MITP workshop, Mainz

July 17th 2014

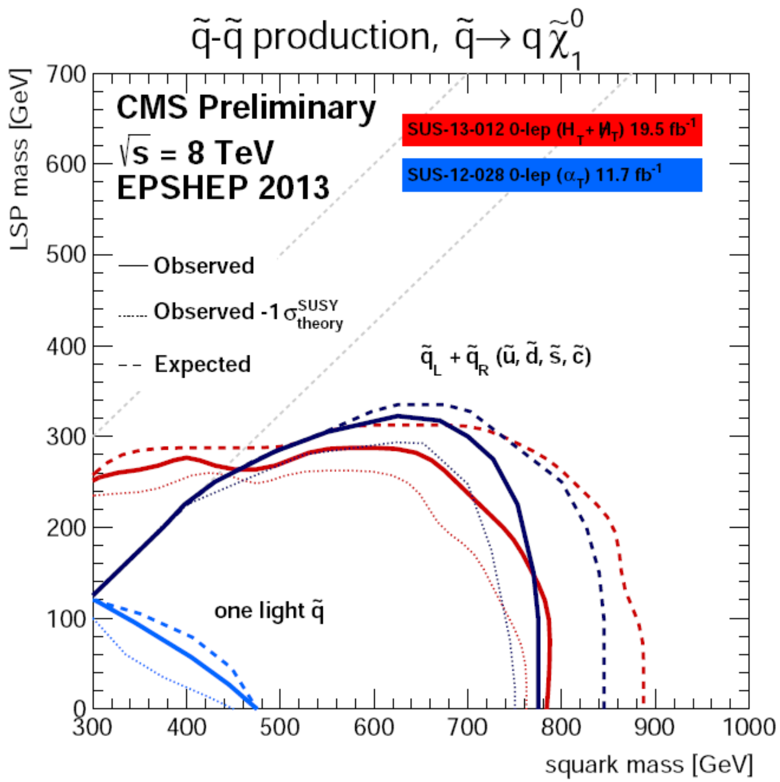
Probing light Neutralino Dark Matter at the LHC

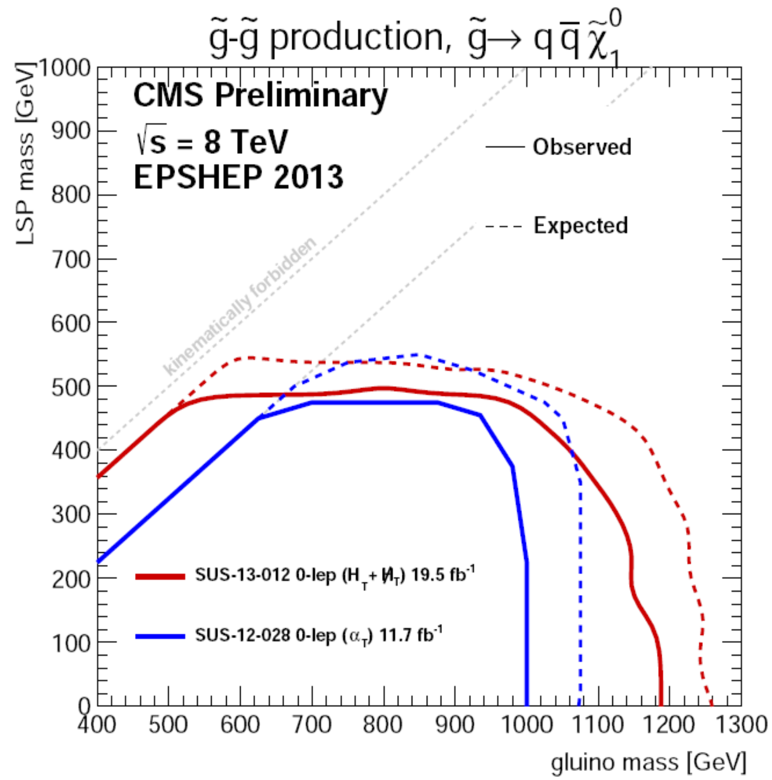
Lorenzo Calibbi

ULB

UNIVERSITÉ LIBRE DE BRUXELLES

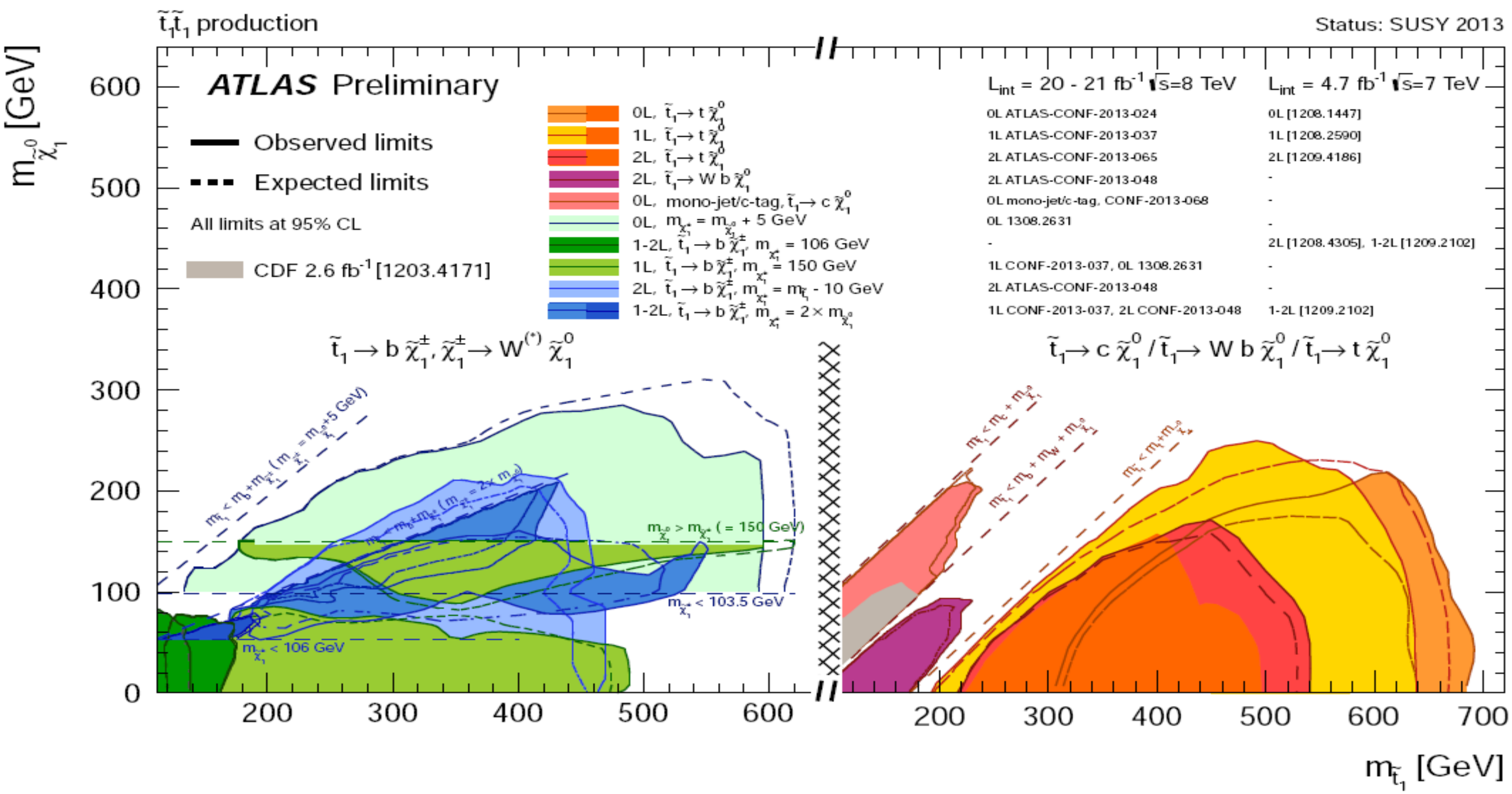
based on collaborations with J. Lindert, T. Ota, Y. Takanishi





Strongly-interacting SUSY particles (gluinos, 1st generation squarks)

typically excluded by the LHC above ~1 TeV



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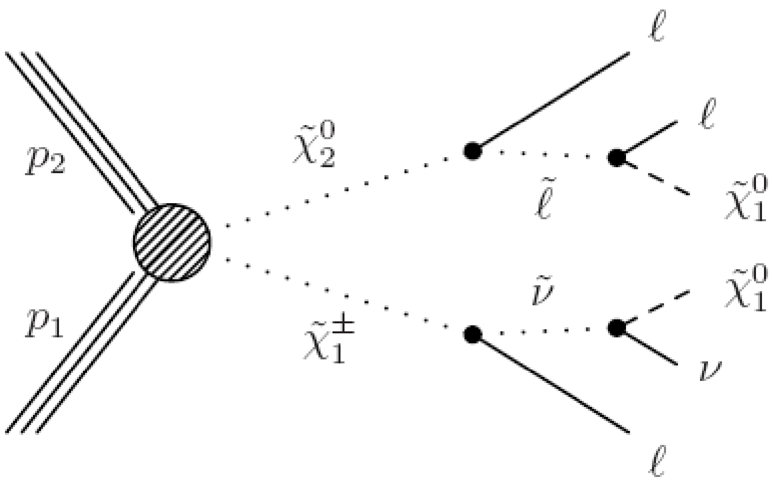
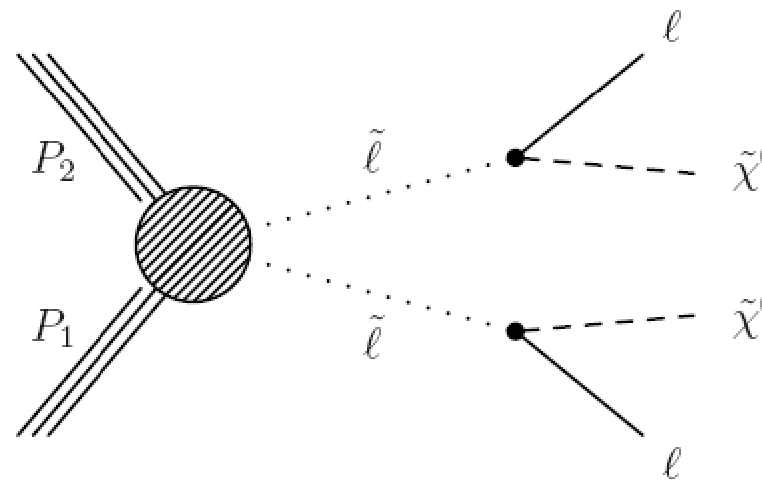
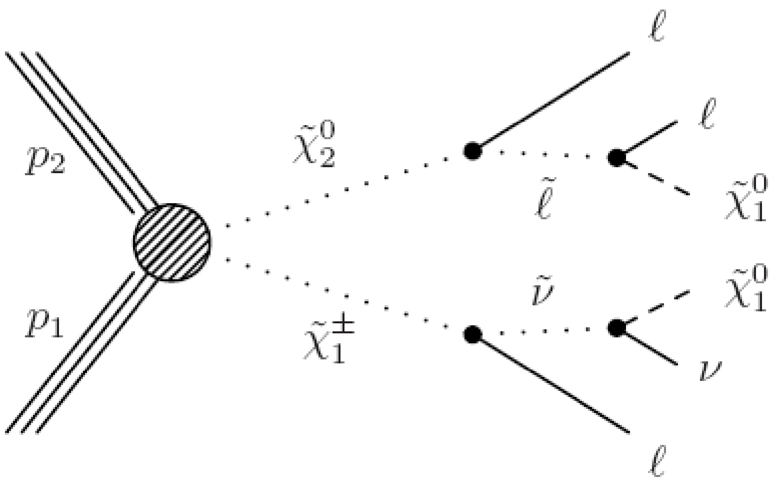
Introduction

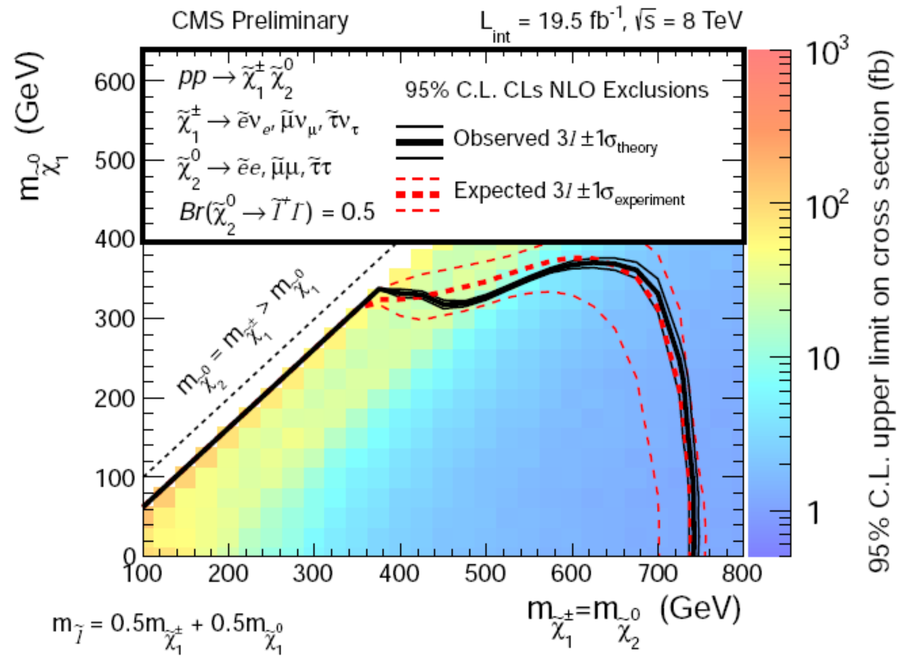




Direct bounds on EW-iteracting particles relatively weaker (smaller production)

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





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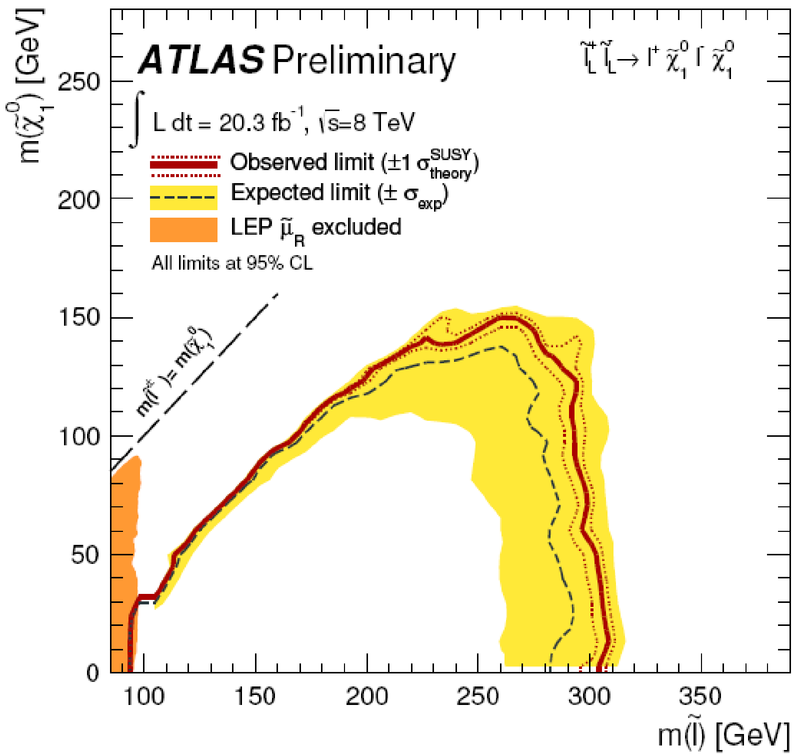

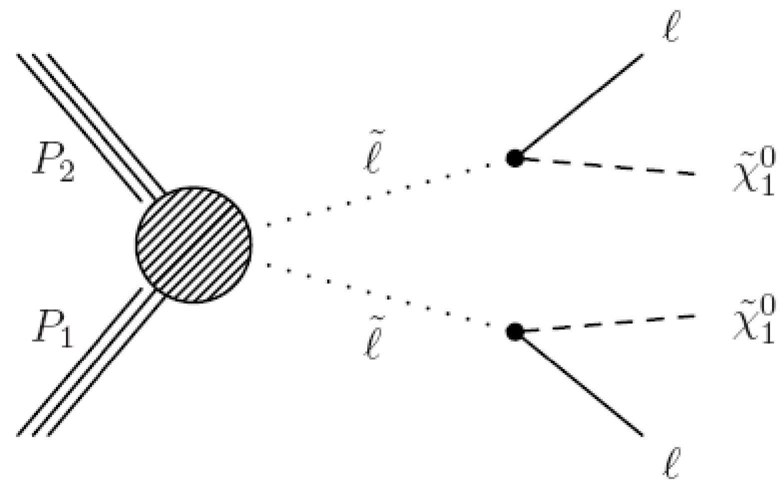

Direct bounds on EW-iteracting particles relatively weaker (smaller production)

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?

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

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

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: $m_{\widetilde{\chi}^\pm} > 103.5$ GeV

⇓

$$M_2,\ \mu \gtrsim 100 \text{ GeV}$$

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

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

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

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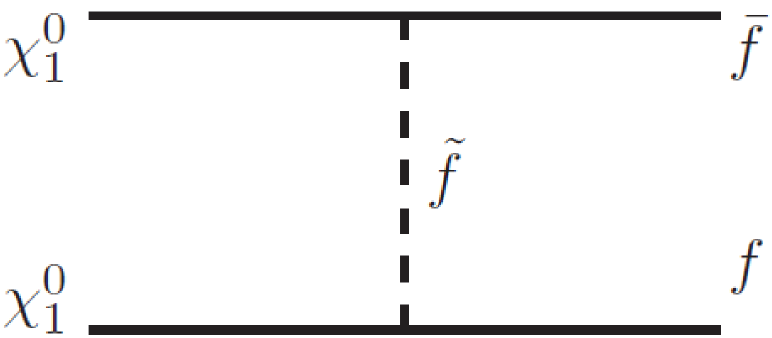
$$m_{\widetilde{\chi}_1^0} \lesssim 30 \text{ GeV} \quad \Rightarrow \quad M_1 \ll M_2,\ \mu \iff \tilde{\chi}_1^0 \approx \tilde{B}$$

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

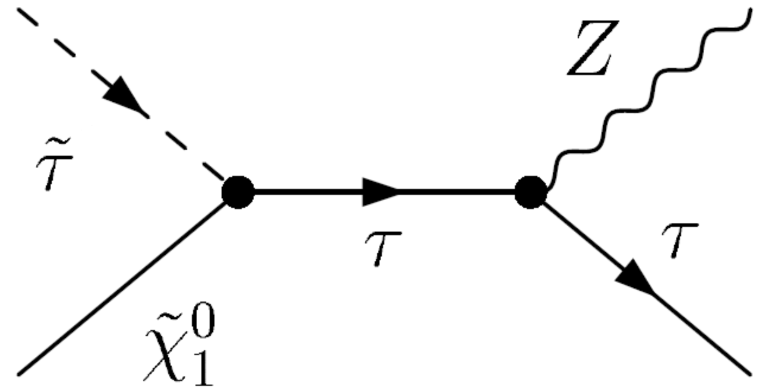
Efficient annihilation required

Annihilation mechanisms

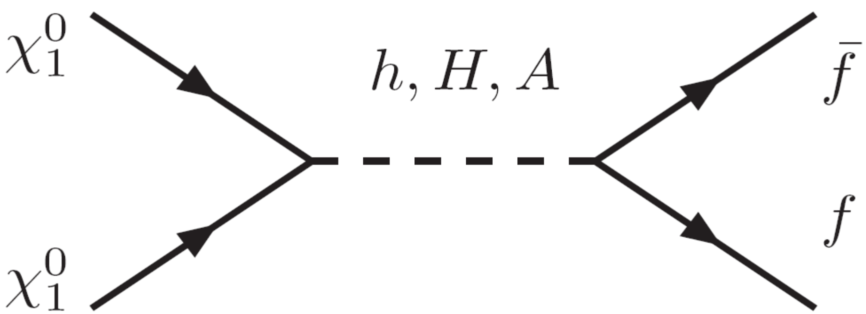
t-channel exchange (e.g. sfermions):



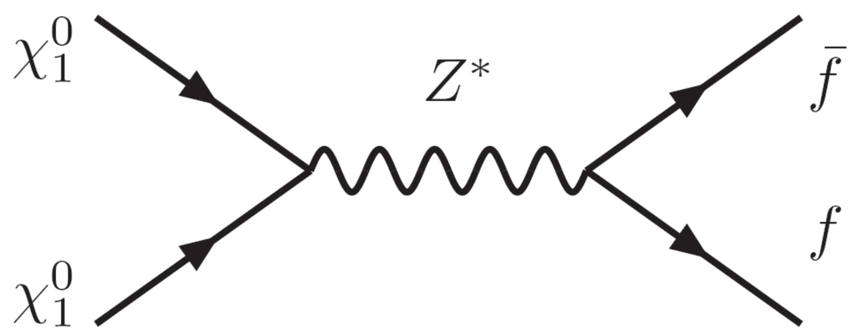
Coannihilations (e.g. stau):



Higgs mediation:



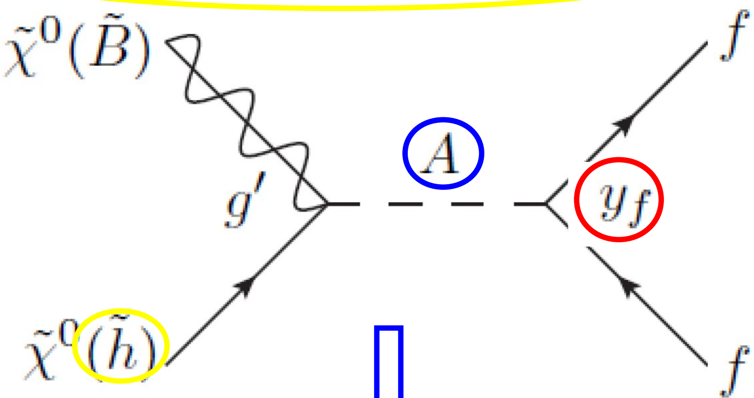
Z mediation:



⇨ different regions of the SUSY parameter space are selected

Annihilation mechanisms: Higgs exchange

- Higgs mediated annihilation:



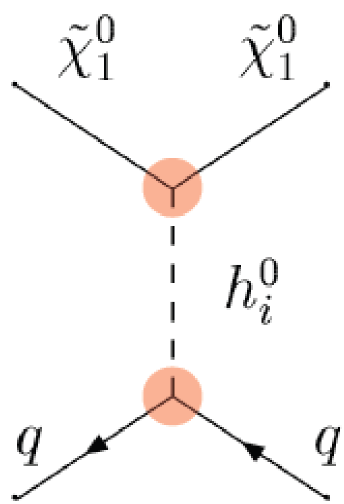
$$\propto \frac{m^2_{\tilde\chi^0_1}}{m_A^2}\,\frac{m_f}{v}\,(N_{11}N_{13,14})\,\tan\beta$$

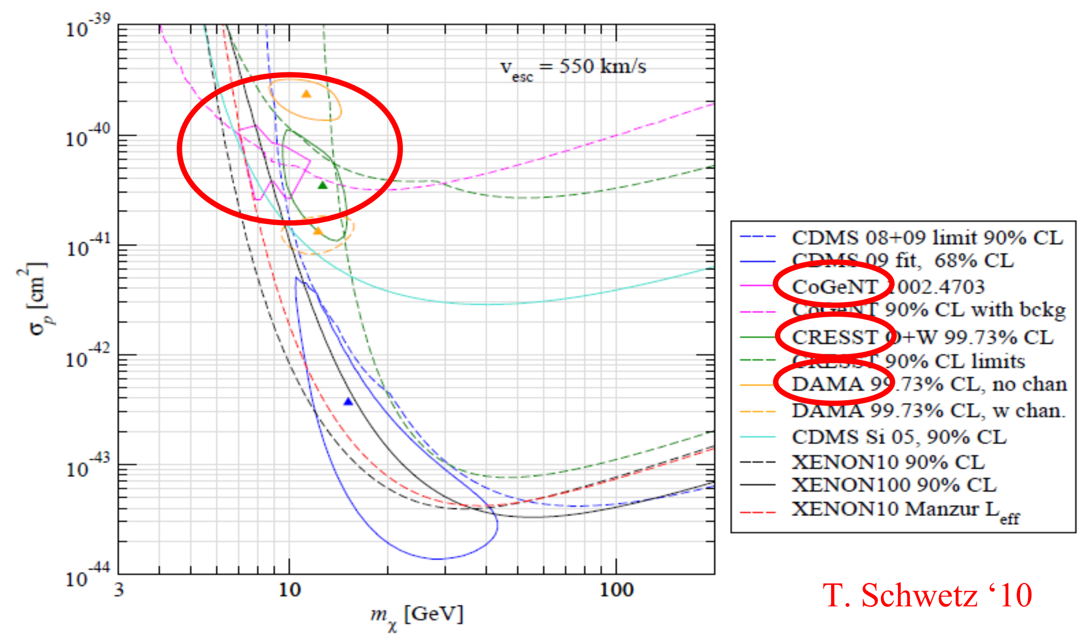
Drees Nojiri '92

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:

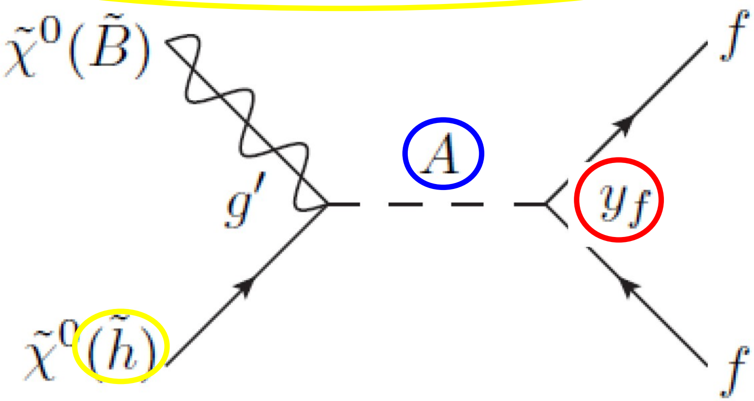




T. Schwetz '10

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:

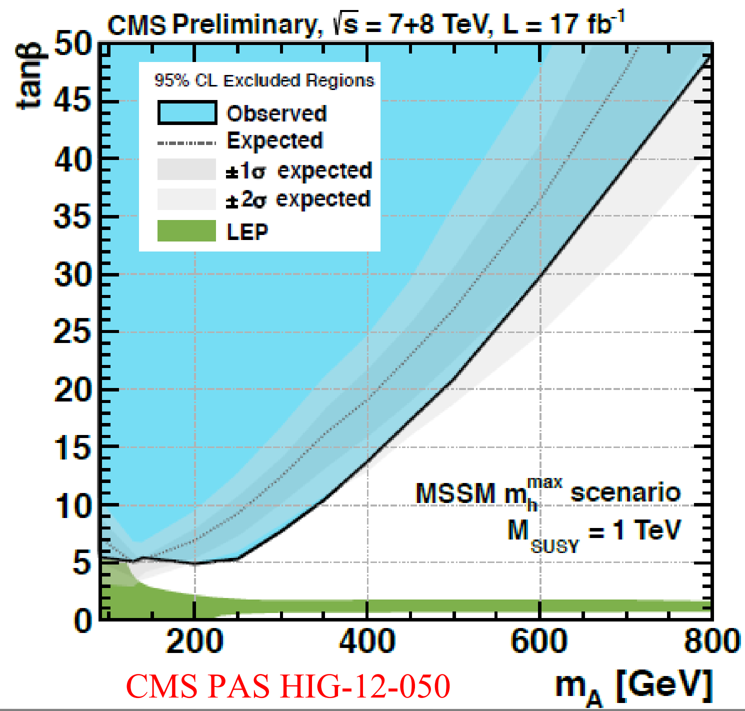
• $B_s \to \mu^+\mu^-$

• Searches for extra Higgses at the LHC,
$pp \to X\,\Phi \to \tau\tau$

Higgs mass and couplings

⇨ MSSM incompatible with DAMA, CoGeNT

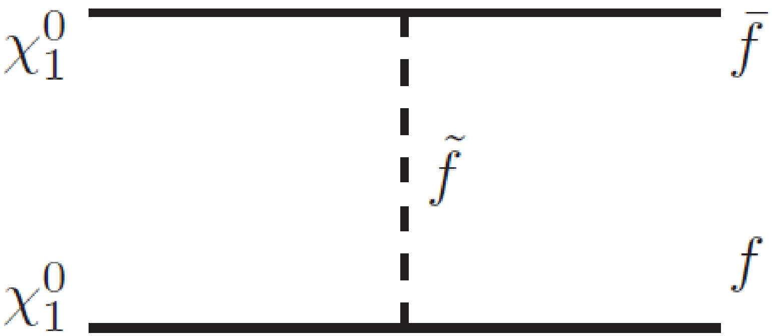
LC Ota Takanishi '11



CMS PAS HIG-12-050

Annihilation mechanisms: sfermion exchange

Sfermion mediated annihilation:



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

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

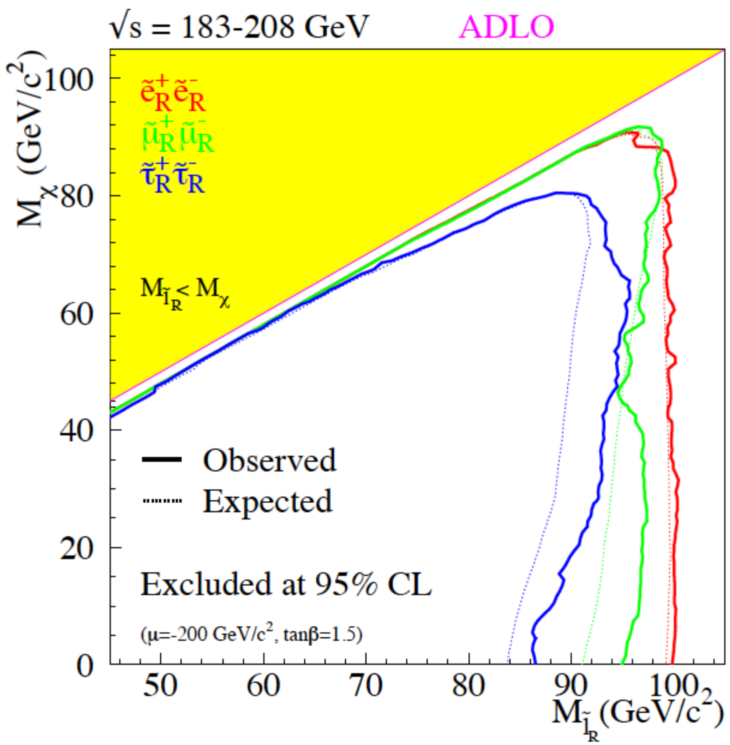
Can one evade it with compressed spectra?

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

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

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

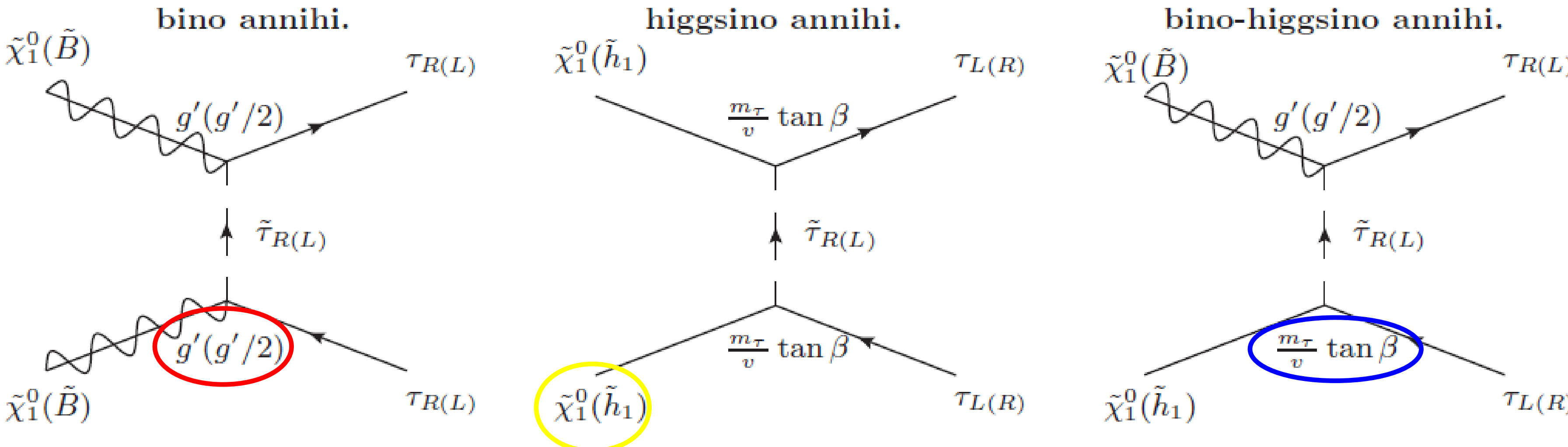
Challenged by LEP bounds, e.g.:



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:

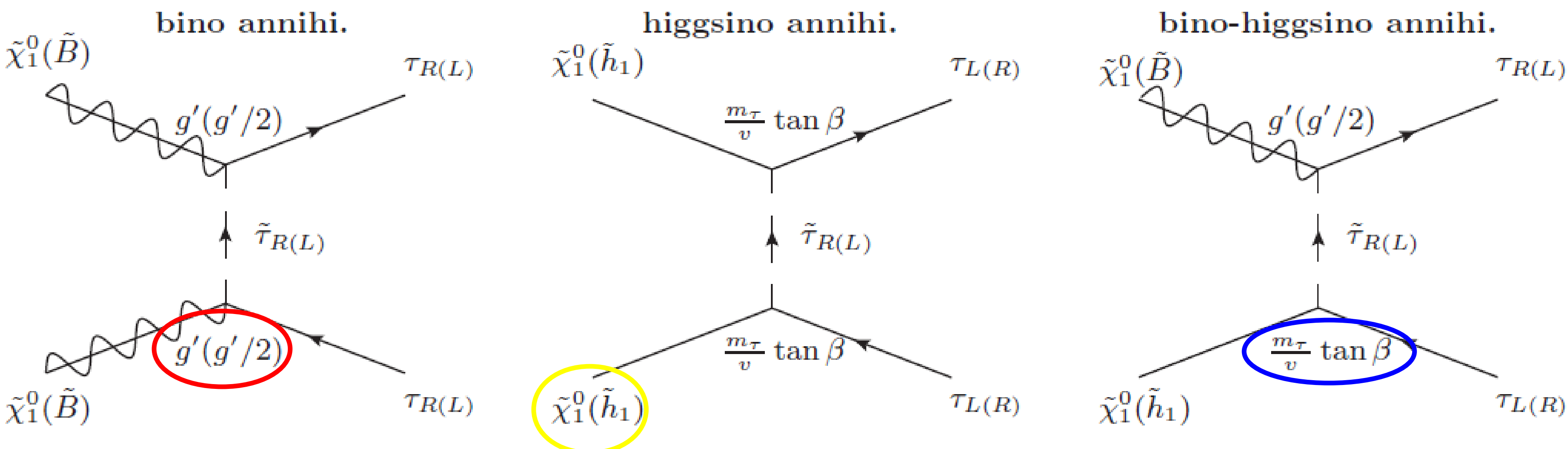
$$M_1, \ m_{\tilde{\tau}_R}, \ \mu, \ \tan\beta$$

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)
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Light neutralino DM necessarily implies:

light stau, light higgsino-like neutralinos and charginos

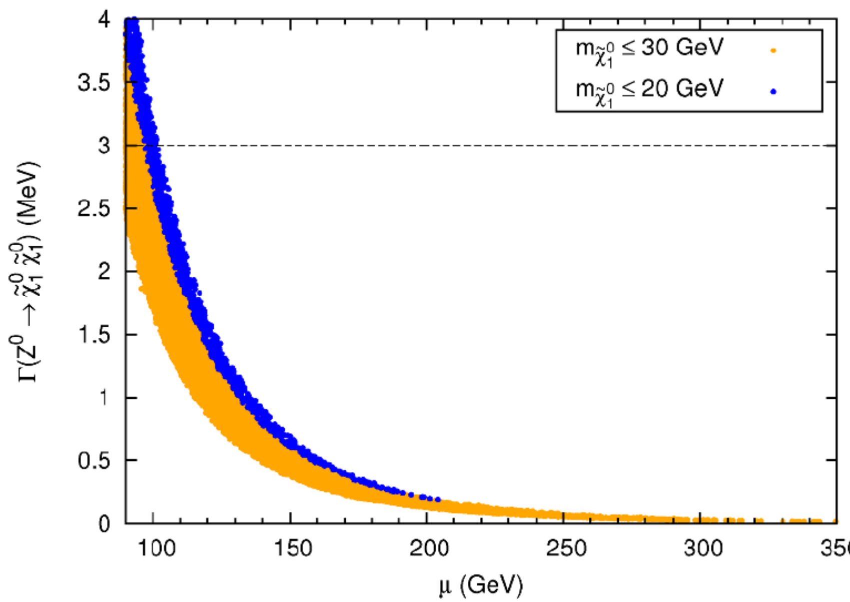
Parameters scan and constraints

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

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

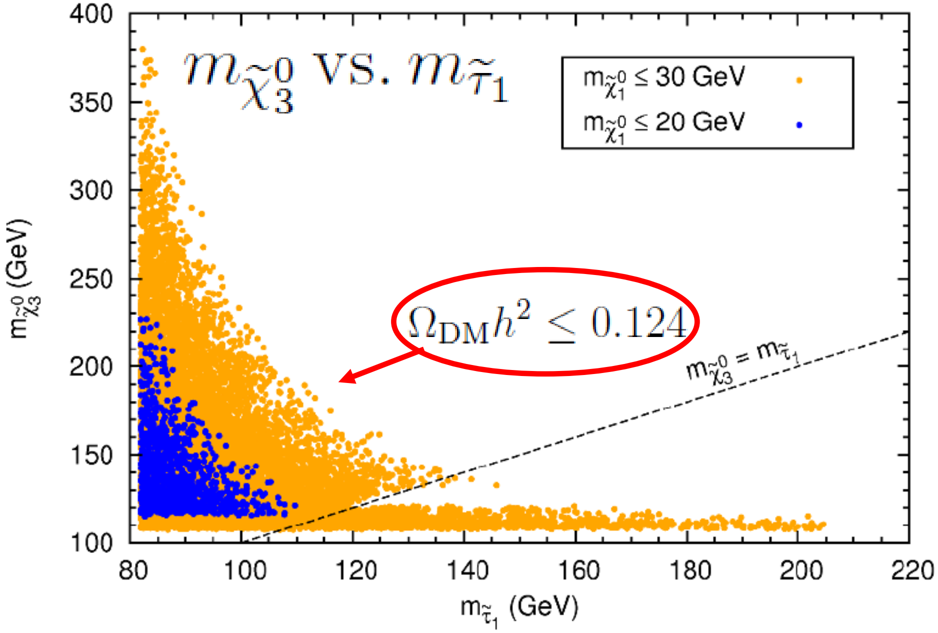
- $m_{\tilde{\chi}_1^0} \leq 30$ GeV
- **CMB**, Planck (3σ): $\Omega_{DM} h^2 \leq 0.124$
- **LEP2**: $m_{\tilde{\tau}_R} \geq 81.9\,\text{GeV}, \quad m_{\tilde{\chi}_1^\pm} \geq 103.5\,\text{GeV}$
- **LHC**: limits on charginos depend on smuon/selectron masses and can be evaded
- **Flavour**: Ω_{DM}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

LC Lindert Ota Takanishi '13



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

LC Lindert Ota Takanishi '13

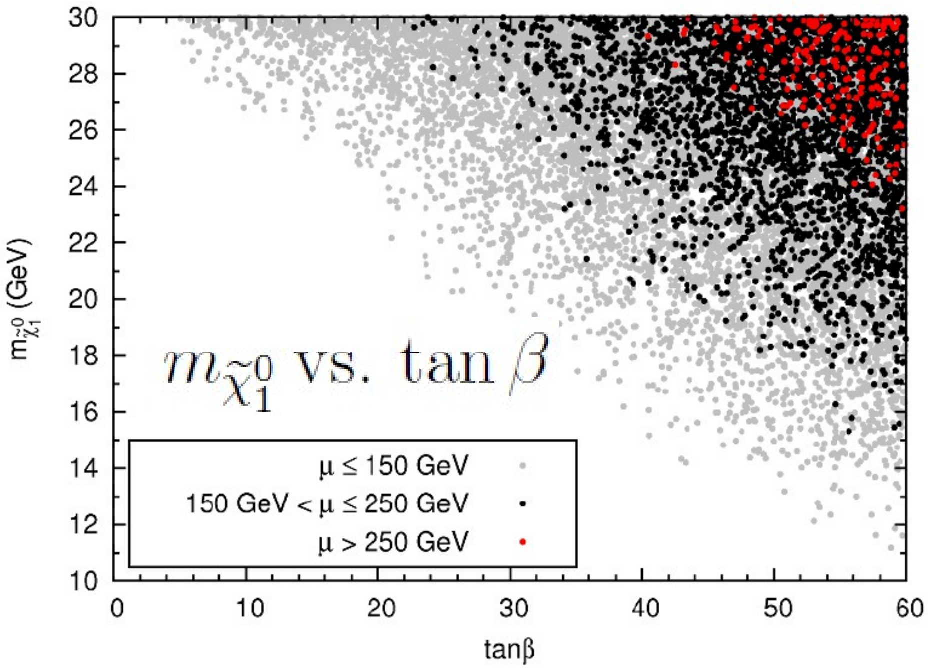


$$m_{\tilde{\chi}_1^0} \gtrsim 11 \text{ GeV}$$

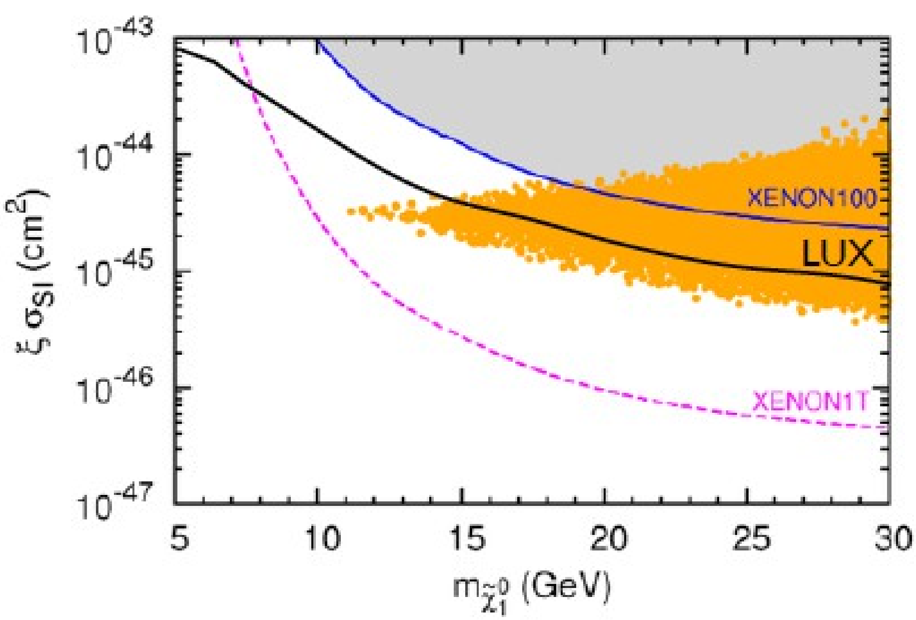
$$(\tan\beta \leq 60)$$

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

$$m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_3^0} \lesssim 380 \text{ GeV}$$



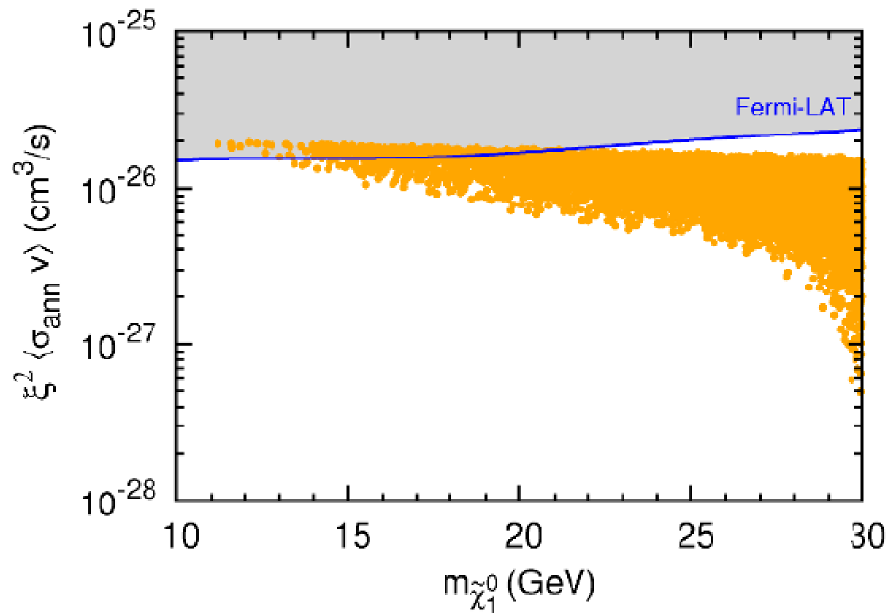
Spin-independent scattering cross section



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:

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

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:

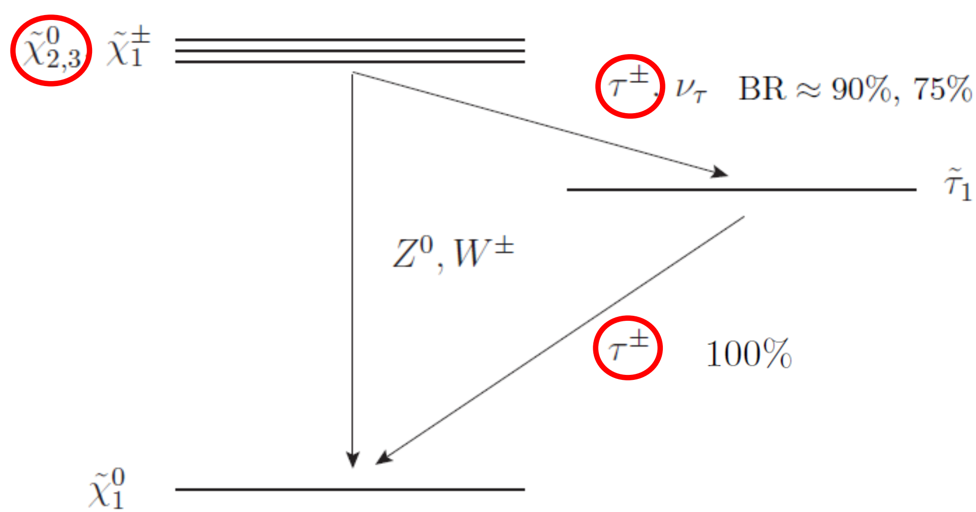
$$m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_{2,3}^0} > m_{\tilde{\tau}_1} > m_{\tilde{\chi}_1^0}$$

⇩

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

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

multi-tau signals!



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

Decays:

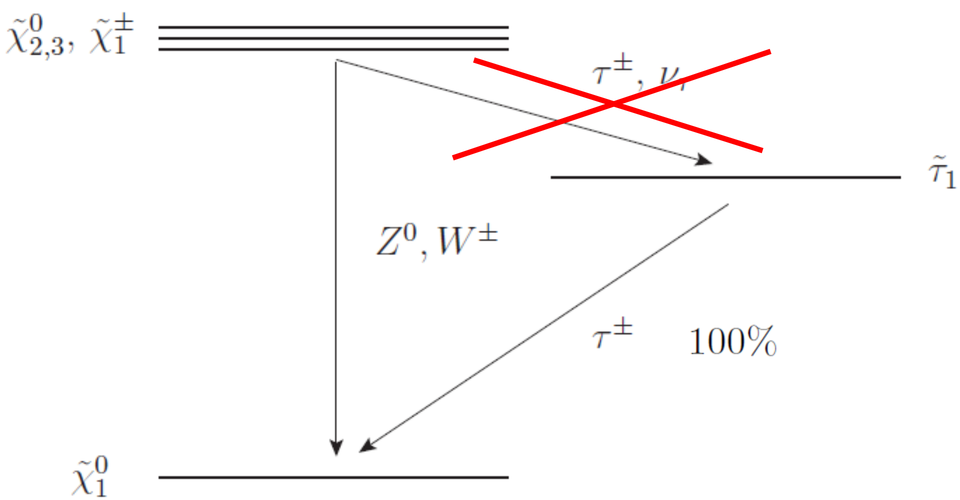
$$m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\chi}_1^0}$$

⇩

3-body decays

it might be more difficult

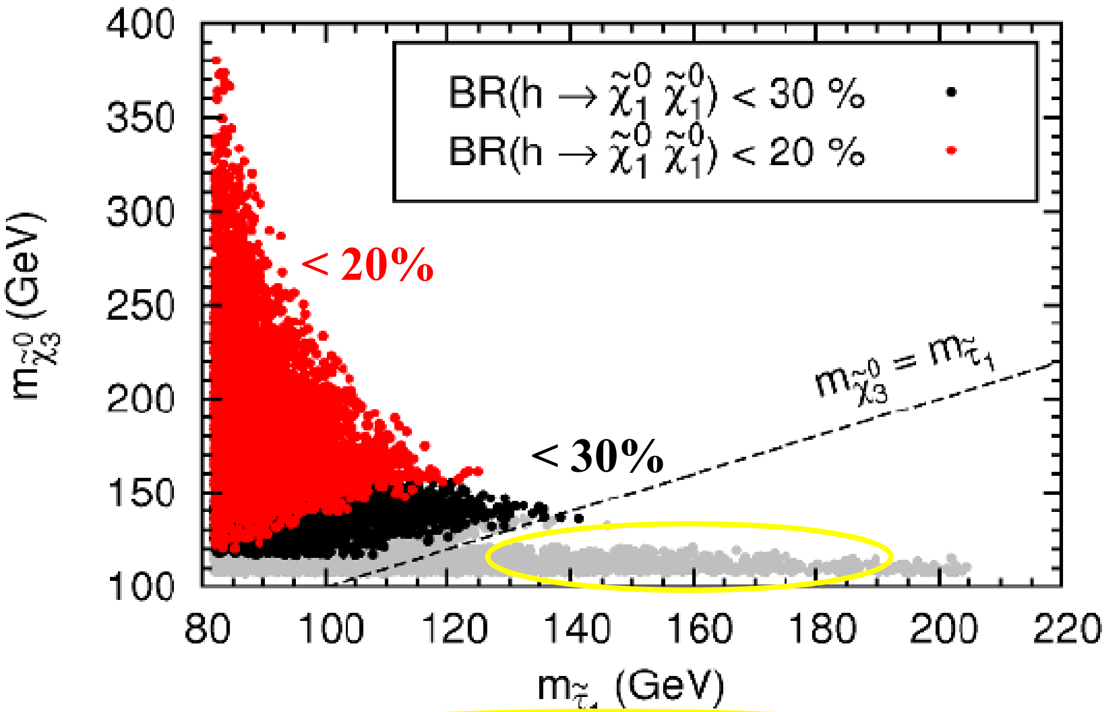
However…



LHC phenomenology: invisible Higgs decay

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

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



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

Last fits to Higgs data:

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

Falkowski et al. ‘13

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

Giardino et al. ‘13

but with 20% theo unc.:

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

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

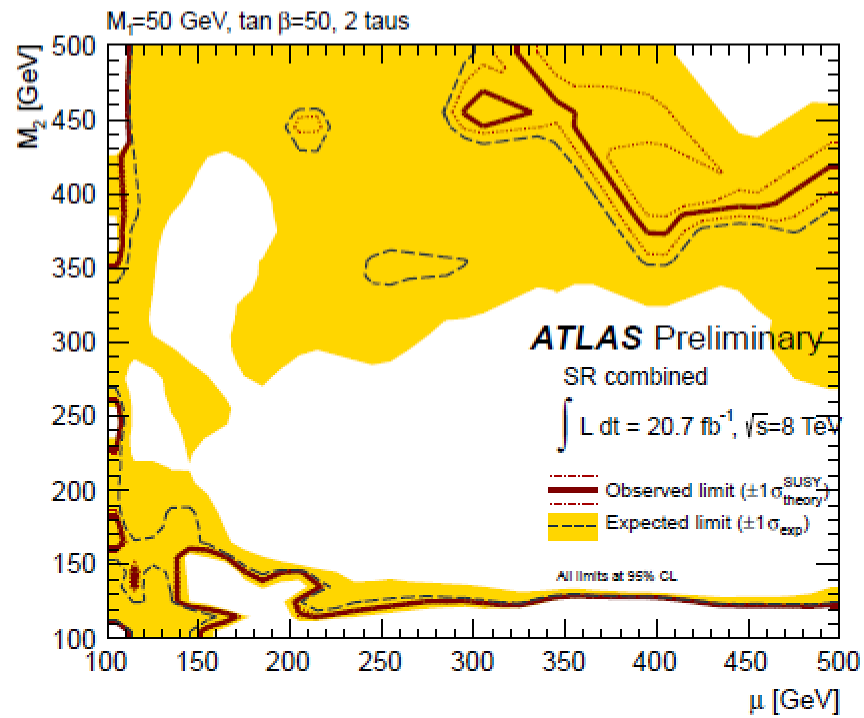
The ATLAS Collaboration

News from Atlas

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

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

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

Herwig++ (event samples)

Prospino 2 (NLO K-factors)

Delphes 3 (fast detector simul.)

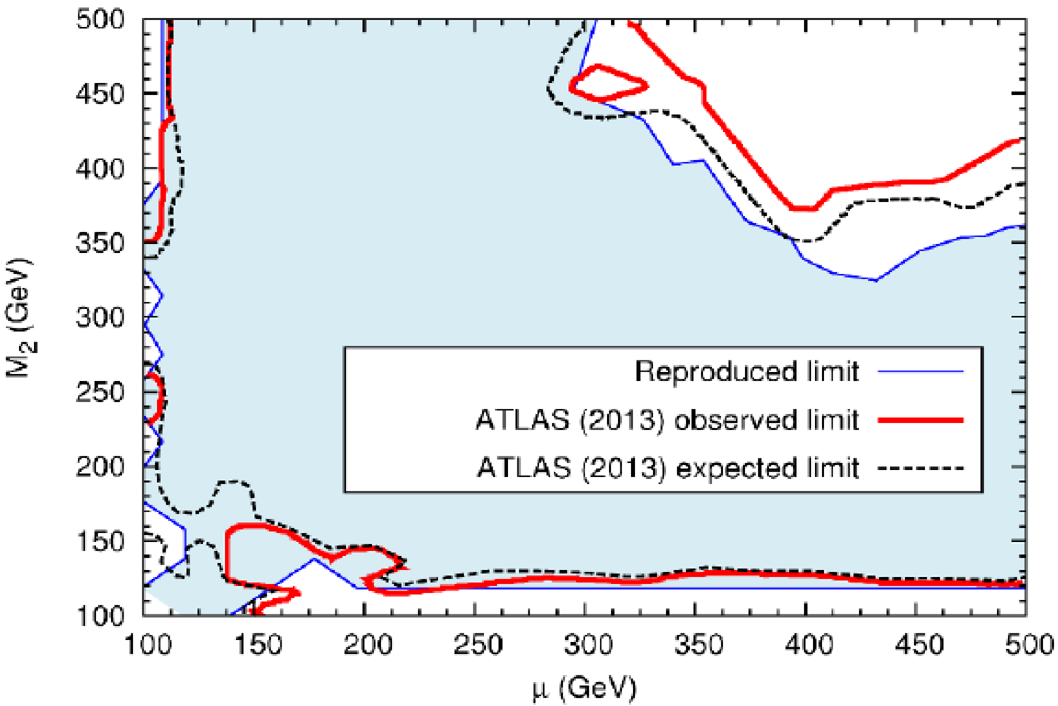
Cuts of two Atlas SR applied

95% CL limits on the number of events:

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

Reproduced limit:

LC Lindert Ota Takanishi '13



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Interpretation on our paramter space:

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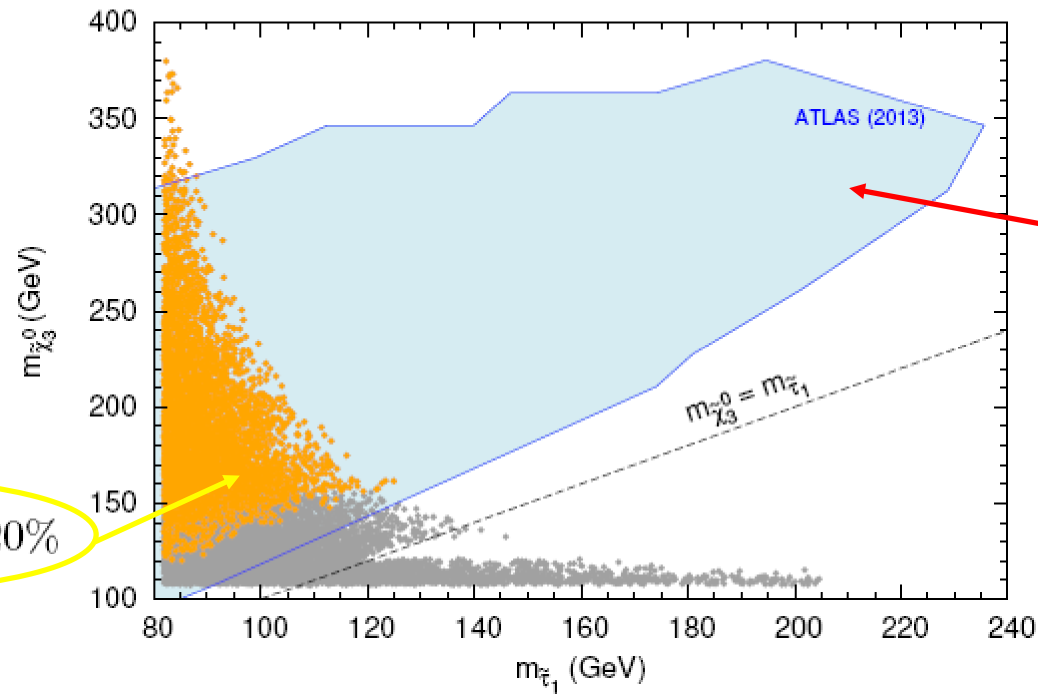

$\mathrm{Br}(h \to \tilde{\chi}^0_1 \tilde{\chi}^0_1) < 20\%$

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

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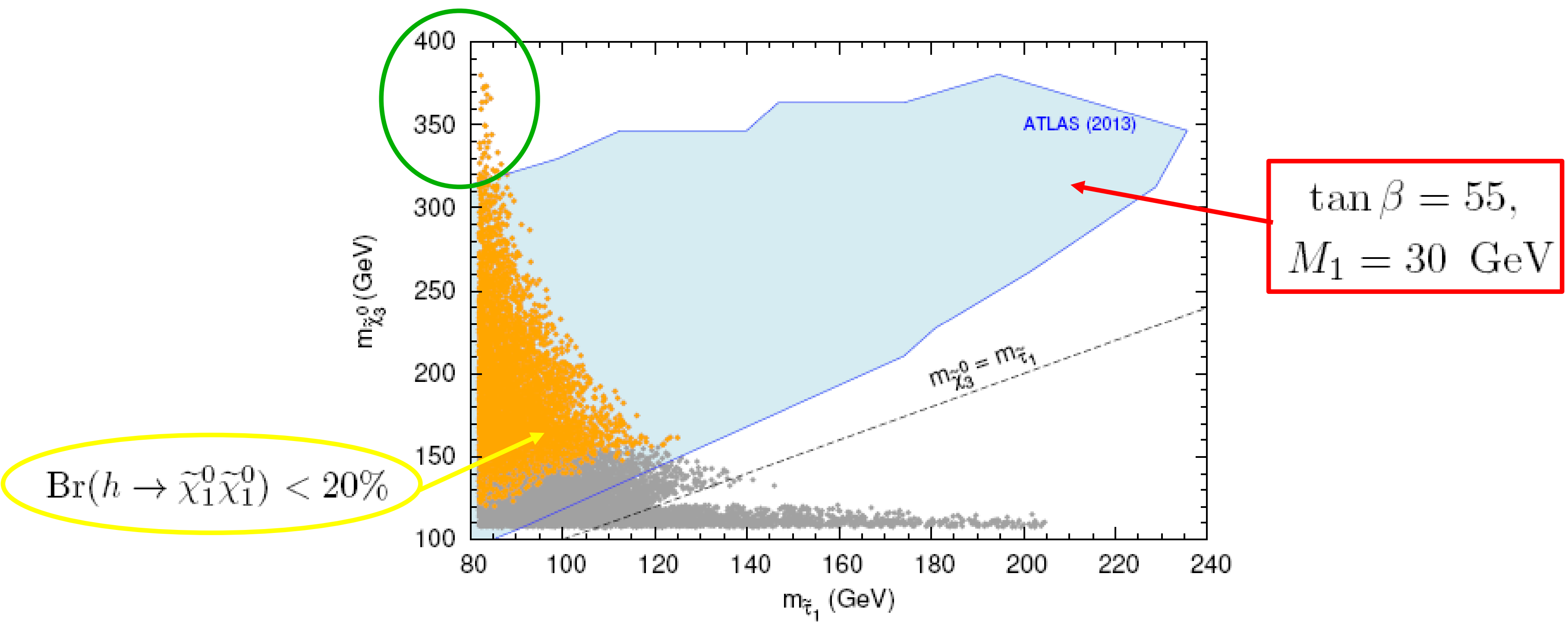
LC Lindert Ota Takanishi '13



Herwig++ (event samples)

Prospino 2 (NLO K-factors)

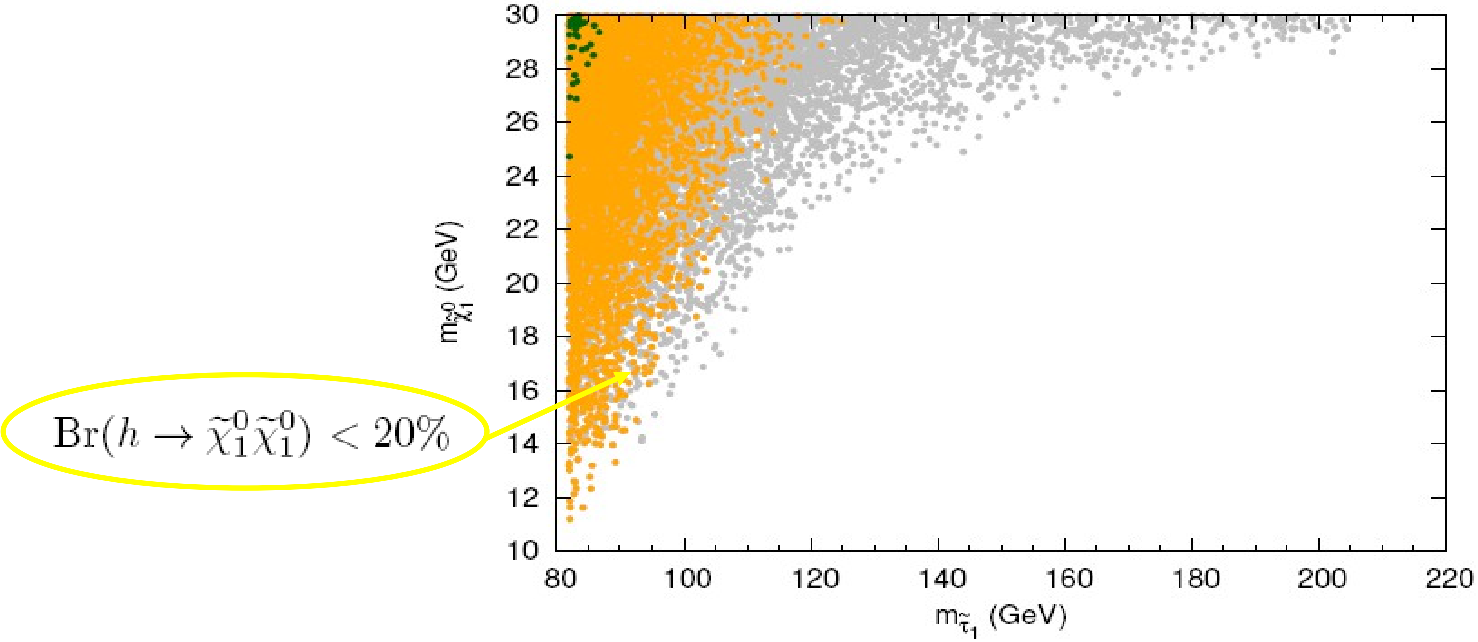
Delphes 3 (fast detector simul.)

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 the stau-neutralino mass plane:



Results

Herwig++ (event samples)

Prospino 2 (NLO K-factors)

Delphes 3 (fast detector simul.)

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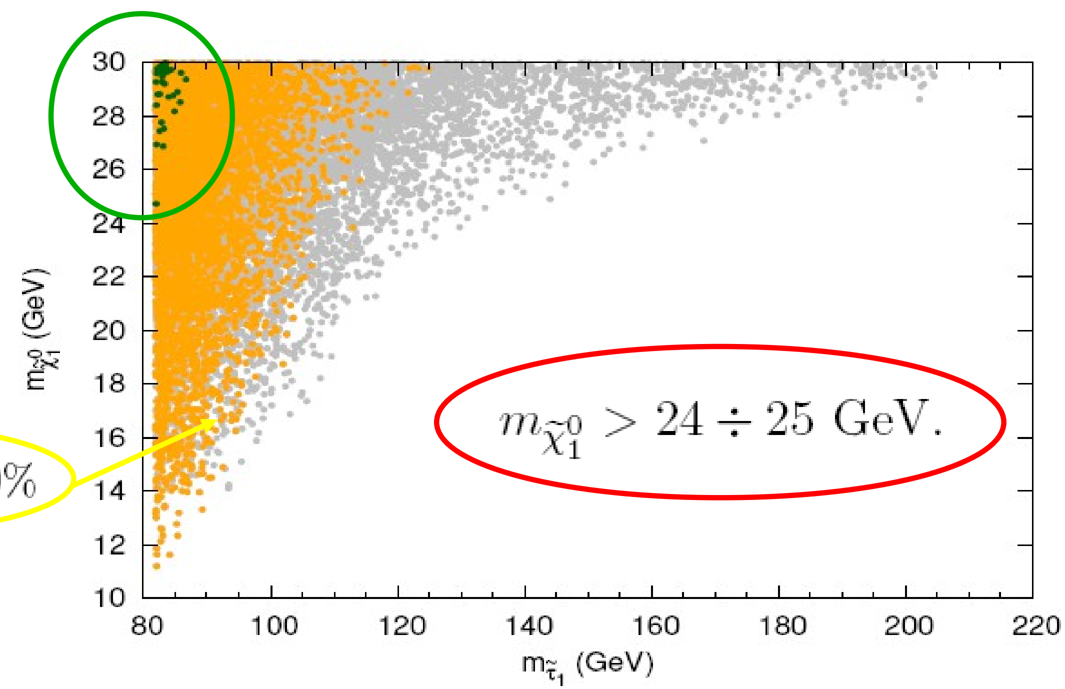

$$\mathrm{Br}(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 20\%$$

$$m_{\tilde{\chi}_1^0} > 24 \div 25 \ \mathrm{GeV}.$$

Negative μ

Flipping the sign of μ:

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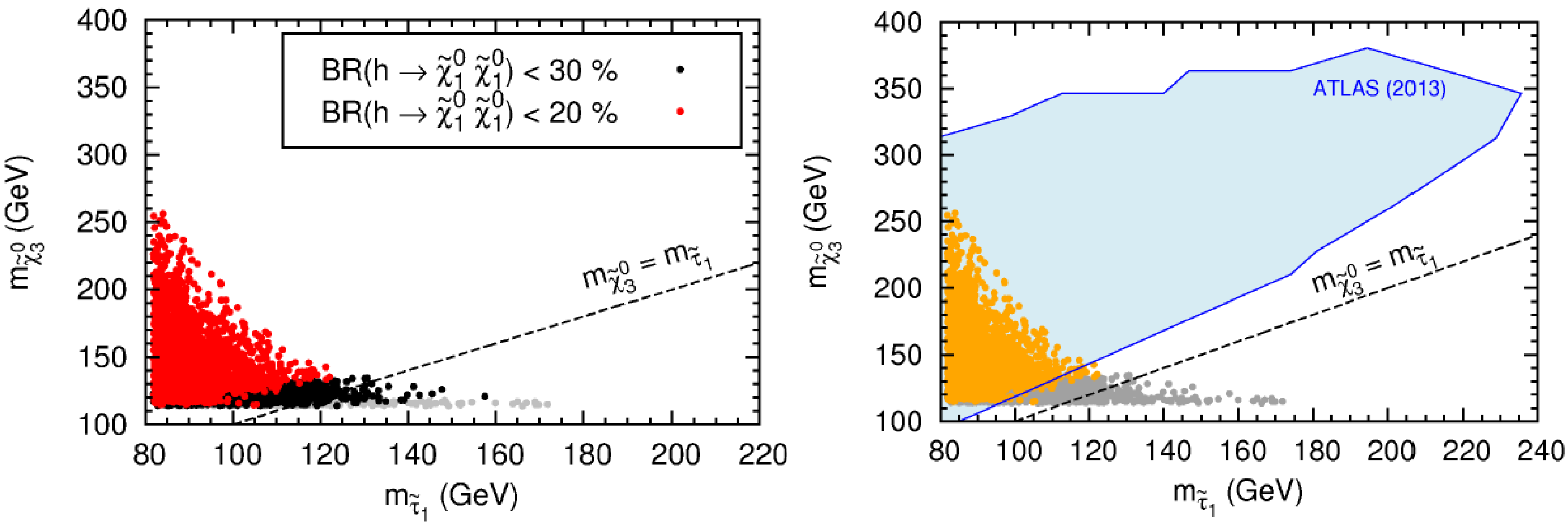
Destructive interference between two annihilation modes: $\tilde{B}\tilde{B}$ and $\tilde{B}\tilde{H}_d$

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

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

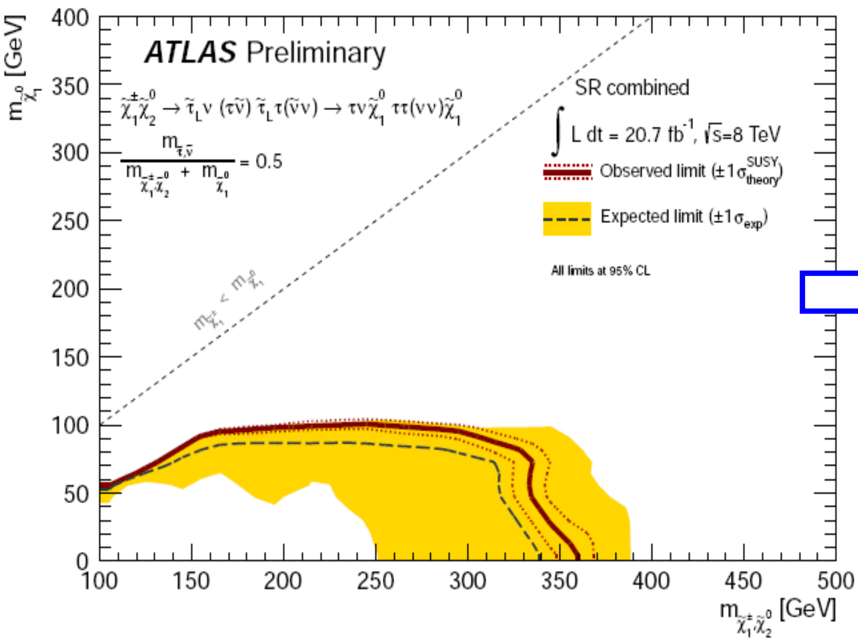


Bound from the invisible decay milder, but DM heavier because annihilation less efficient

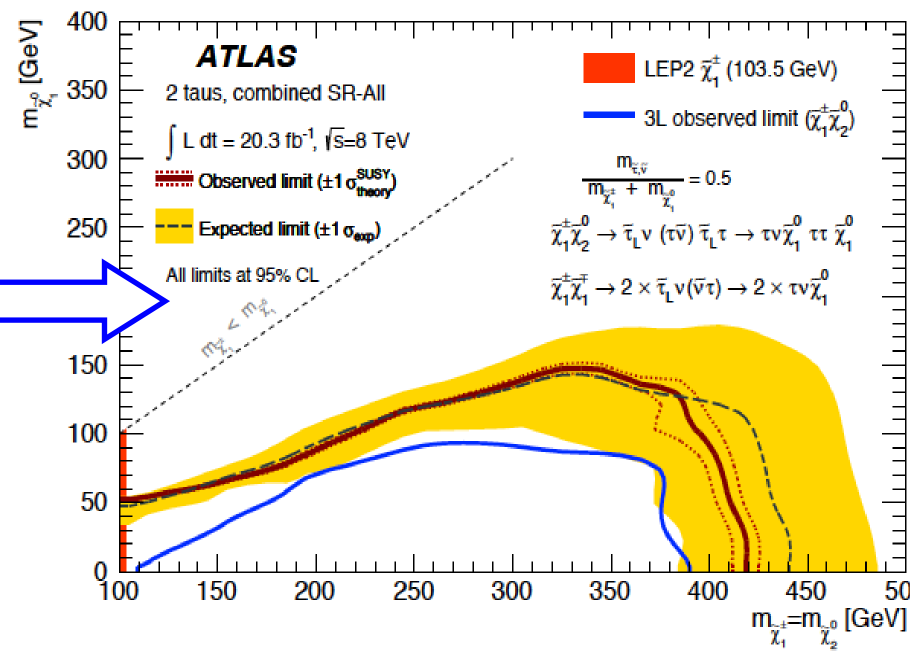
⇒ limit on the neutralino mass similar to the case μ>0

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



Conclusions

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 Higgs -> invisible)

Limit stronger than direct/indirect DM searches

Nice interplay among different experimental info (collider and not)

Outlook

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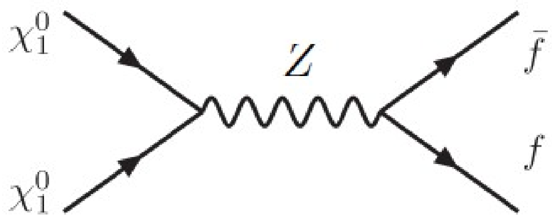
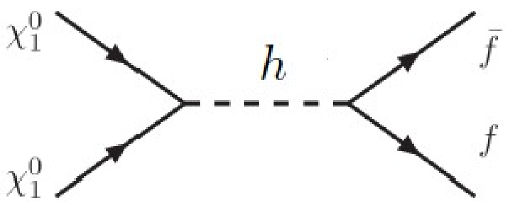
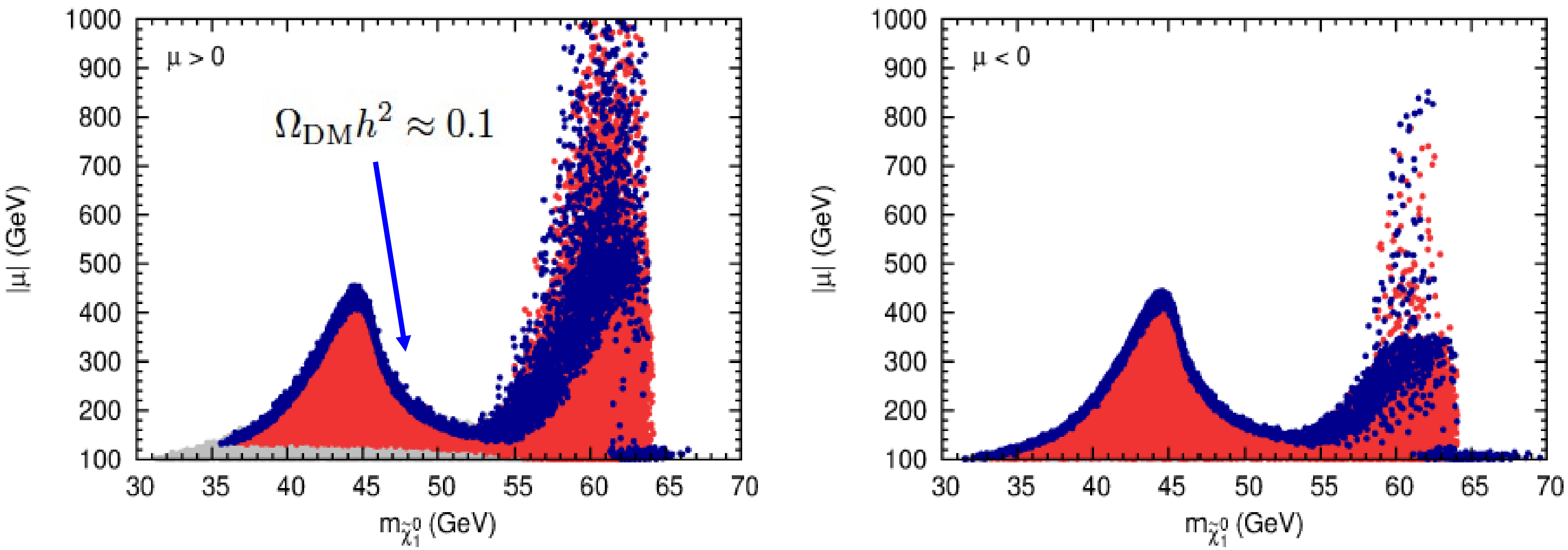
What if there are no scalars below few hundreds GeV?

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





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



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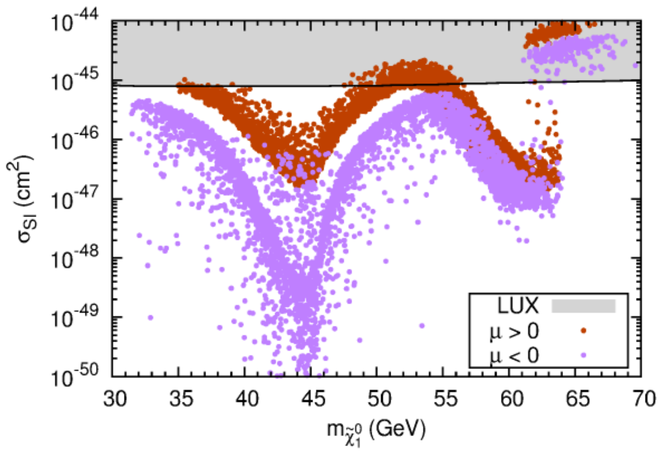
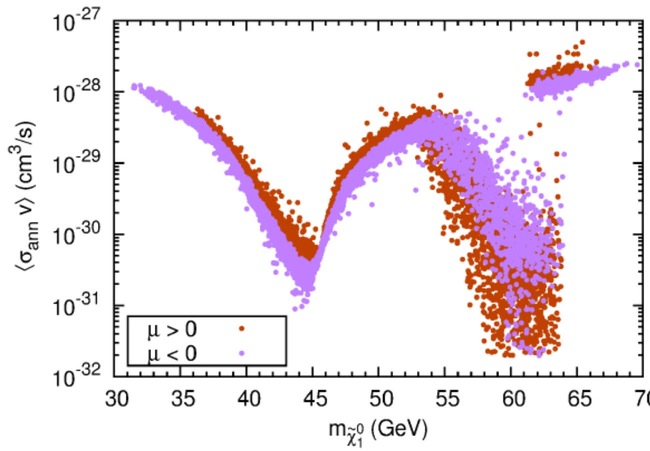
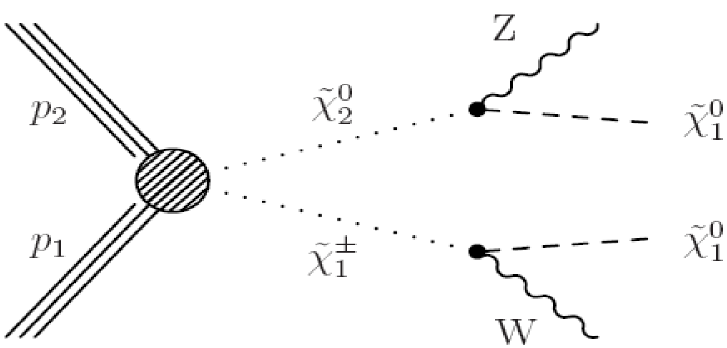
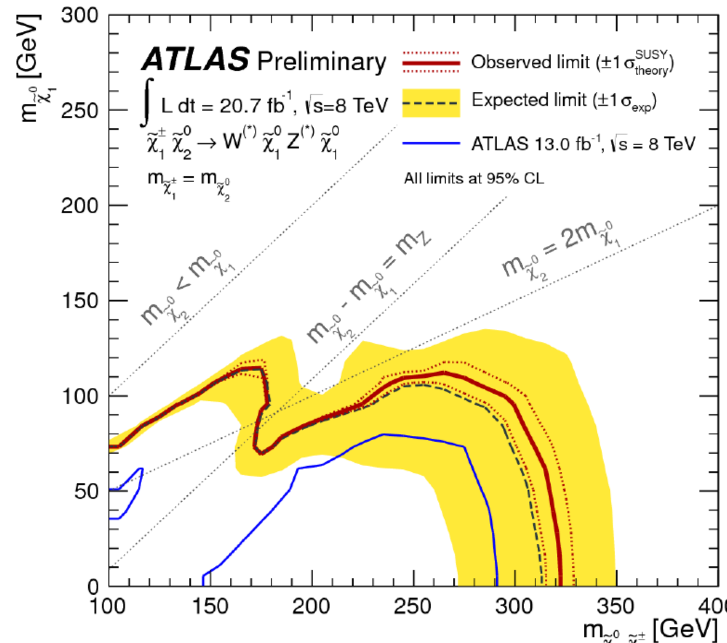
Close to the resonances, the scenario might be problematic for direct/indirect DM searches:





Again, LHC searches can test it!





Outlook

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

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