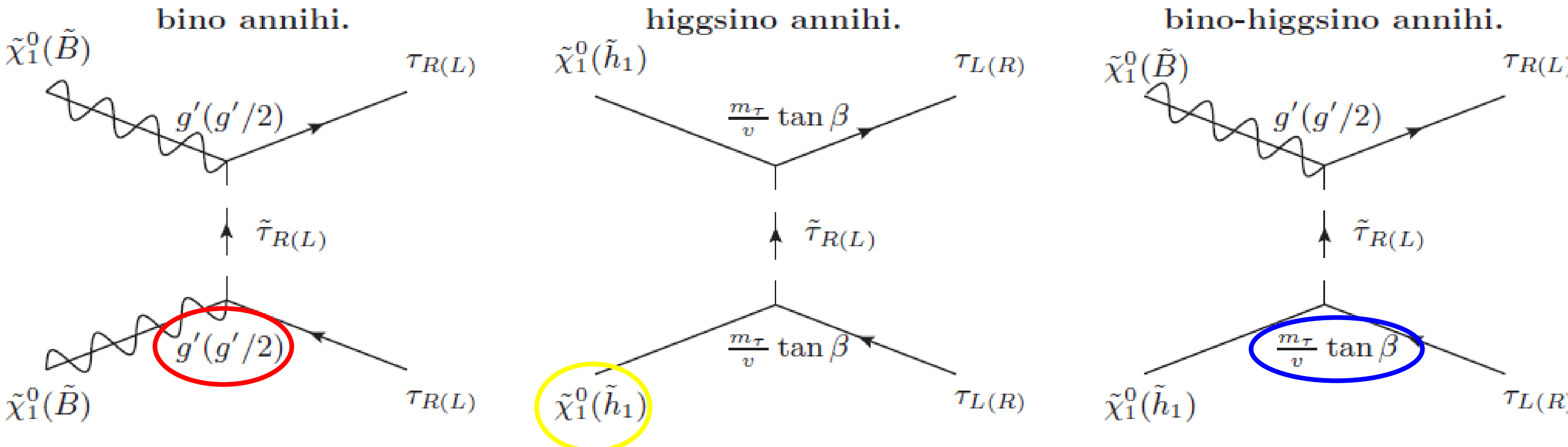


Stau-mediated annihilation

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

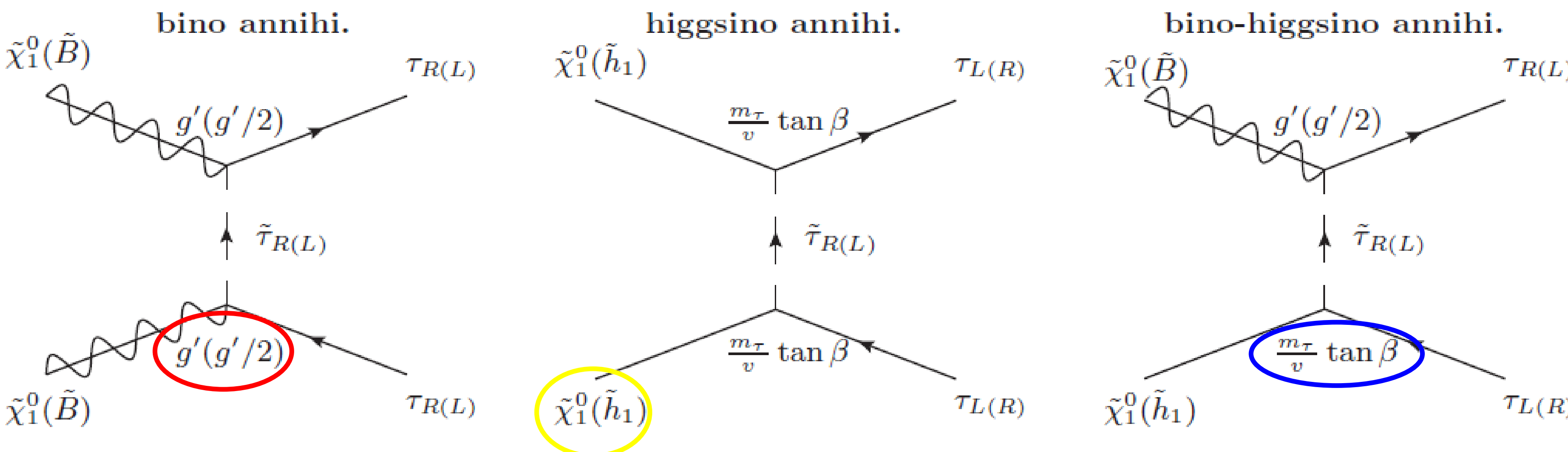
Relic density essentially controlled by 4 parameters only:

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

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

Light neutralino DM necessarily implies:

light stau, light higgsino-like neutralinos and charginos

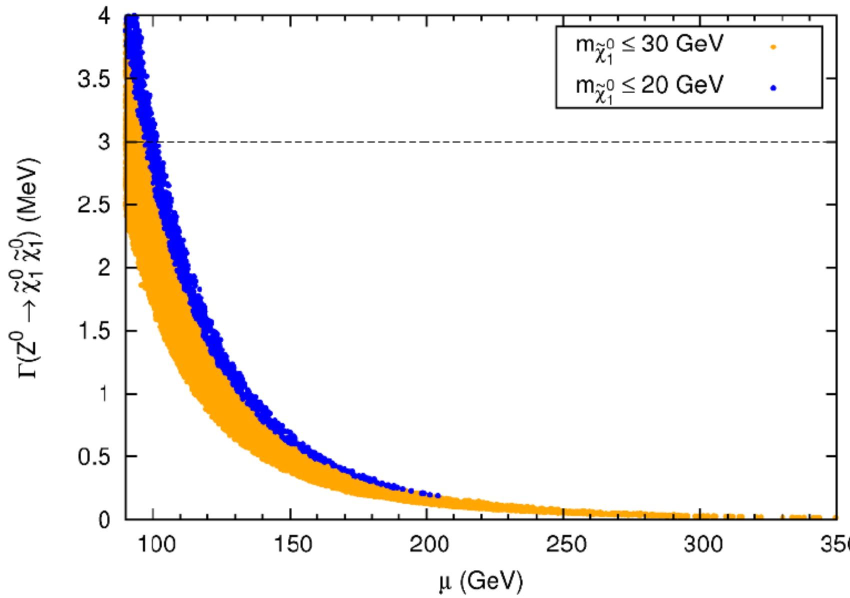
Parameters scan and constraints

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

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

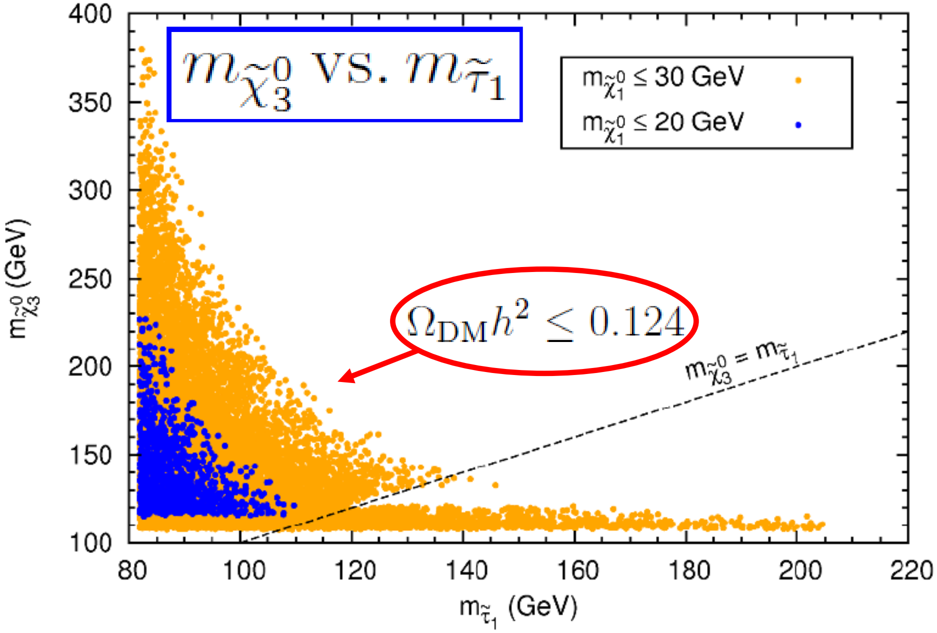
- $m_{\tilde{\chi}_1^0} \le 30\ \text{GeV}$
- **CMB**, Planck (3σ): $\Omega_{\text{DM}} h^2 \le 0.124$
- **LEP2**: $m_{\tilde{\tau}_R} \ge 81.9\,\text{GeV}, \quad m_{\tilde{\chi}_1^\pm} \ge 103.5\,\text{GeV}$
- **LHC**: limits on charginos depend on smuon/selectron masses and can be evaded
- **Flavour**: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

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



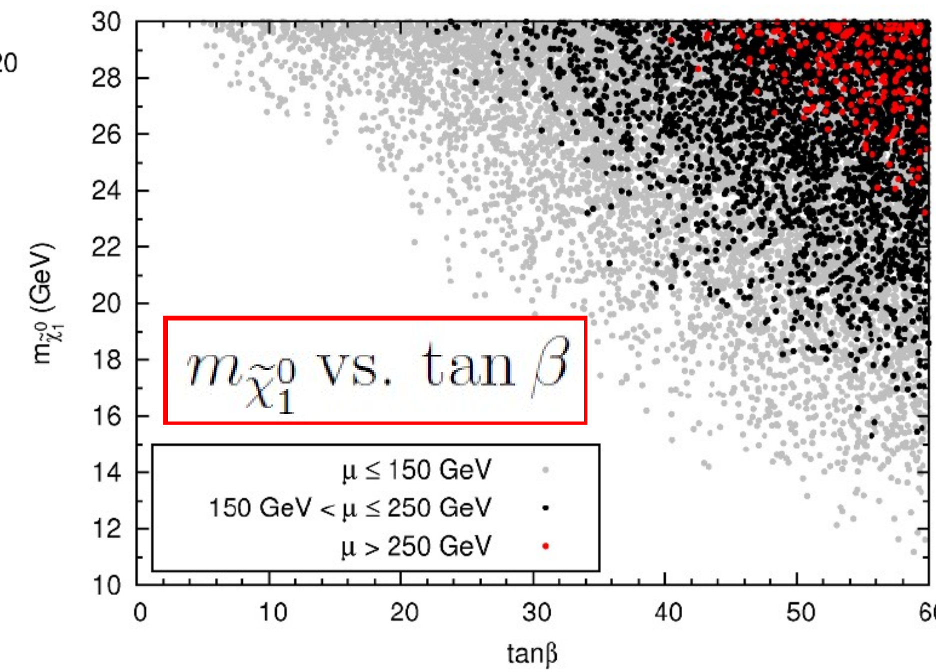
LC Lindert Ota Takanishi '13

$$m_{\tilde\chi_1^0} \gtrsim 11\ \mathrm{GeV}$$

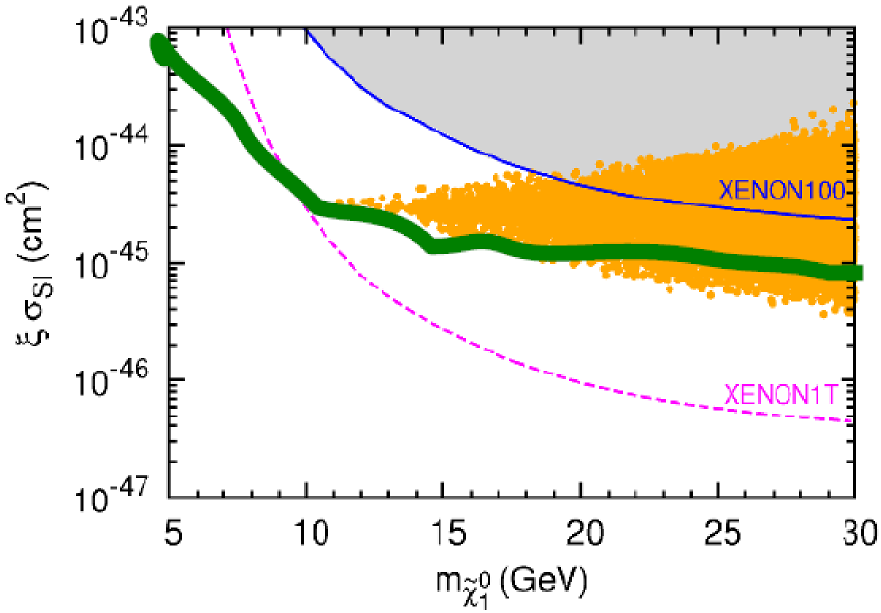
$$(\tan\beta \le 60)$$

$$m_{\tilde\tau_1} \lesssim 210\ \mathrm{GeV}$$

$$m_{\tilde\chi_1^\pm} \approx m_{\tilde\chi_2^0} \approx m_{\tilde\chi_3^0} \lesssim 380\ \mathrm{GeV}$$



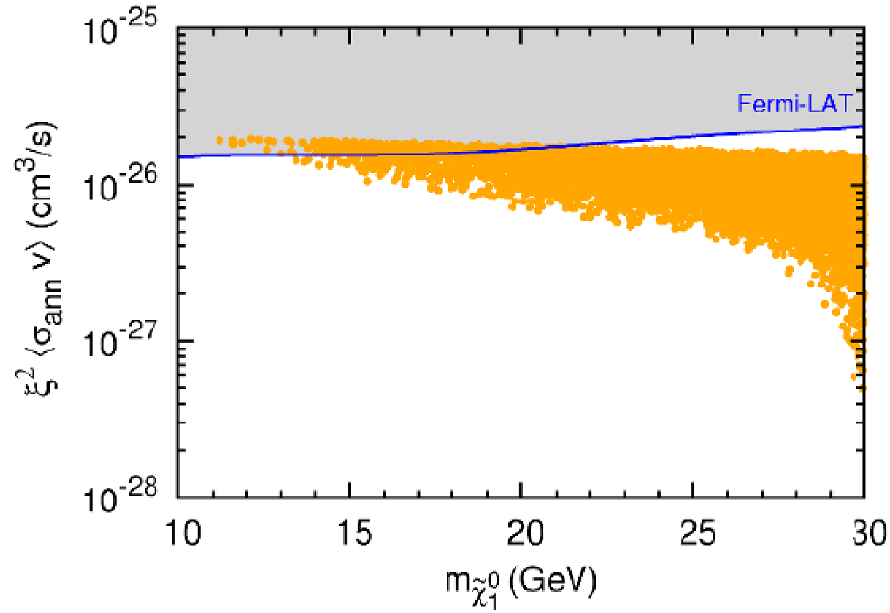
Spin-independent scattering cross section



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

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

Annihilation cross-section



Gamma rays from satellite galaxies

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

$$\widetilde{\tau}_1,\ \widetilde{\chi}^0_2,\ \widetilde{\chi}^0_3,\ \widetilde{\chi}^\pm_1$$

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

$$pp \to \widetilde{\tau}^+_1\,\widetilde{\tau}^-_1 + X,\quad pp \to \widetilde{\chi}^0_i\,\widetilde{\chi}^0_j + X,\quad pp \to \widetilde{\chi}^0_i\,\widetilde{\chi}^\pm_1 + X,\quad pp \to \widetilde{\chi}^+_1\,\widetilde{\chi}^-_1 + X$$

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

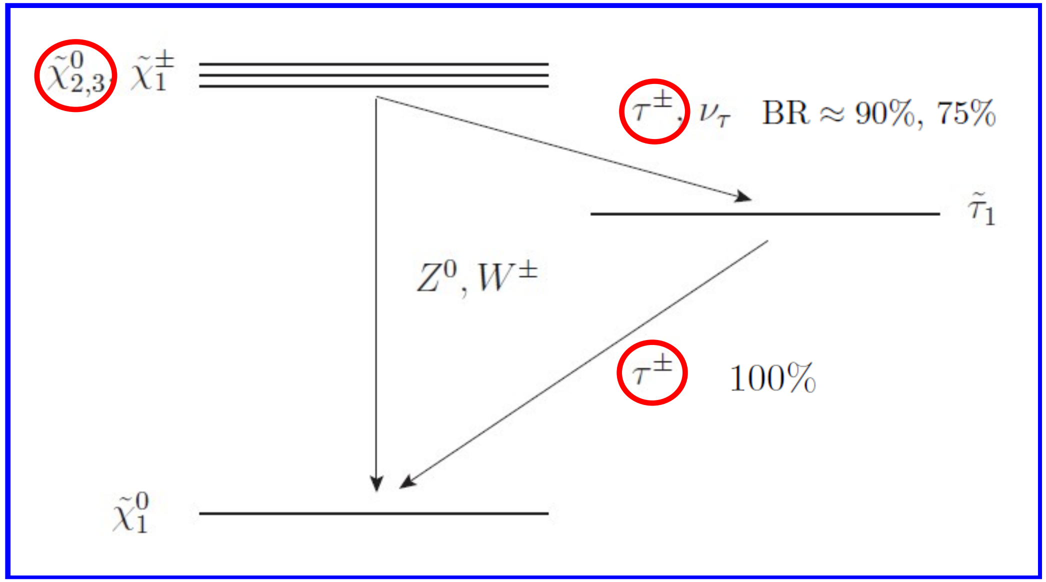
Decays:

$$m_{\tilde{\chi}^\pm_1} \simeq m_{\tilde{\chi}^0_{2,3}} > m_{\tilde{\tau}_1} > m_{\tilde{\chi}^0_1}$$

$$\Downarrow$$

$$pp \to \widetilde{\chi}^0_{2,3}\,\widetilde{\chi}^0_{2,3} \to 4\tau + \not{E}_T$$
$$pp \to \widetilde{\chi}^0_{2,3}\,\widetilde{\chi}^\pm_1 \to 3\tau + \not{E}_T$$

multi-tau signals!



LHC phenomenology: production and decays

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:

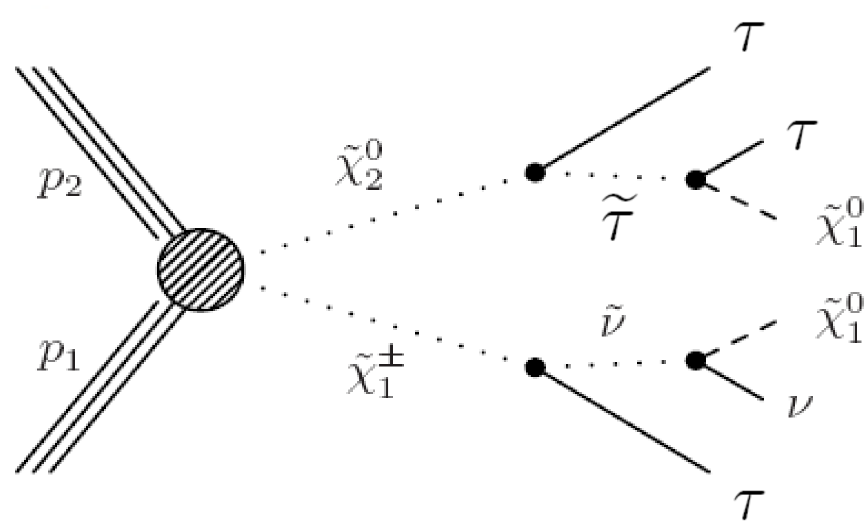
$$m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_1^0}$$

⇓

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

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

multi-tau signals!



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$$\tilde{\tau}_1,\ \tilde{\chi}^0_2,\ \tilde{\chi}^0_3,\ \tilde{\chi}^\pm_1$$

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

$$pp \to \tilde{\tau}^+_1\, \tilde{\tau}^-_1 + X, \quad pp \to \tilde{\chi}^0_i\, \tilde{\chi}^0_j + X, \quad pp \to \tilde{\chi}^0_i\, \tilde{\chi}^\pm_1 + X, \quad pp \to \tilde{\chi}^+_1\, \tilde{\chi}^-_1 + X$$

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

Decays:

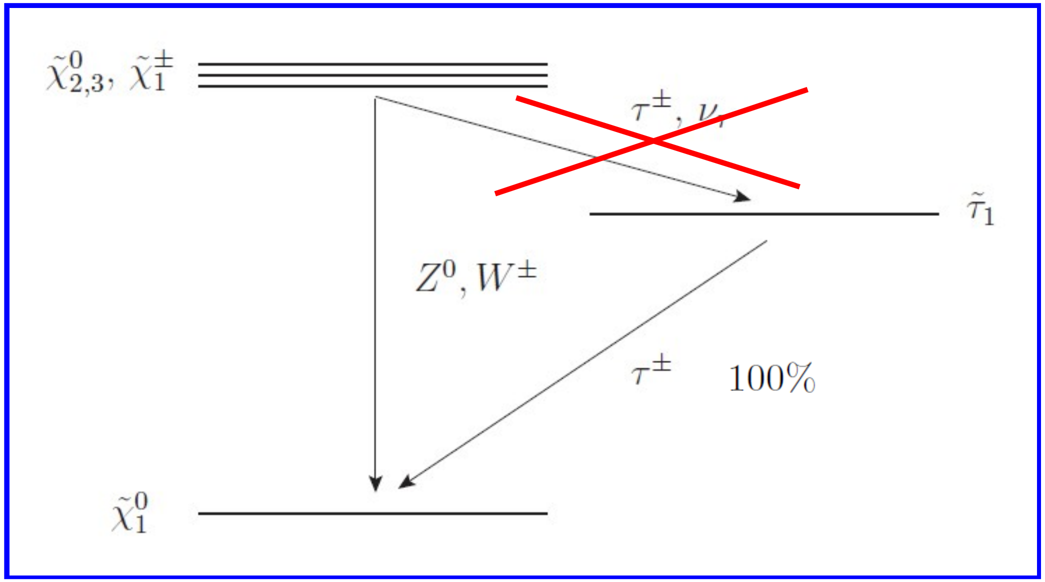
$$m_{\tilde{\tau}_1} > m_{\tilde{\chi}^0_{2,3}} > m_{\tilde{\chi}^0_1}$$

⇓

3-body decays

it might be more difficult

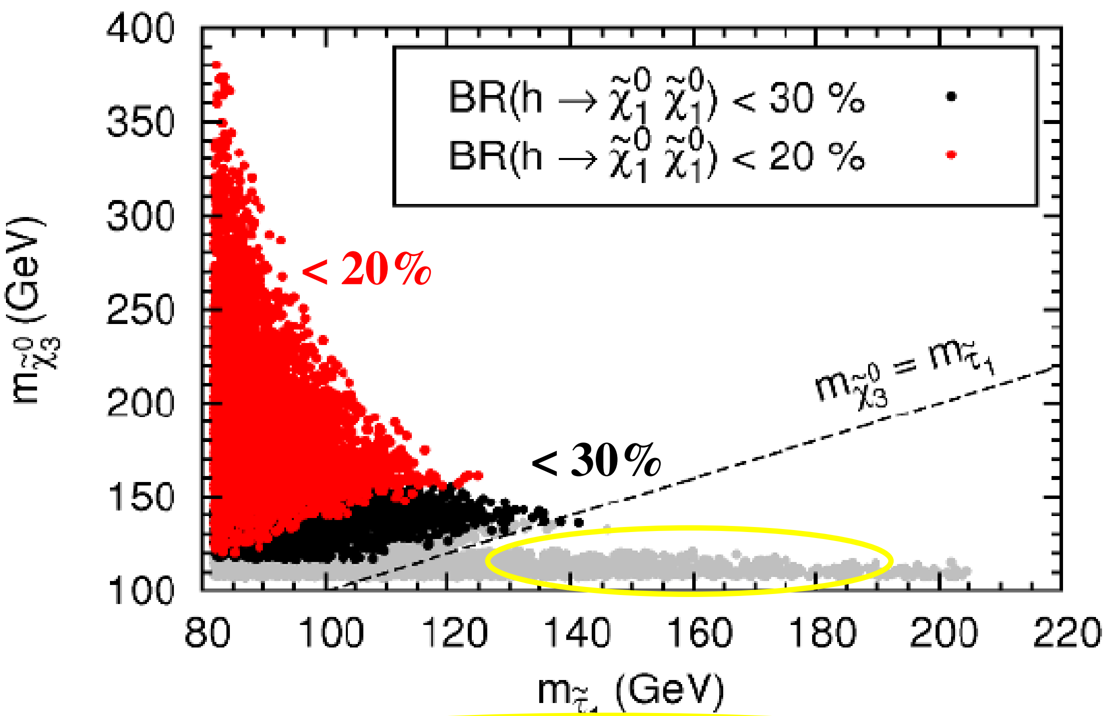
However…



LHC phenomenology: invisible scalar decay

$$\Gamma(h \to \tilde\chi_1^0\tilde\chi_1^0) = \frac{G_F M_W^2 m_h}{2\sqrt{2}\pi}\left(1 - 4m_{\tilde\chi_1^0}^2/m_h^2\right)^{3/2} |C_{h\tilde\chi_1^0\tilde\chi_1^0}|^2$$

$$C_{h\tilde\chi_1^0\tilde\chi_1^0} = (N_{12} - \tan\theta_W\, N_{11})(\sin\beta\, N_{14} - \cos\beta\, N_{13})$$



$$m_{\tilde\tau_1} > m_{\tilde\chi_3^0} \;\Rightarrow\; \mathrm{BR}(h \to \tilde\chi_1^0\tilde\chi_1^0) \gtrsim 30\%$$

Last fits to Higgs data:

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

Falkowski et al. '13

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

Giardino et al. '13

but with 20% theo unc.:

$\mathrm{BR}_h^{\mathrm{inv}} < 52\%$ (68% 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

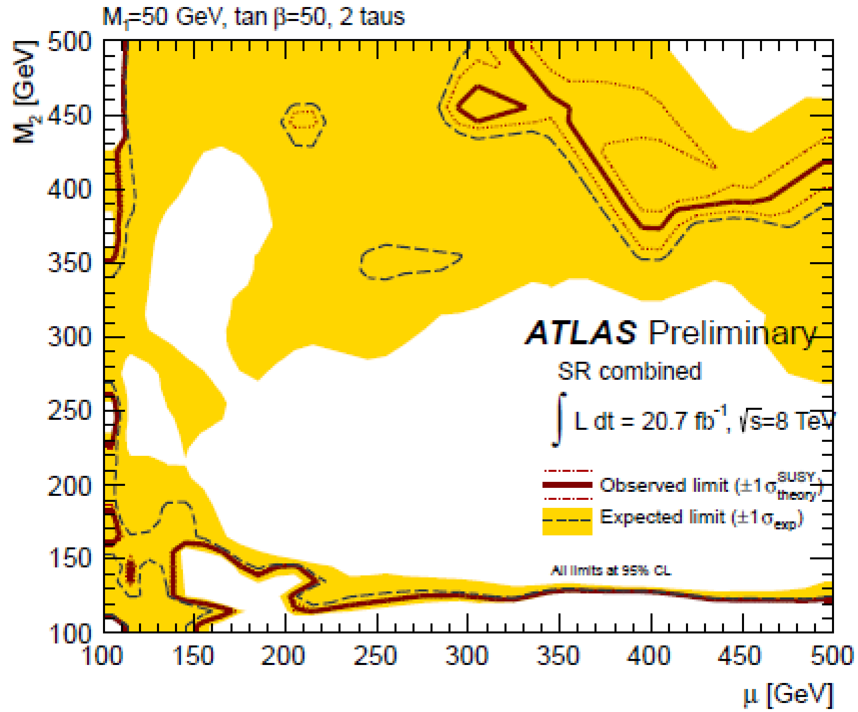
Search for electroweak production of supersymmetric particles in final states with at least two hadronically decaying taus and missing transverse momentum with the ATLAS detector in proton-proton collisions at $\sqrt{s}$ = 8 TeV

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	$0.2 \pm 0.5 \pm 0.1$	$1.6 \pm 0.8 \pm 1.2$
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

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

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

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:

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

Reproduced limit:

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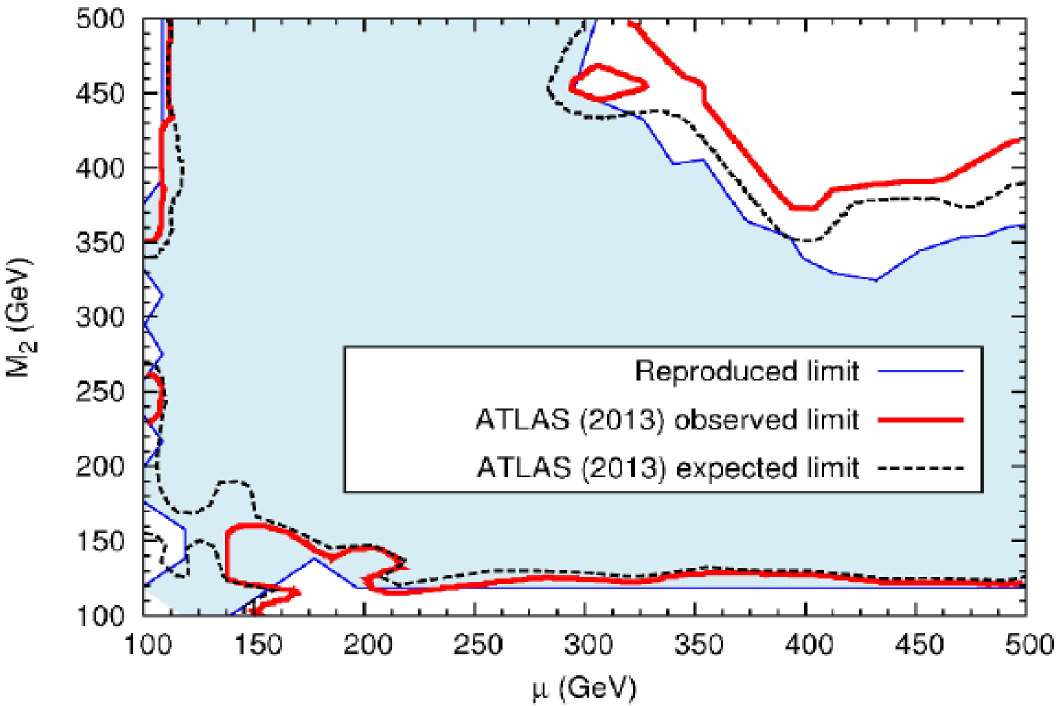

Results

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 paramter space:

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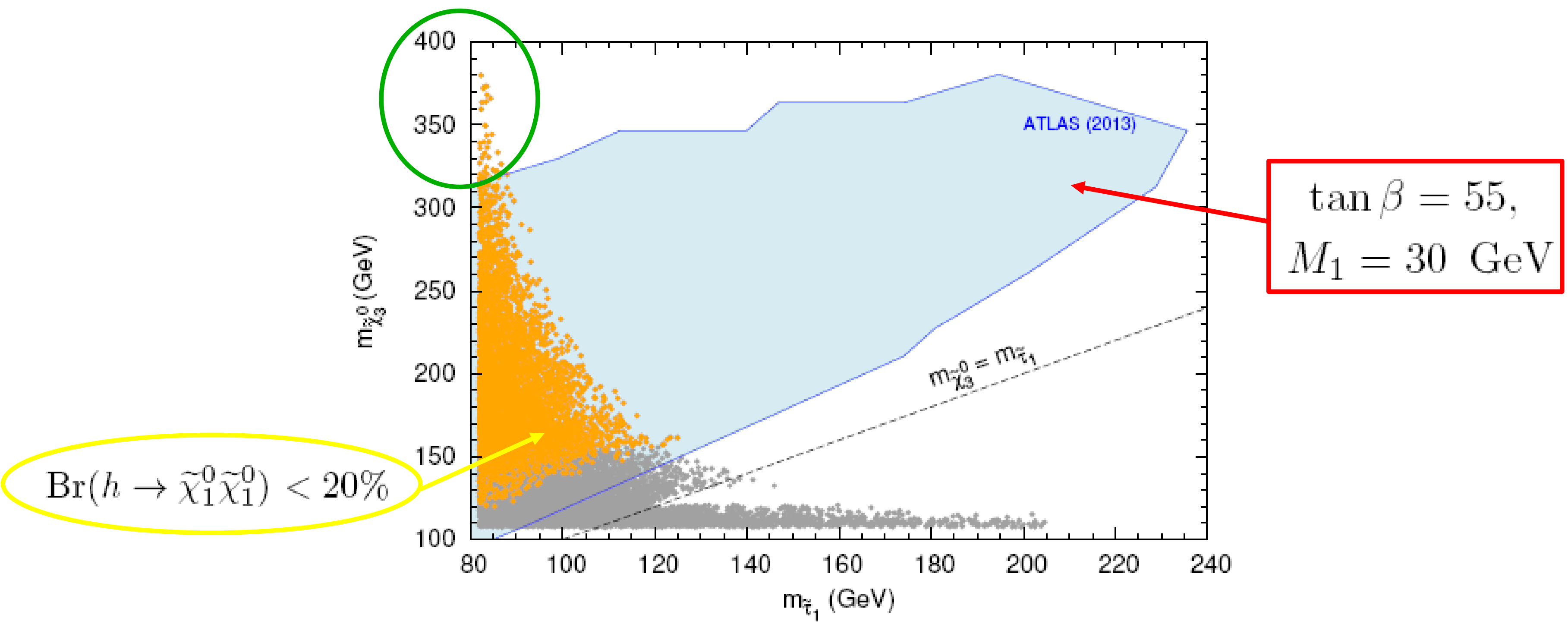

Herwig++ (event samples)

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Cuts of two Atlas SR applied

95% CL limits on the number of events:

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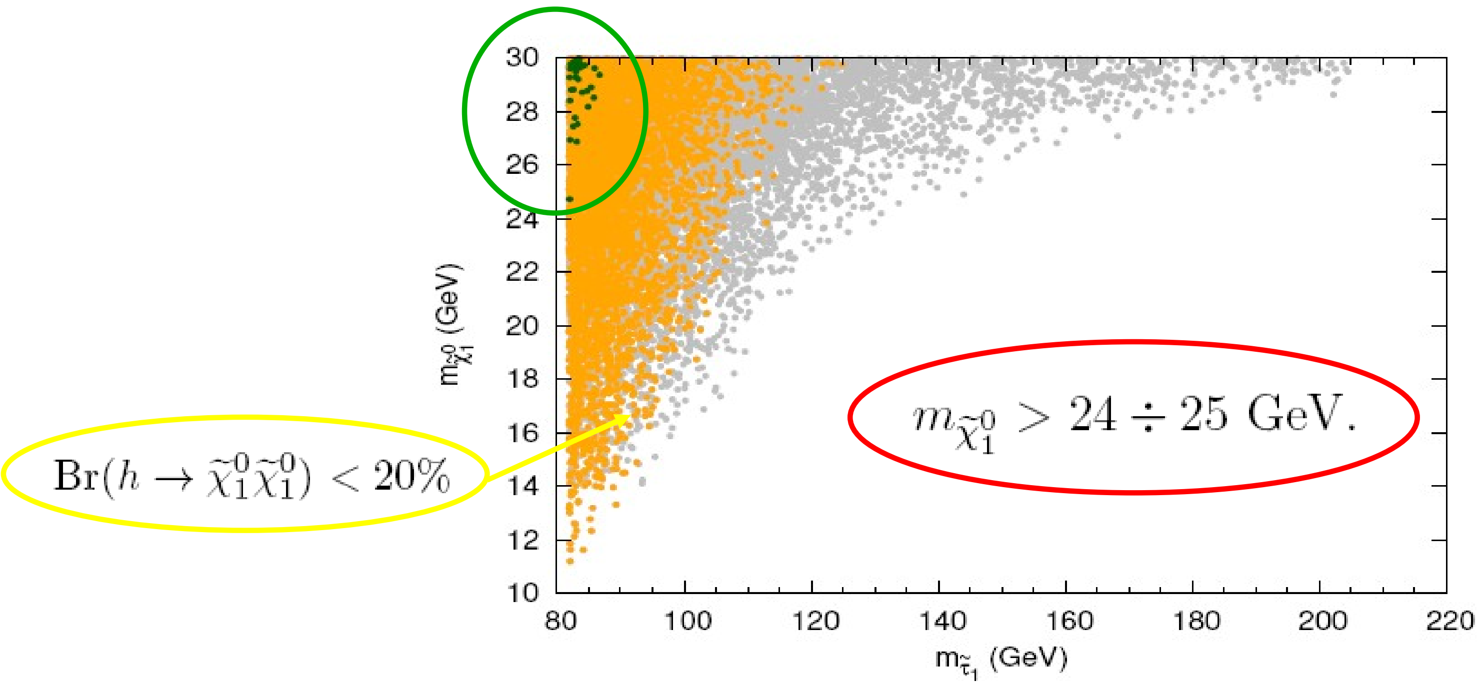
Interpretation on the stau-neutralino mass plane:

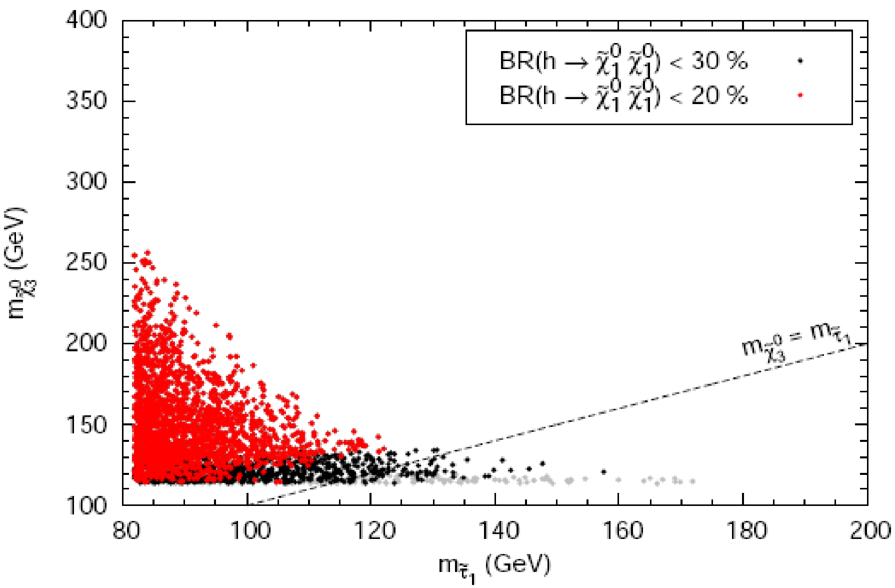


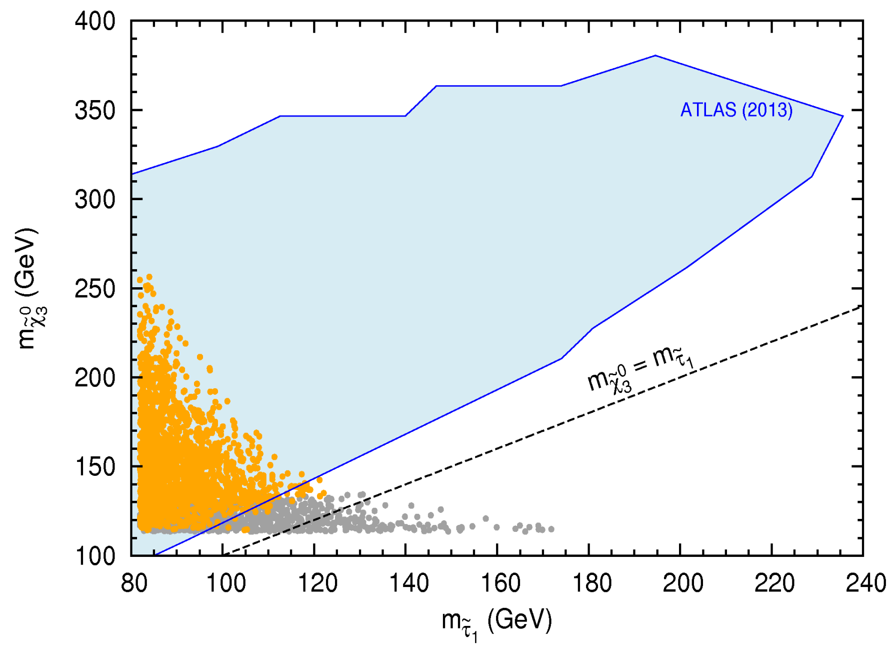
Negative μ

Flipping the sign of μ:

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 $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$





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

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

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

Few parameters involved: manageable simplified model

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

Reinterpreation of a ATLAS search sets strong constraint on light Neutralino Dark Matter (in combination with scalar -> invisible)

Limit stronger than direct/indirect DM searches

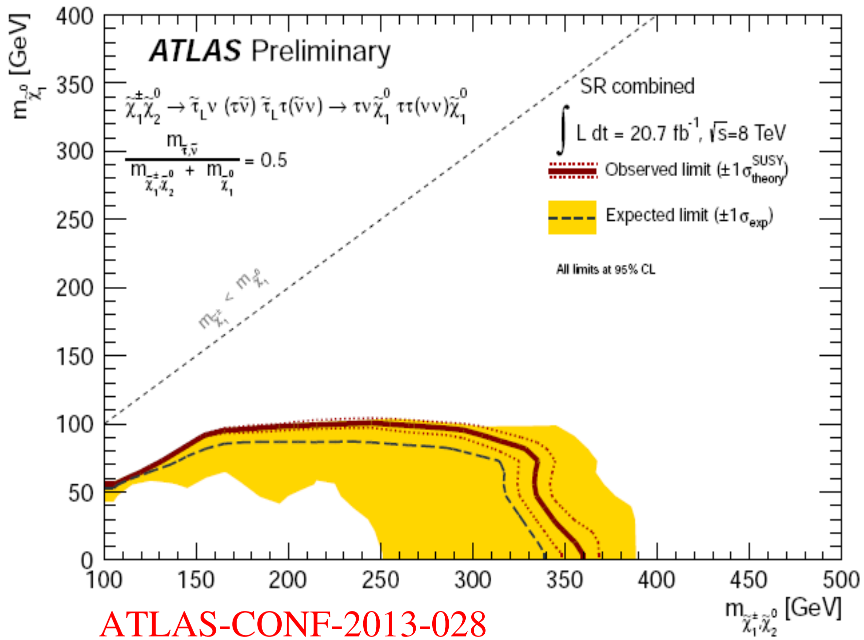
Nice interplay among different experimental info (collider and not)

Backup slides

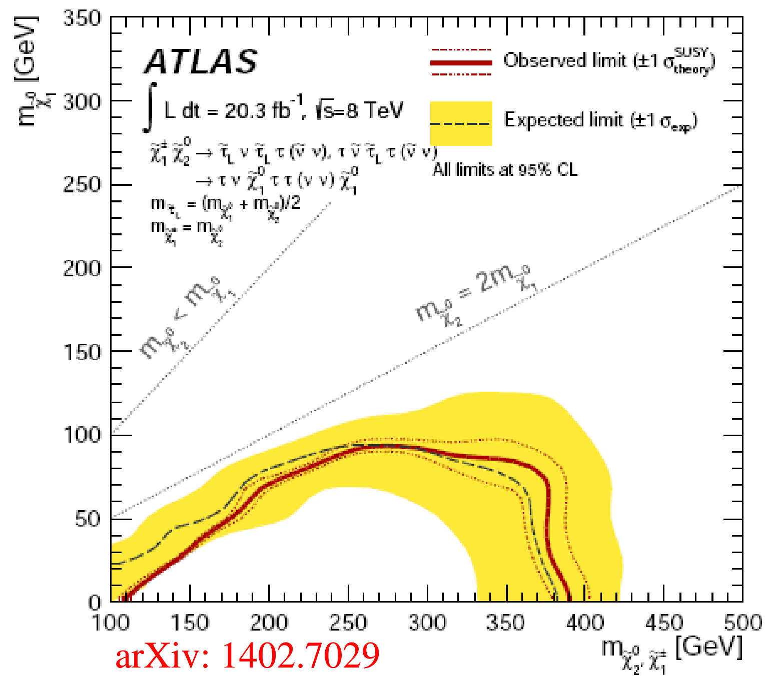
Other related searches: ATLAS arXiv:1402.7029

Table 5. Summary of the selection requirements for the validation regions. Energies, momenta and masses are given in units of GeV.

Region name	N(ℓ)	N(τ)	Flavour/sign	Z boson	E_T^{miss}	N(b-tagged jets)	Target process
VR0τnoZa	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	m_{SFOS} & $m_{3\ell}$ veto	35–50	–	WZ^*, Z^*Z^*, Z^*+jets
VR0τZa	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	request	35–50	–	WZ, Z+jets
VR0τnoZb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	m_{SFOS} & $m_{3\ell}$ veto	>50	1	$t\bar{t}$
VR0τZb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	request	>50	1	WZ
VR0τb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	binned	binned	1	WZ, $t\bar{t}$
VR1τa	2	1	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	–	35–50	–	WZ, Z+jets
VR1τb	2	1	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	–	>50	1	$t\bar{t}$
VR2τa	1	2	$\tau\tau\ell$	–	35–50	–	W+jets, Z+jets
VR2τb	1	2	$\tau\tau\ell$	–	>50	1	$t\bar{t}$



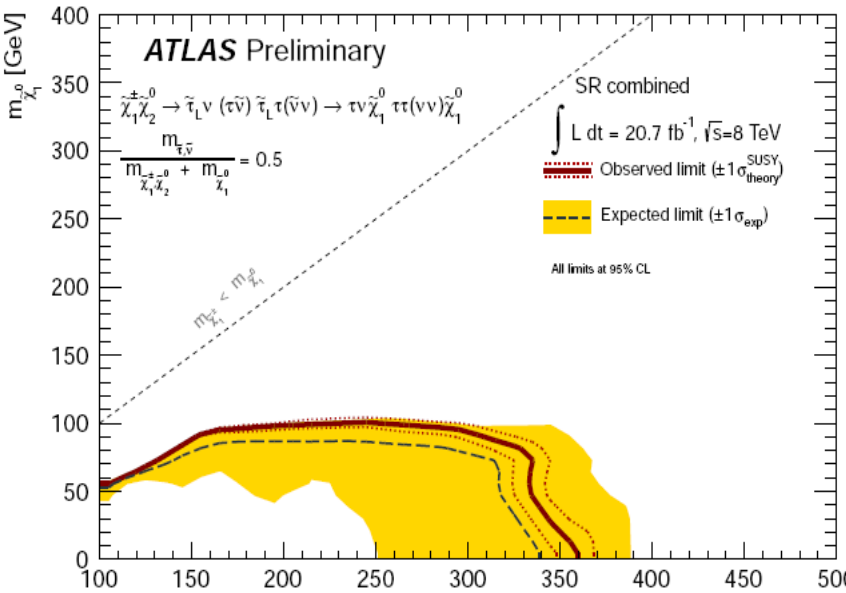
ATLAS-CONF-2013-028



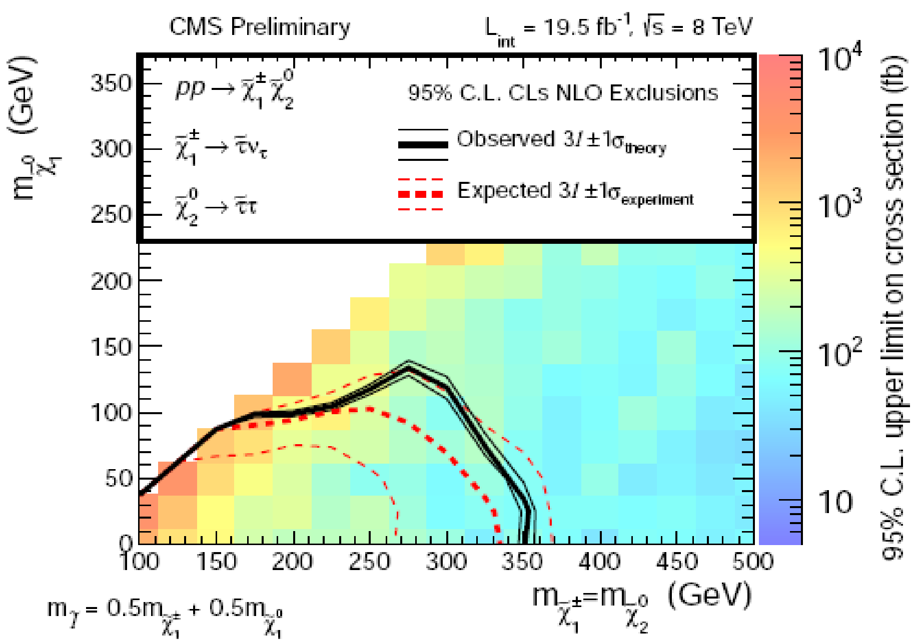
arXiv: 1402.7029

Other related searches: CMS-PAS-SUS-13-006

Search for electroweak production of charginos, neutralinos, and sleptons using leptonic final states in pp collisions at $\sqrt{s} = 8$ TeV



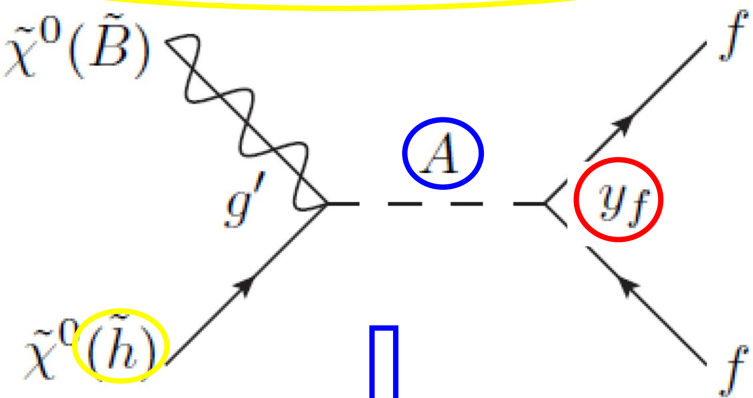
ATLAS-CONF-2013-028



CMS-PAS-SUS-13-006

Annihilation mechanisms: CP-odd scalar exchange

- Higgs mediated annihilation:



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

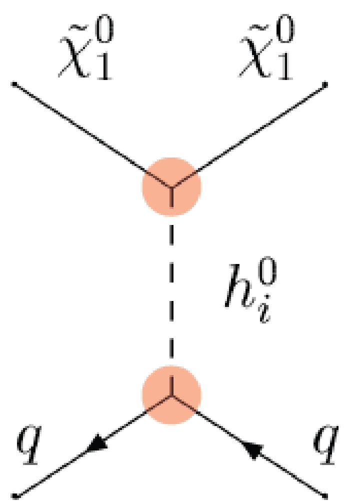
Drees Nojiri '92

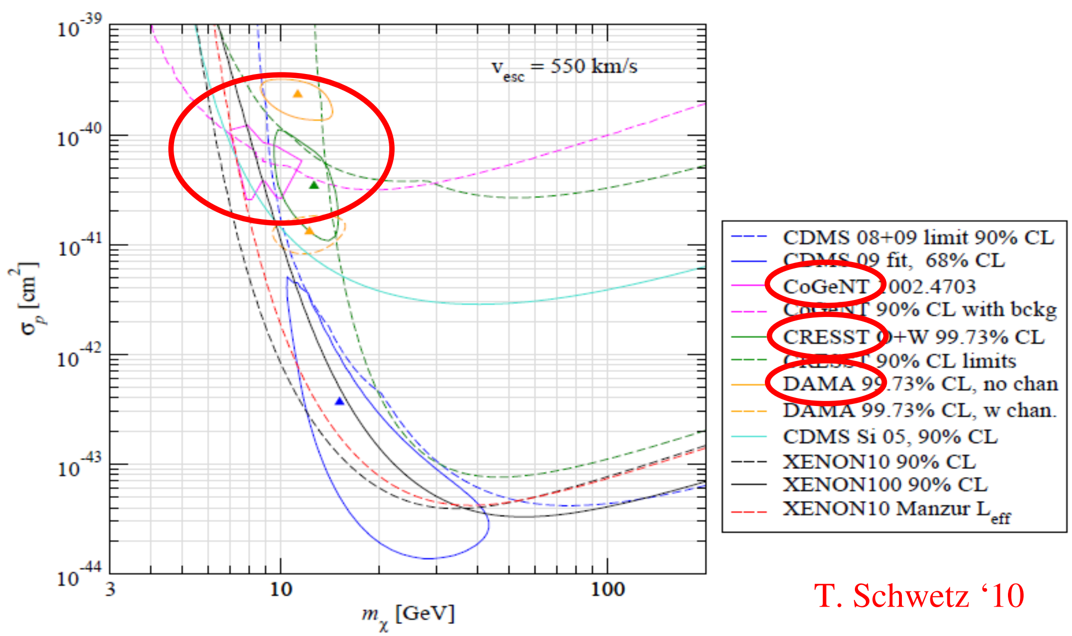
Small $m_{\tilde{\chi}^0_1} \Longleftrightarrow$ large $\tan\beta$, small m_A (and μ)

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

Bottino et al. '02- '10

Large scattering cross-section with nuclei:





T. Schwetz '10

Annihilation mechanisms: CP-odd scalar exchange

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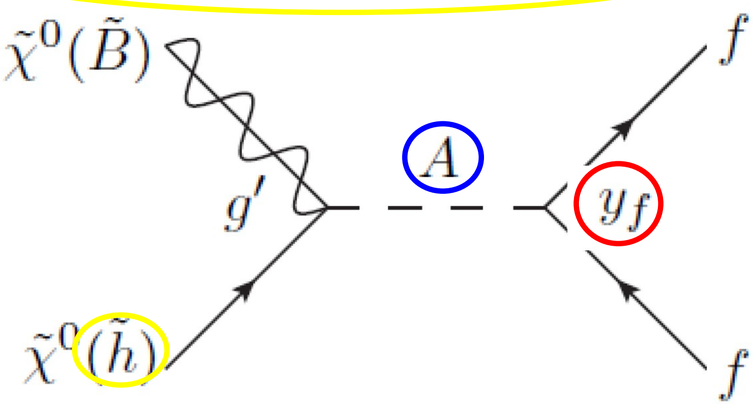


$$\propto \frac{m^2_{\tilde\chi^0_1}}{m^2_A}\,\frac{m_f}{v}\,(N_{11}N_{13,14})\,\tan\beta$$

Drees Nojiri '92

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

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

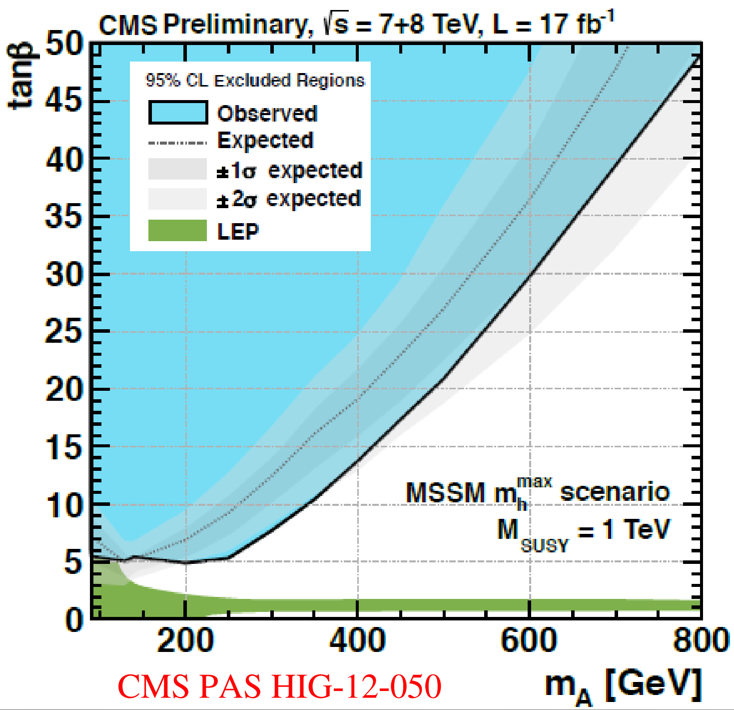
Bottino et al. '02- '10

This parameter space for light neutralinos is now excluded by:

- $B_s \to \mu^+\mu^-$
- Searches for extended scalr sector at the LHC, $pp \to X\,\Phi \to \tau\tau$
- Mass and couplings of the 126 GeV scalar

LC Ota Takanishi '11

⇨ MSSM not compatible with 10 GeV DM

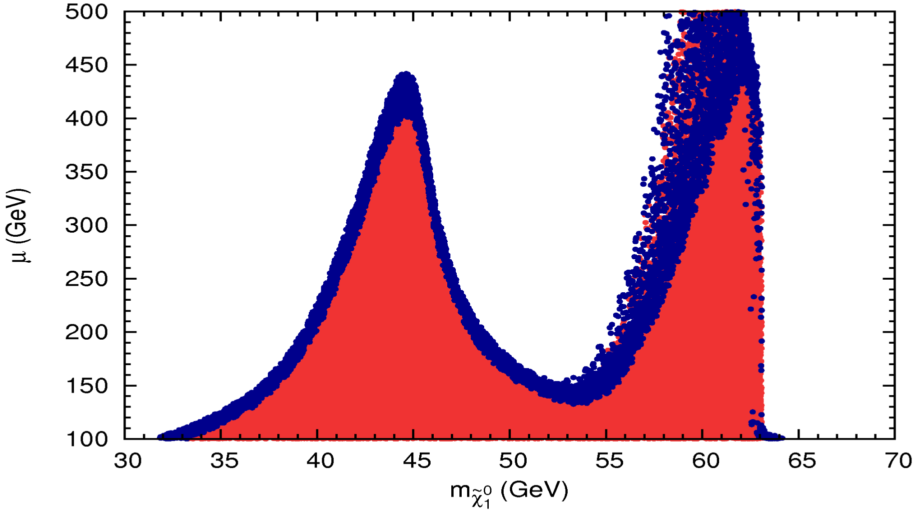


CMS PAS HIG-12-050

LC Lindert Ota Takanishi, work in progress

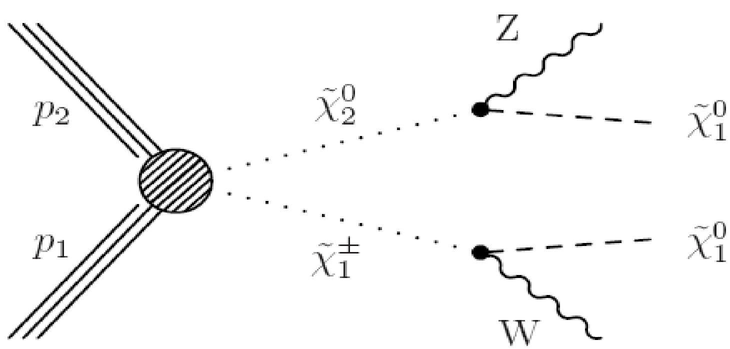
What if all sfermions are heavy?

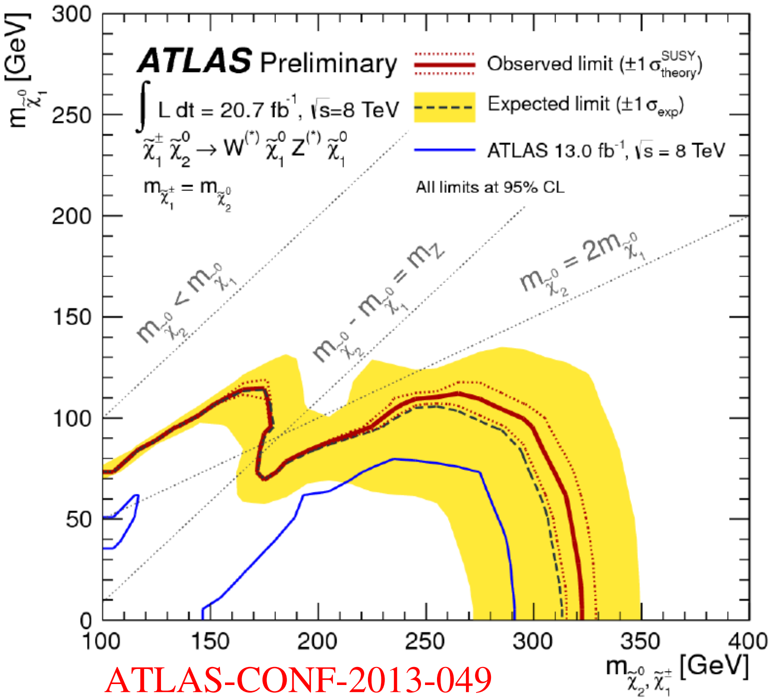
Dark Matter can hide close to the Z or h resonances



Problematic for direct/indirect searches

Again, LHC searches can test it!





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