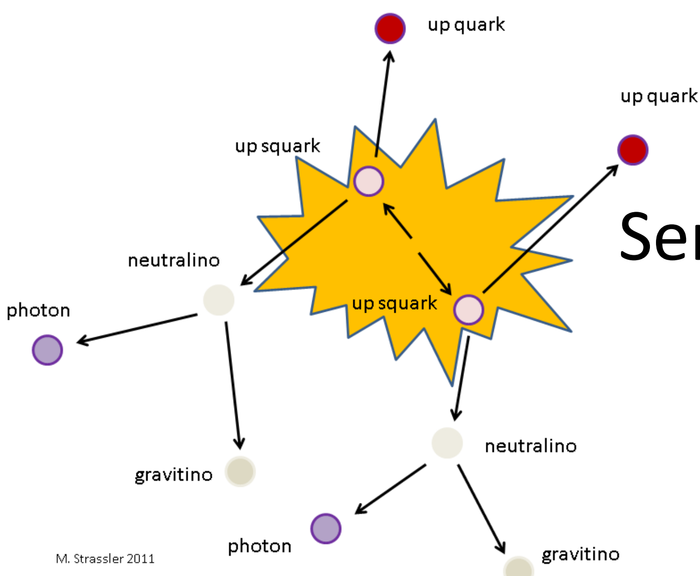
Electroweakinos, dark matter and the LHC

Aoife Bharucha (TU Munich)

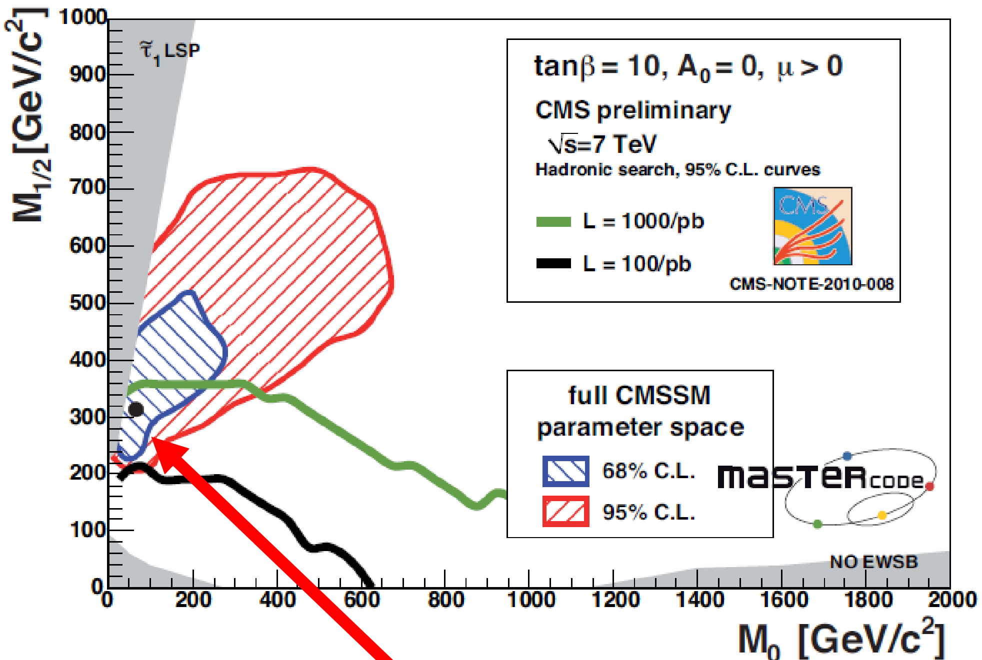


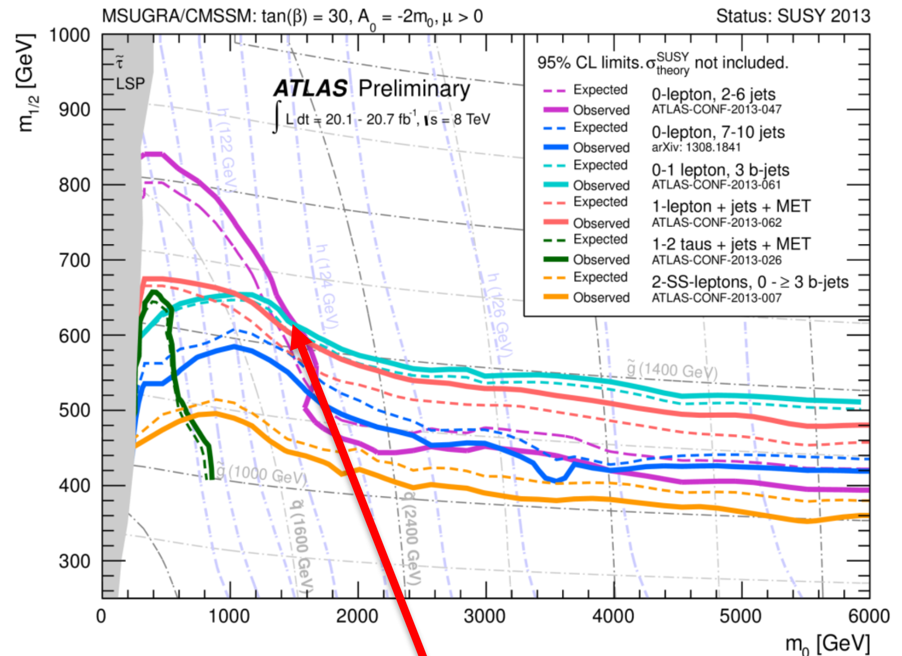
Seminar@L2C Montpellier
March 6th 2014

Outline

- The Higgs and dark matter in the MSSM
- Possibilities for electroweakinos at the LHC:
  - Bino-like LSP at the LHC:
    $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ production
  - Higgsino-like LSPs: monojet searches
  - Gravitino LSP's at the LHC: $\tilde{\chi}_1^0$ decays

Pre-LHC8 CMSSM dreams $\xrightarrow{\text{yields}}$ Post-LHC8 reality





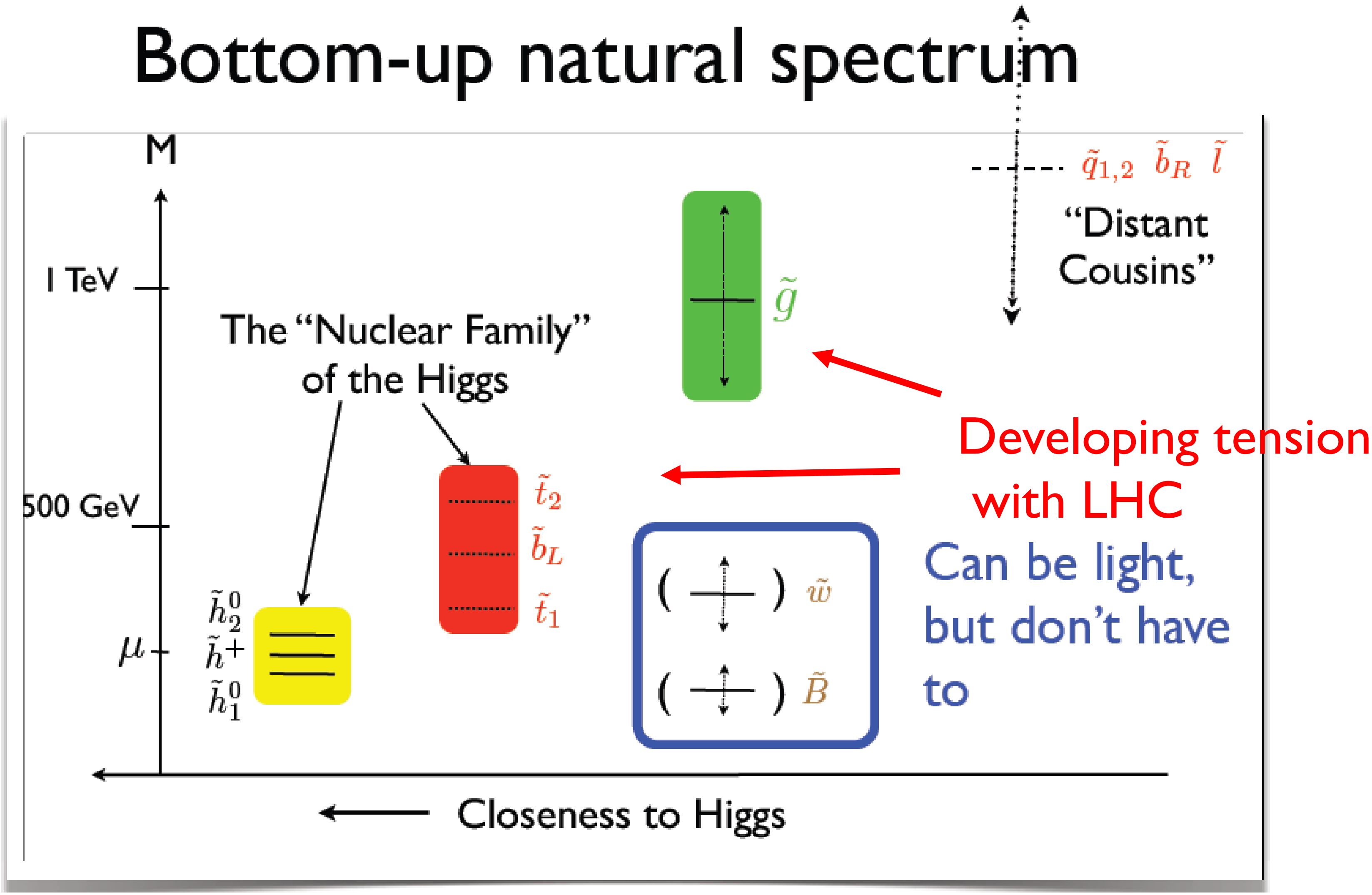
See e.g. [Supersymmetry in Light of 1/fb of LHC Data](#) - [Buchmueller, O.](#) *et al.* Eur.Phys.J. C72 (2012) 1878 arXiv:1110.3568 [hep-ph]

Driven by g-2

Corresponds to $m_{\tilde{g}} > 1.4$ TeV or $m_{\tilde{q}} > 2$ TeV

Is there any point looking for the electroweak sector at the LHC?

'Natural' SUSY: Ancient History?



From Lawrence Hall's talk@LBL c.a. 2011

The great(?) Higgs discovery

- We now know, thanks to the LHC, that m_h =**126 GeV**
- At tree level the Higgs mass is $m_Z\sqrt{\cos 2\beta}$**<91 GeV**
- At 1 loop, the leading corrections take the form:

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_t^2}{m_t^2}\right) + \frac{X_t^2}{\overline{m}_t^2}\left(1 - \frac{X_t^2}{12\overline{m}_t^2}\right)\right)$$

- Therefore two possibilities: **heavy stops or large stop mixing**.
- If heavy stops: no longer **natural**, for "natural" scenarios~800 GeV*, require here> 3 TeV
- In gravity mediation use large A_t (careful about **charge and colour breaking minima**) Problem for gauge mediation.

*Depends on naturalness measure

~~CMSSM~~ post-LHC8

SUSY Theorists

According to Savas Dimopoulos (SUSY 2013)

- The **Orthodox**: Stick with Naturalness no matter the cost (model complexity)
- The **Ultra-orthodox**: Stick with MSSM no matter the cost (tuning, model complexity)
- The **Heretics**: Abandon Naturalness and Move to the Landscape (10^{500} Universes!)

The ultra-orthodox approach

Stick with the MSSM and keep looking for the electroweak sector.
They are produced weakly @LHC, but prod. rate higher than the sleptons therefore the experiments are more sensitive to them

Neutralinos, j = 1 to 4 : $\tilde{\chi}_j^0$

Charginos, j = 1 to 2 : $\tilde{\chi}_j^-$

$$\mathcal{L}_{\tilde{\chi}} = \overline{\tilde{\chi}_i^-}(\not{p}\,\delta_{ij} - \omega_L(U^* X V^\dagger)_{ij} - \omega_R(V X^\dagger U^T)_{ij})\tilde{\chi}_j^- + \frac{1}{2}\overline{\tilde{\chi}_i^0}(\not{p}\,\delta_{ij} - \omega_L(N^* Y N^\dagger)_{ij} - \omega_R(N Y^\dagger N^T)_{ij})\tilde{\chi}_j^0$$

$$X = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

diagonalised via $\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

diagonalised via $\mathbf{M}_{\tilde{\chi}^0} = N^* Y N^\dagger$

Electroweakino searches at the LHC

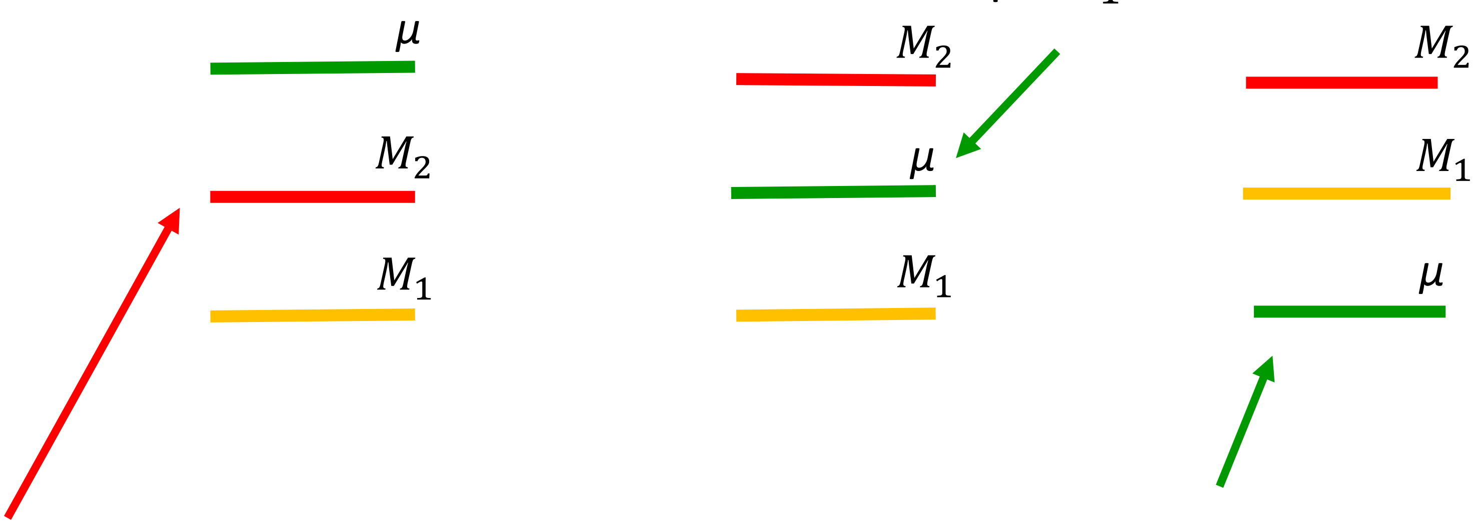
Coloured sector heavy, light EW sector: M_1, M_2 , μ, ($m_{\tilde{l}}$)

Assume $M_1 < \mathrm{M}_2$ (true for typical SUSY breaking scenarios)

→ μ or M_1 is the LSP

Same decays for Higgsino production

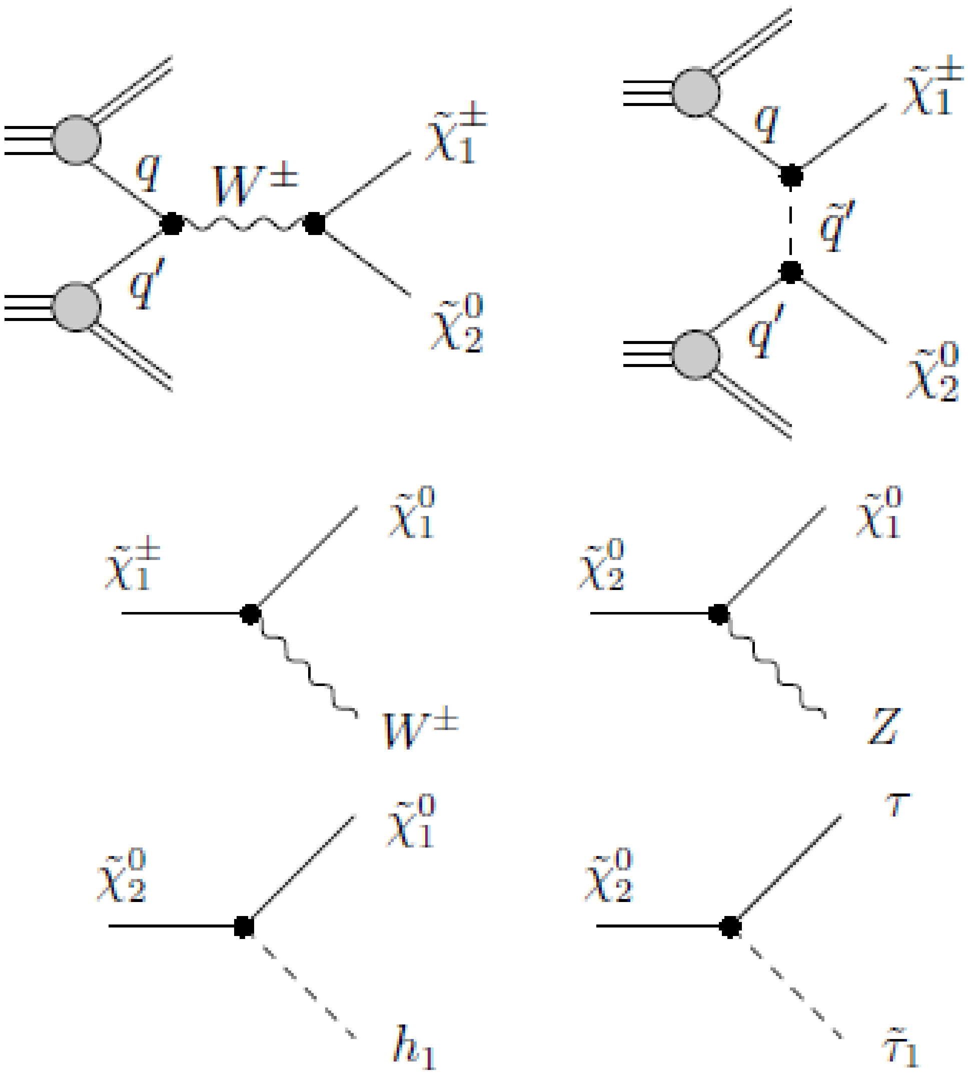
if μ> M_1: No bound so far



Wino production largest coupling, decay to $\tilde{l}$, W/Z/H or 3 body

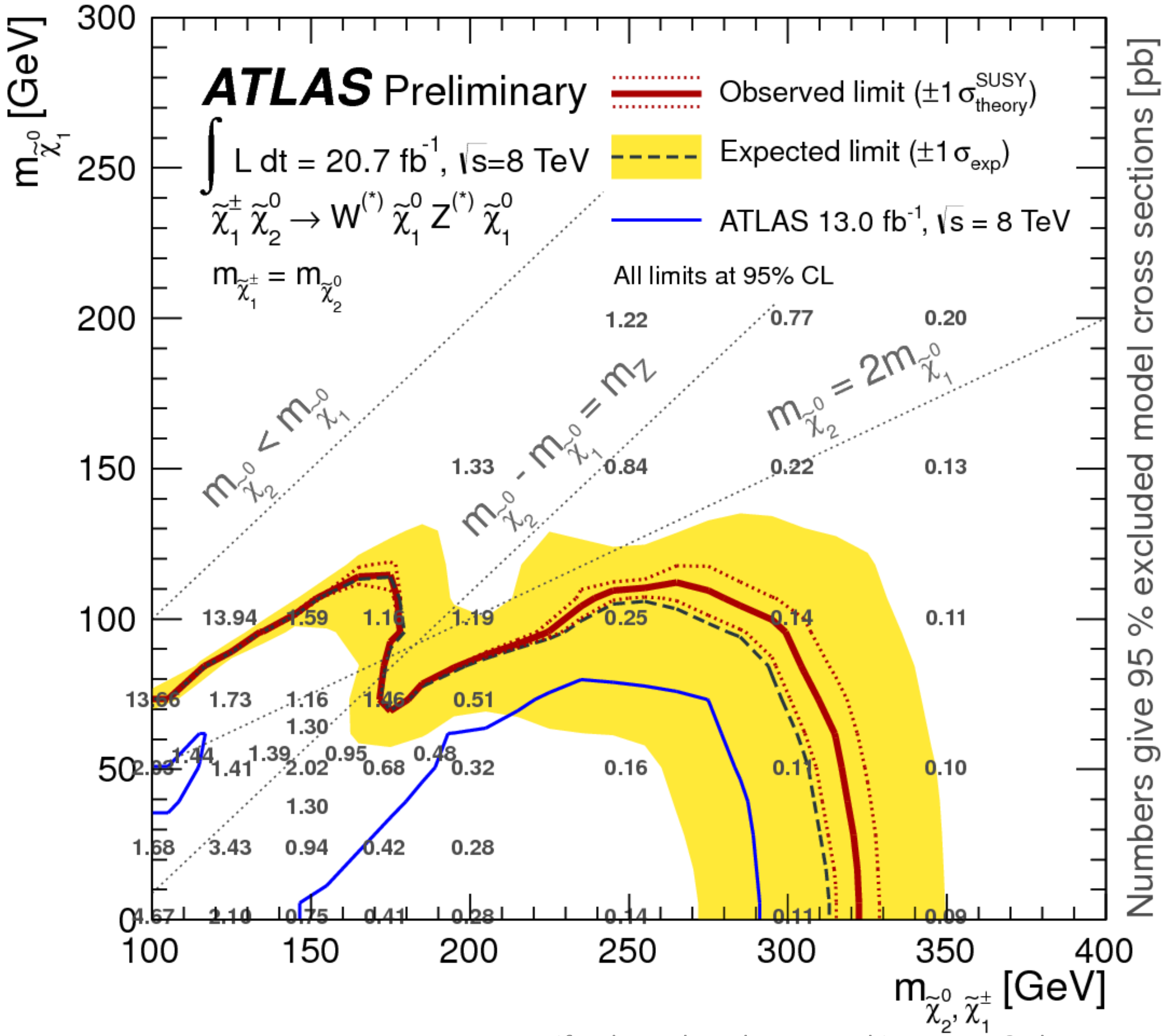
Direct production of LSP requires monojets

Direct chargino-neutralino production



- Golden EW-ino production channel is wino-like $\tilde{\chi}_1^+\tilde{\chi}_2^0$ decaying to 3 leptons
- When sleptons light, this channel provides a powerful constraint in the wino/bino plane
- For case of heavy sfermions, simplified models assume 100% BR to $W^{(*)}Z^{(*)}$

Limits from Atlas (WZ,3l+E_t^{miss})



- However, as soon as the Higgs channel opens, the branching ratio of the neutralino to Z is drastically reduced.
- What are the ACTUAL bounds in this region?

Calculation in the complex MSSM:

Cross section requires production and decay

- Calculated using Prospino 2.1 (neglect φ_{M1})
- Production of wino pairs dominates, largest contribution from *s*-channel gauge bosons
- Consider scenarios where BR($\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^{+/-}$)=100%, so the BRs
- for $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^0/h_1$ are only relevant ones
- Calculate decays at NLO in on-shell scheme FeynArts/LoopTools/FormCalc/FeynHiggs4
- Decay for $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1$ to most sensitive to φ_{M1} due to the the relative CP between the bino-like $\tilde{\chi}_2^0$ and the wino-like $\tilde{\chi}_1^0$

NLL corrections to the gaugino production cross section calculated in Fuks et al. 2012 are not included, and we estimate effect to be O(%).
Although the *t* and *u*-channel suppressed if squarks heavy, destructive interference of the *t*-channel squark exchange and *s*-channel gauge bosons can be significant
AB, Heinemeyer, von der Pahlen and Schappacher, arXiv:1208.4106 [hep-ph], Phys. Rev D.
LO results (e.g. Gunion and Haber, Phys. Rev. D 37 (1988) 2515) encoded in SDECAY(Muehlleitner, Djouadi and Mambrini, Comput. Phys. Commun. 168 (2005) 46)

Parameters considered

Scenario	φ_{M_1}	μ	$\tan\beta$	$M_{\rm SUSY}$	$M_{\tilde{\tau}_R}$
$S_{\rm ATLAS}$	0	1000	6	2000	$M_{\rm SUSY}$
$S_{\rm ATLAS}^{\varphi_{M_1}}$	$0 \ldots \pi$	1000	6	2000	$M_{\rm SUSY}$
$S_{\rm ATLAS}^{\tan\beta}$	0	1000	$6 \ldots 20$	2000	$M_{\rm SUSY}$
$S^{\rm DM}$	$0 \ldots \pi$	1000	$6, 20$	2000	$\lvert M_1 \rvert$
$S_{{\rm low}-\mu}$	0	$100 \ldots 400$	6	2000	$M_{\rm SUSY}$

$$|M_1| = 0 \ldots 200 \text{ GeV}, \; M_2 = 100 \ldots 400(500) \text{ GeV},$$
$$M_3 = 1.5 \text{ TeV}, \; M_{\tilde{q}_{1,2}} = M_{\tilde{q}_3} = M_{\tilde{\ell}} = 2 \text{ TeV}, \; A_t \approx 2.8 \text{ TeV} \; .$$

Direct Chargino-Neutralino Production at the LHC: Interpreting the Exclusion Limits in the Complex MSSM, A. Bharucha S. Heinemeyer, F. Pahlen, Eur.Phys.J. C73 (2013) 2629, arXiv:1307.4237

Simple expressions for the decay widths

Assuming $M_Z < M_1, M_2 < \mu$ and $tan\beta \ll 1$:

Depends on relative sign of M_1 and M_2, i.e. φ_{M_1}

$$C^L_{\tilde{\chi}^0_1\tilde{\chi}^0_2 Z} \approx \frac{e}{2}\frac{M_Z^2}{\mu^2}\exp\left(\frac{i\varphi_{M_1}}{2}\right) ,$$

$$C^L_{\tilde{\chi}^0_1\tilde{\chi}^0_2 h_1} \approx \frac{e}{2}\frac{M_Z}{\mu}\left(\frac{M_1+M_2}{\mu}+\frac{4}{\tan\beta}\right)\exp\left(\frac{-i\varphi_{M_1}}{2}\right) ,$$

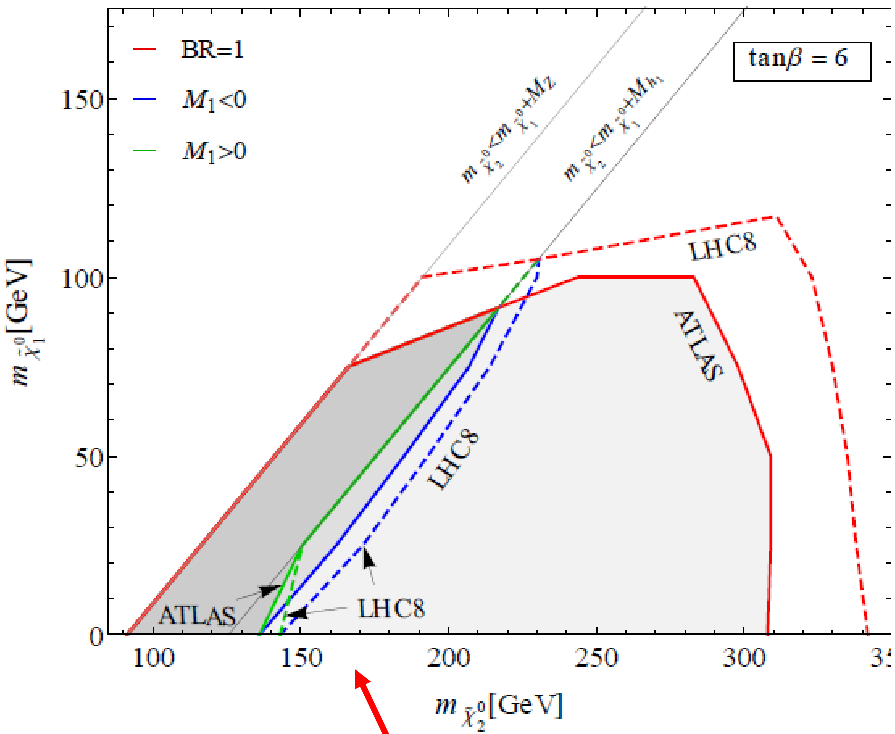
Depends on $\tan\beta$

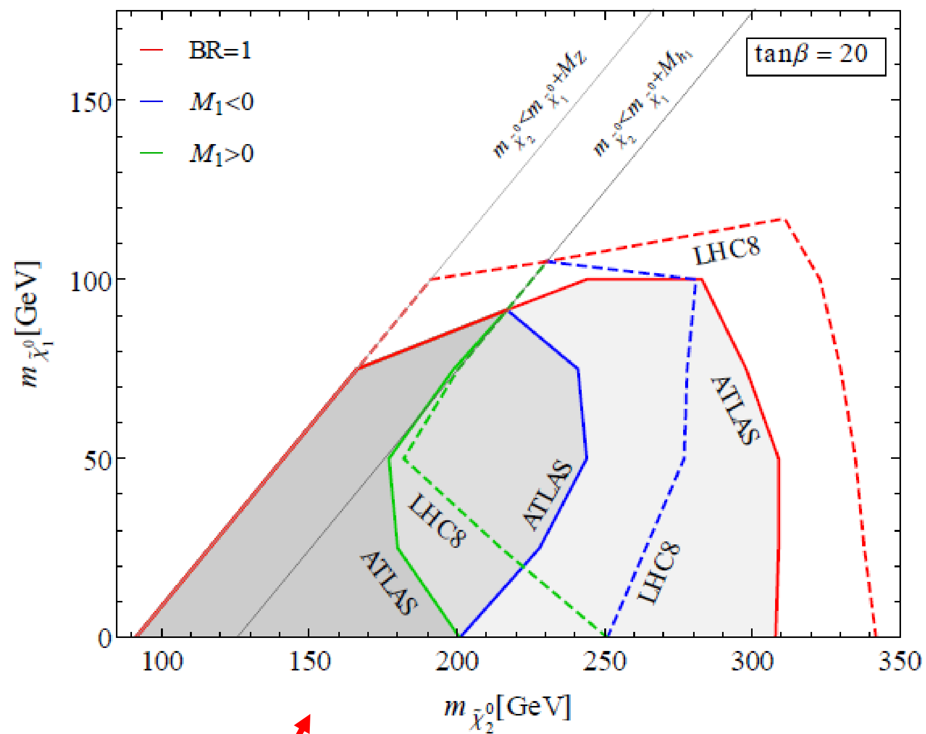
$$\Gamma^{\rm tree}_{\tilde{\chi}^0_2\to\tilde{\chi}^0_1 Z} \approx \frac{K(Z)}{\mu^2/M_Z^2}\left(m^2_{\tilde{\chi}^0_2}+m^2_{\tilde{\chi}^0_1}-2M_Z^2+\frac{(m^2_{\tilde{\chi}^0_2}-m^2_{\tilde{\chi}^0_1})^2}{M_Z^2}+6\cos(\varphi_{M_1})m_{\tilde{\chi}^0_2}m_{\tilde{\chi}^0_1}\right)$$

$$\Gamma^{\rm tree}_{\tilde{\chi}^0_2\to\tilde{\chi}^0_1 h_1} \approx K(h_1)\left|\frac{M_1+M_2}{\mu}+\frac{4}{\tan\beta}\right|^2\left(m^2_{\tilde{\chi}^0_2}+m^2_{\tilde{\chi}^0_1}-m^2_{h_1}+2\cos(\varphi_{M_1})m_{\tilde{\chi}^0_2}m_{\tilde{\chi}^0_1}\right)$$

Direct Chargino-Neutralino Production at the LHC: Interpreting the Exclusion Limits in the Complex MSSM, A. Bharucha S. Heinemeyer, F. Pahlen, Eur.Phys.J. C73 (2013) 2629, arXiv:1307.4237

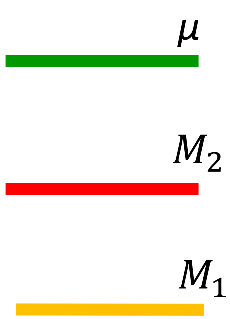
The effect of including the Higgs





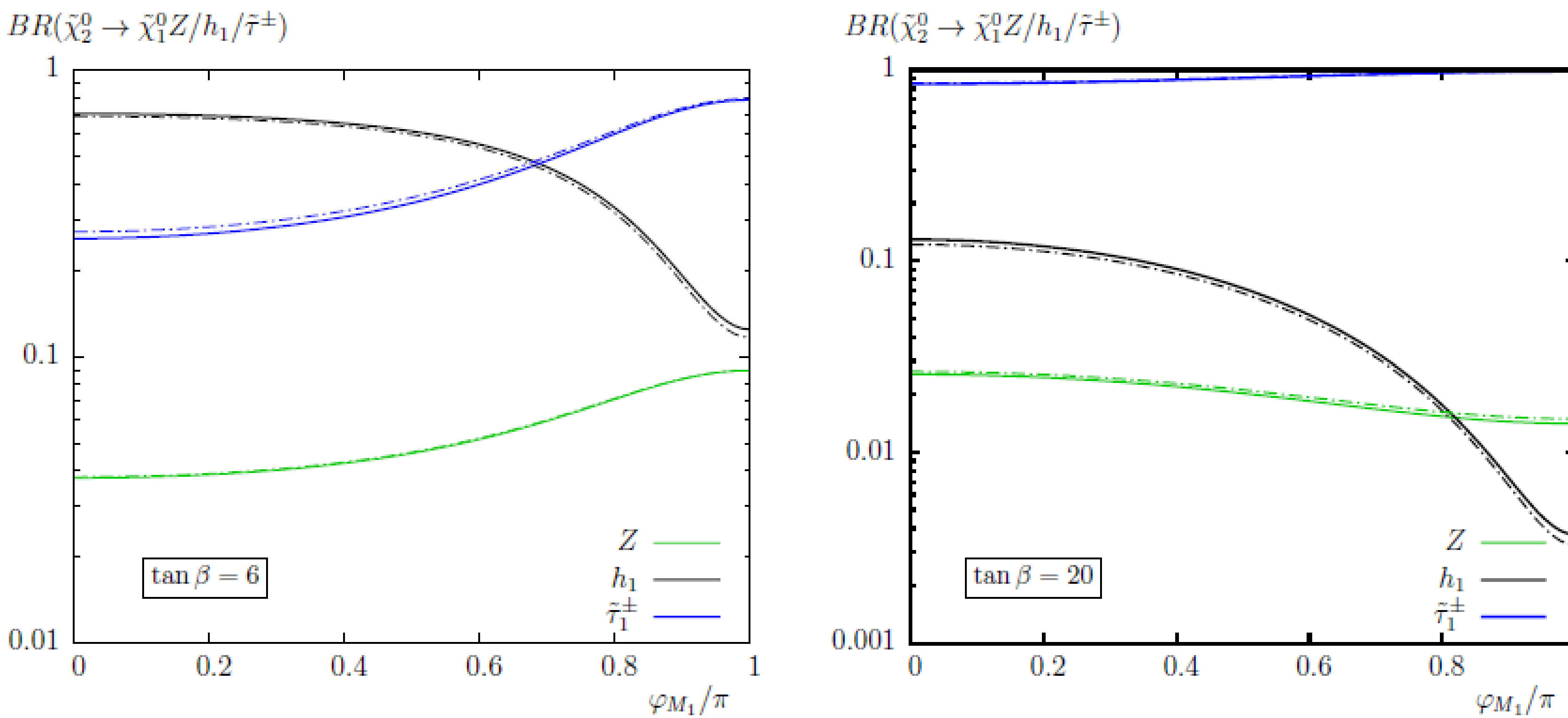
Dramatic reduction in sensitivity when $m_{\chi_2^0} - m_{\chi_1^0} > m_h$

Less dramatic for larger tanβ, but depends strongly on sign of M_1



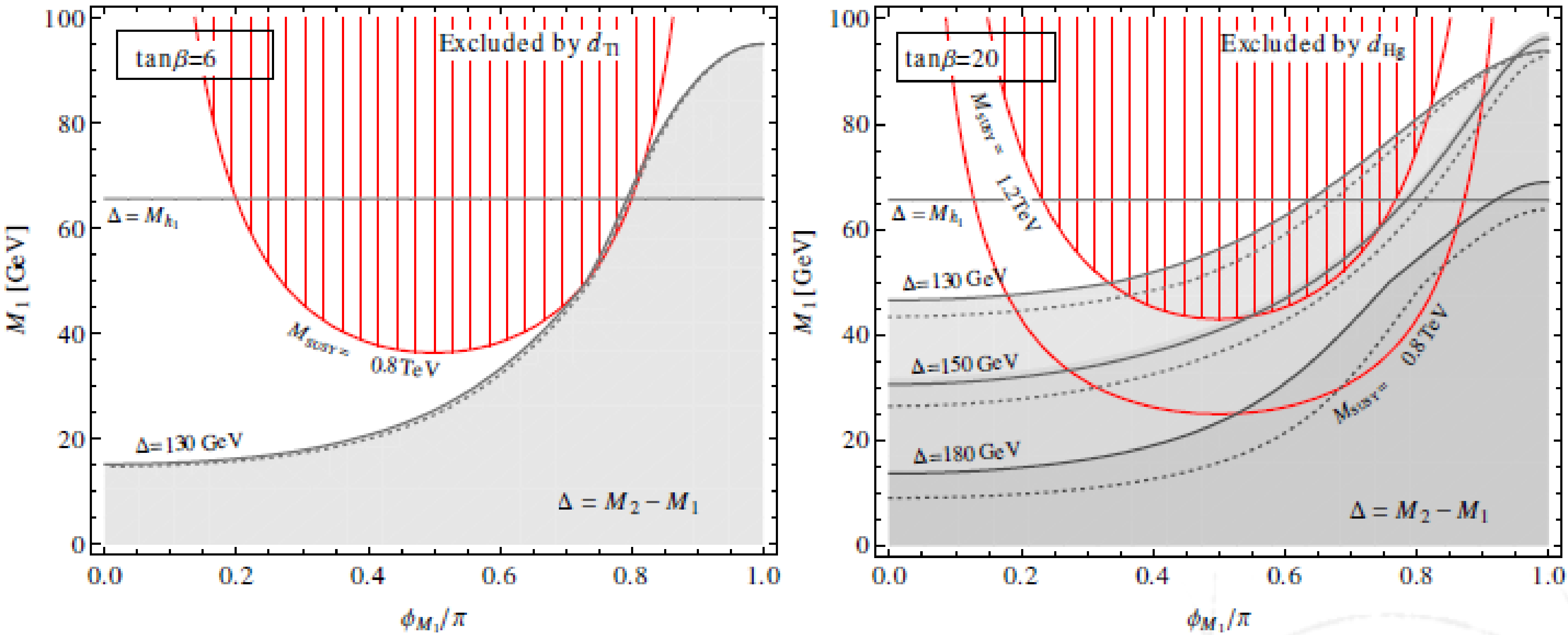
The DM scenario: bring in the stau

Avoiding overabundance of LSP with $M_{\tilde{\tau}_R} = M_1$

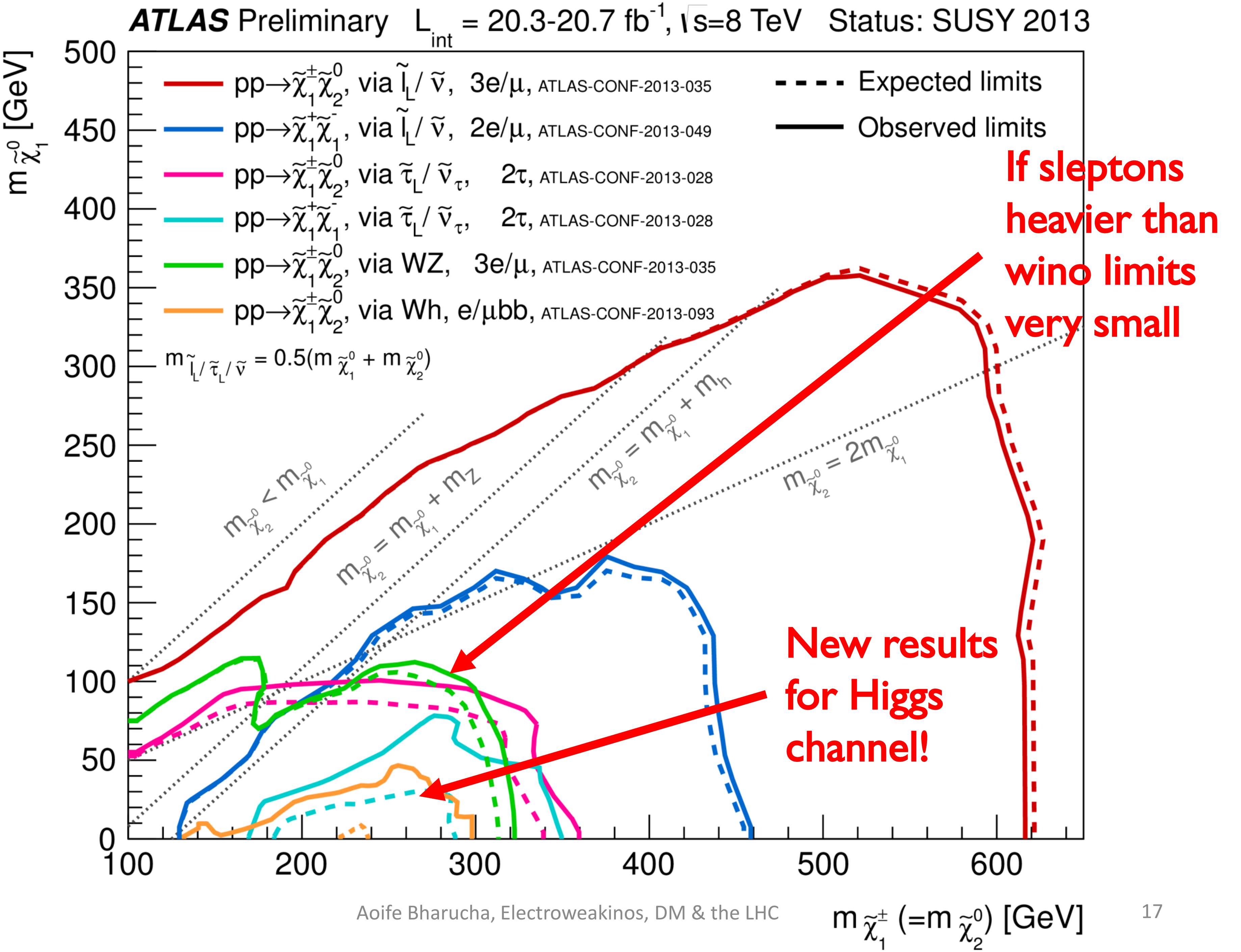


- Decay to $\tilde{\tau}_R$ is Yukawa suppressed
- Extreme sensitivity to off-diagonal term $m_\tau \mu \tan\beta$ (A_τ = 0)
- Decay to *Z* suppressed to 2-3%, max 9% at $\varphi_{M_1} = \pi$

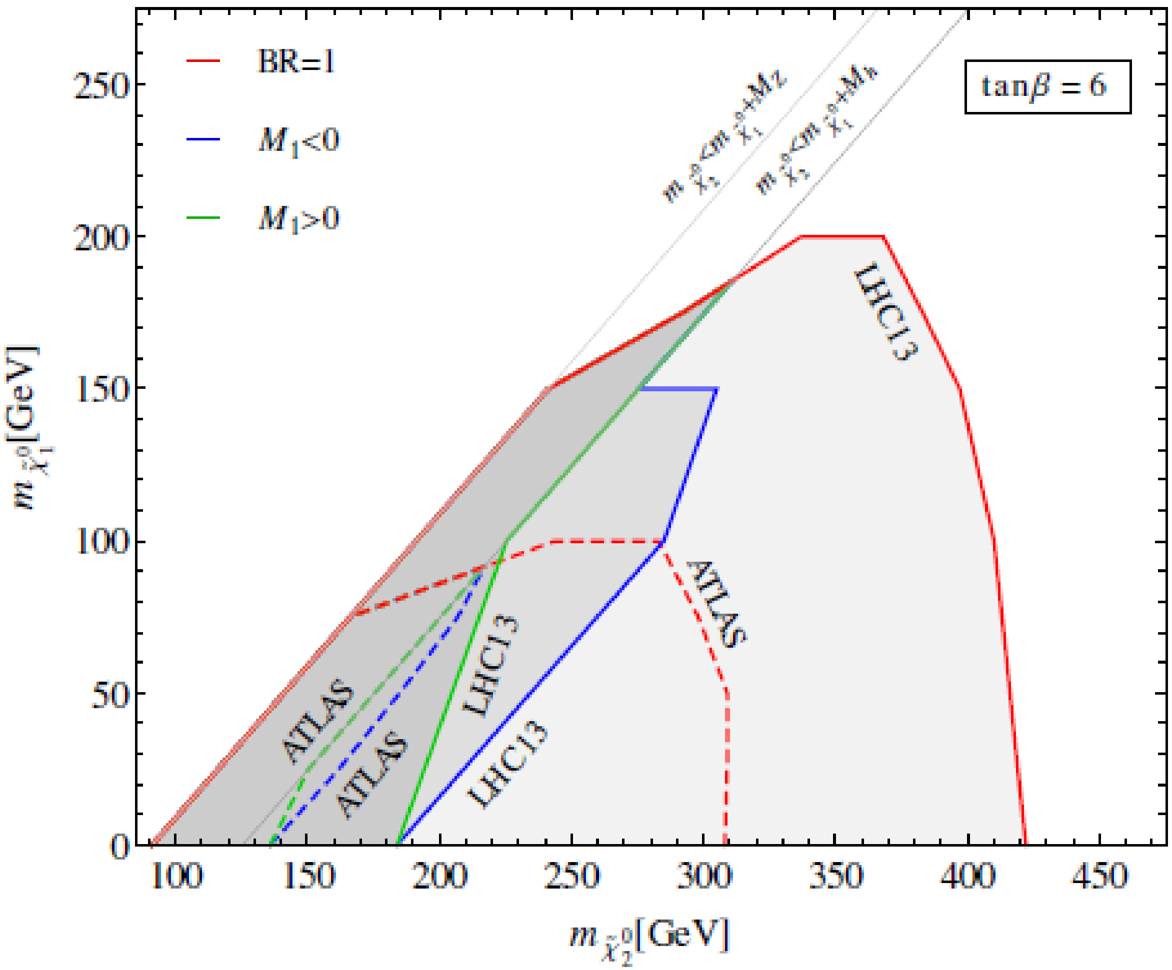
Constraining the phase of M_1



- Strong dependence of M_1, no exclusion for tanβ=6, Δ=150 GeV and for tanβ=20, Δ=210 GeV
- Interesting complementarity with EDM limits on φ_{M_1} for tanβ=20


ATLAS Preliminary L_{int} = 20.3-20.7 fb^{-1}, $\sqrt{s}$=8 TeV Status: SUSY 2013
$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, via $\tilde{l}_L / \tilde{\nu}$, 3e/μ, ATLAS-CONF-2013-035
$pp \to \tilde{\chi}_1^{+}\tilde{\chi}_1^-$, via $\tilde{l}_L / \tilde{\nu}$, 2e/μ, ATLAS-CONF-2013-049
$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, via $\tilde{\tau}_L / \tilde{\nu}_\tau$, 2τ, ATLAS-CONF-2013-028
$pp \to \tilde{\chi}_1^{+}\tilde{\chi}_1^-$, via $\tilde{\tau}_L / \tilde{\nu}_\tau$, 2τ, ATLAS-CONF-2013-028
$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, via WZ, 3e/μ, ATLAS-CONF-2013-035
$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, via Wh, e/μbb, ATLAS-CONF-2013-093
$m_{\tilde{l}/\tilde{\tau}_L/\tilde{\nu}} = 0.5(m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})$
Expected limits
Observed limits
$m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_h$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ (=$m_{\tilde{\chi}_2^0}$) [GeV]
0
50
100
150
200
250
300
350
400
450
500
100
200
300
400
500
600
If sleptons heavier than wino limits very small
New results for Higgs channel!

Projections for LHC13



Rescale exclusion sensitivity for LHC8 by factor:

$$R_{13/8} = \sqrt{R_{\text{bkg}} \frac{L_{LHC8}}{L_{LHC13}}}$$

Dominant background is diboson production

$$R_{\text{bkg}} = \frac{\sigma_{WZ}(13\ \text{TeV})}{\sigma_{WZ}(8\ \text{TeV})} \frac{L_{\text{LHC13}}}{L_{\text{LHC8}}}$$

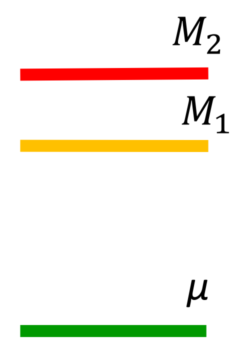
$$R_{13/8} \approx \sqrt{2}\sqrt{\frac{21}{100}}$$

Improvement is approx. 35%

Degenerate NLSPs and the Focus Point

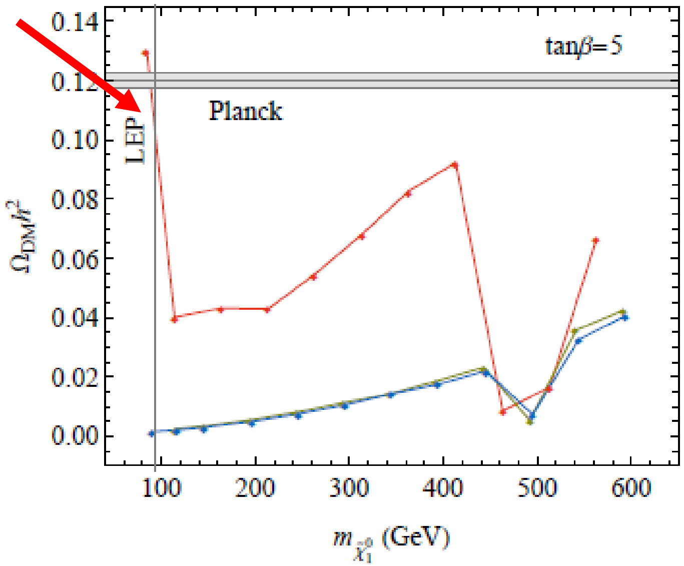
- Things become even more challenging when the NLSPs are (quasi-) degenerate, e.g. Higgsino LSP
- Focus point/Hyperbolic branch: cancellations between the $m_0 = m_{H_u}^2$ at μ_{GUT} lead to natural scenarios with low μ
- Best chance to detect degenerate LSPs in far FP (for $M_1 > 1$ TeV, splitting between $\tilde{\chi}_1^+$ and $\tilde{\chi}_{1/2}^0$ ~ O(5 GeV) is via monojets, or direct detection exps.
- If M_1 also low, there might be a small splitting between $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^+$ or $\tilde{\chi}_{1/2}^0$ leading to soft but detectable leptons, interesting but not studied here

FP/HB: Chan et al , hep-ph/9710473, Feng, Matchev et al. hep-ph/9908309, hep-ph/9909334, arXic:1112.3021, Baer, Barger, and Mickelson, 1309.2984, Baer, Belyaev, Krupovnickas, and O'Farrill, hep-ph/0405210
Monojets and degenerate spectra: Alves, Izaguirre, and Wacker, 1102.5338, Dreiner, Kramer, and Tattersall, 1207.1613, Han, Kobakhidze, Liu, Saavedra, Wu et al, 1310.4274, Han, Kribs, Martin, and Menon, 1401.1235

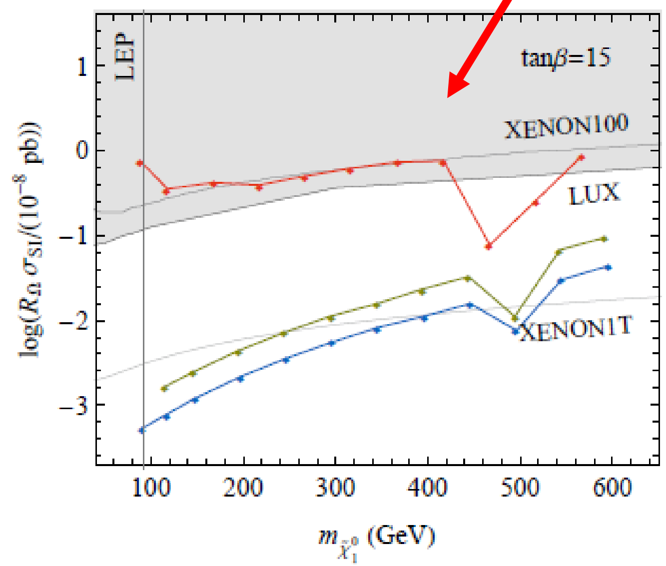


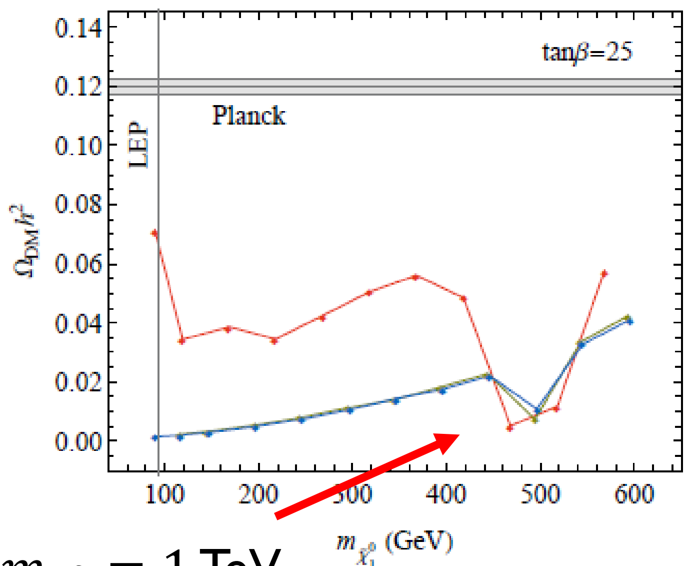
$\Omega_\chi h^2$ and σ_{SI}

Only predict $\Omega_\chi^{Planck} h^2$ if $\mu = M_1$



$\mu = M_1$ excluded up to $\mu \sim 450$ GeV



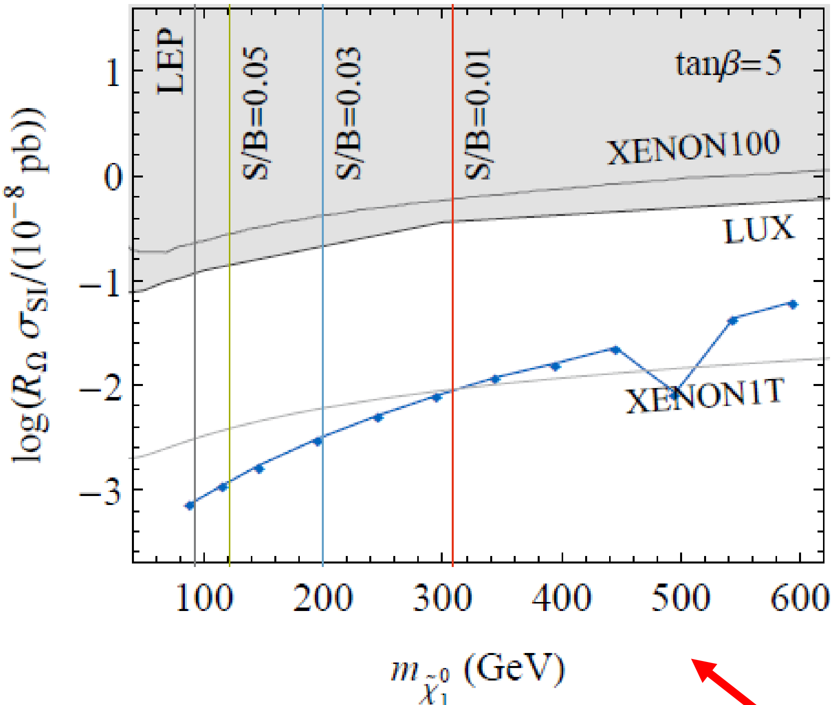


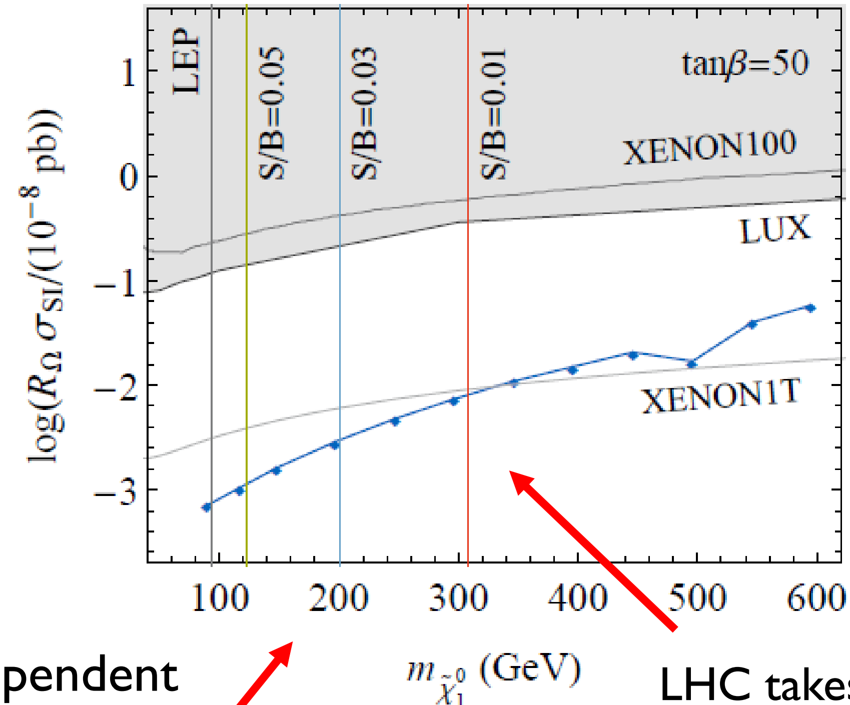
$m_{A^0} = 1$ TeV

Assume that the remaining relic density is accounted for either by:

- an additional LSP e.g. the axion
- the fact that the higgsino is non-thermally produced

Complementarity with Direct Detection





$\alpha = 2\left(\sqrt{S+B} - \sqrt{B}\right)$

α=2, L=1500 fb^{-1}

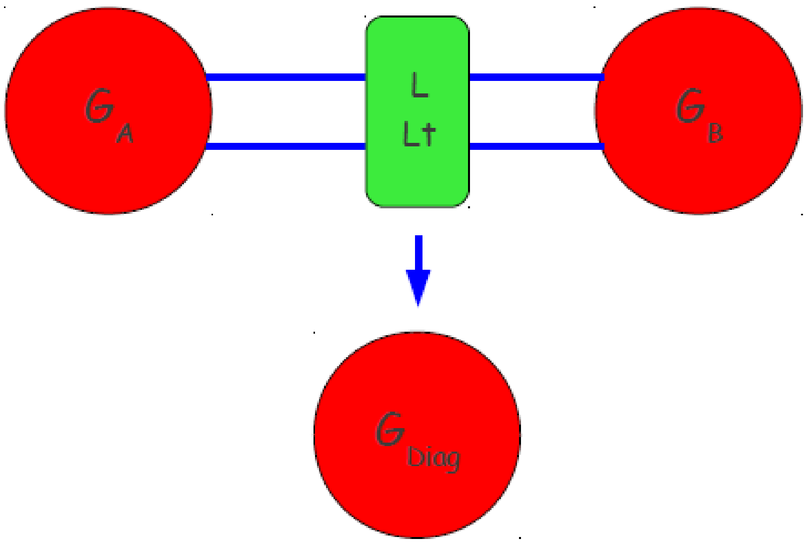
Independent of nature of $\tan\beta$ and M_1

LHC takes over from XENON1T

- Overwhelming background from Z($\rightarrow \nu\bar{\nu}$)+jet: best S/B~1/10, therefore systematics at percent level + high pT cut required
- Event generation: MadGraph, and PYTHIA, fast simulation with Delphes3
- Strong dependence on S/B sensitivity: if 5% then reach <120 GeV

An orthodox example: gauge mediation

Gauge extensions of the SM gauge group at high scales may lead to **tree level contributions** to the Higgs mass via non-decoupled D terms



$$m_{h,0}^2 = \left[m_z^2 + \left(\frac{g_1^2 \Delta_1 + g_2^2 \Delta_2}{2} \right) v_{ew}^2 \right] \cos 2\beta$$

$$\Delta_1 = \left(\frac{g_{A1}^2}{g_{B1}^2} \right) \frac{m_L^2}{m_{v1}^2 + m_L^2} \quad , \quad \Delta_2 = \left(\frac{g_{A2}^2}{g_{B2}^2} \right) \frac{m_L^2}{m_{v2}^2 + m_L^2}$$

Higgs enhanced when **m_v is small or m_L is large**

Sleptons/higgsinos suppressed when m_v small compared to standaerd GMSB: could be seen at LHC

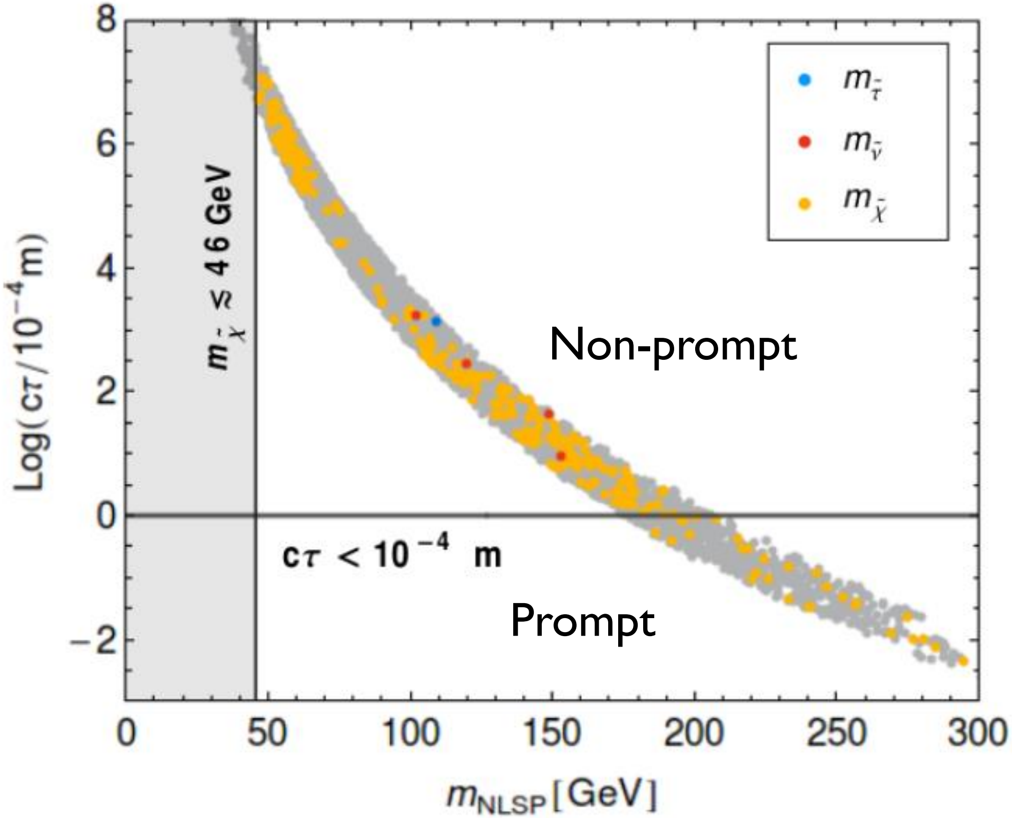
See Csaki et al, hep-ph/0106044, Cheng et al hep-ph/0106098, Batra et al, hep-ph/0404251, Delgado,hep-ph/0409073, De Simone et al arXiv:0808.2052, Medina et al, arXiv:0904.1625, McGarrie, arXiv:1009.0012, Craig et al, arXiv:1103.3708, Auzzi et al,arXiv:1208.6263, Huo et al, arXiv:1212.0560, D'Agnolo et al, arXiv:1212.1165, AB, Goudelis, McGarrie, arXiv:1310.4500 [hep-ph]

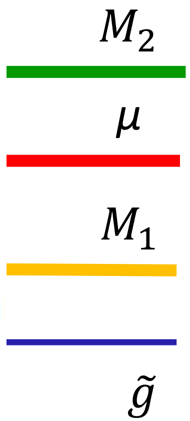
*No offence to orthodox believers intended

Decaying neutralinos in the QMSSM

The crucial differentiators for the phenomenology of gauge gaugino mediated models are the lifetime and nature of the NLSP

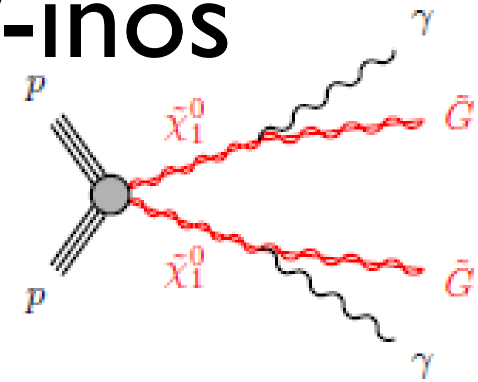
- 2-loop RGE spectrum generator developed using SARAH and Spheno for QMSSM
- Search channel depends on nature of NLSP and production mode
- NLSP decay might be prompt or non-prompt
- If all other sparticles heavy rely on **direct EW-ino production**

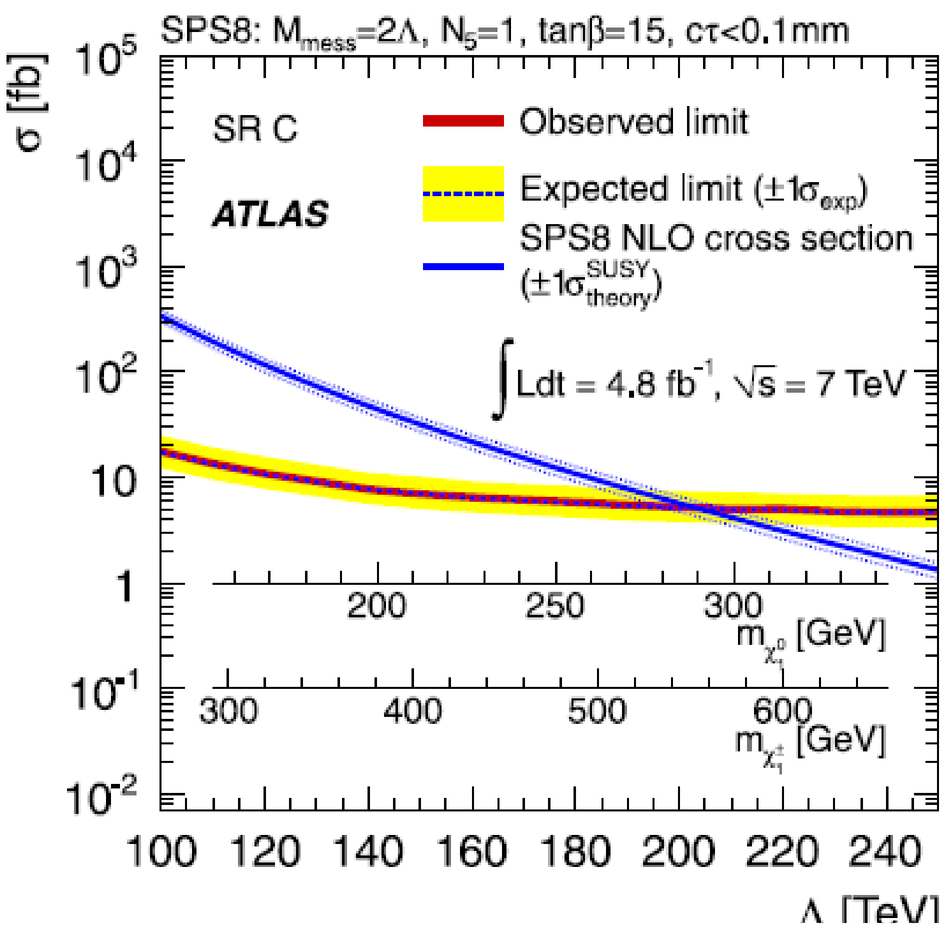




En-gauging Naturalness , AB, Andreas Goudelis, Moritz McGarrie, **arXiv:1310.4500 [hep-ph]**

The search for NLSP EW-inos



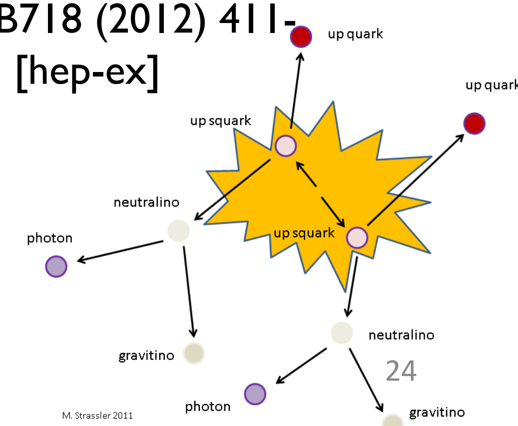


$M_{\rm mess} = 2\Lambda$, $N_5 = 1$, $\tan\beta = 15$ and $c\tau_{\rm NLSP} < 0.1$ mm.

Most sensitive channel is di-NLSP productions, if bino-like neutralino then **di-photon final state**

Would be interesting to see more bounds

Search for diphoton events with large missing transverse momentum in 7 TeV proton-proton collision data with the ATLAS detector, ATLAS Collaboration (Georges Aad *et al*, Phys.Lett. B718 (2012) 411-430, arXiv:1209.0753 [hep-ex]



Summary

- Discussed searches for electroweakinos at the LHC

Exclusion limits on charginos and neutralinos:

- When sleptons are heavy ($WZ + E_T^{miss}$ search), above threshold **decay to h_1 dominates**, so Simplified model limits ($m_{\chi_2} > 300$ GeV) **optimistic**, especially for low $\tan\beta$, but LHC13 could achieve this, improvement~35%
- In low μ region, suppression, **no limit** even combining $\chi_2 + \chi_3$
- Monojet searches could probe degenerate higgsinos to 300 GeV assuming good systematic control, If S/B sensitivity 5% then reach <120 GeV
- Interesting to probe binos decaying to gravitinos via diphoton searches in light of MSSM extensions: Prompt decaying neutralino>300 GeV for SPS8

A glimpse of the future:

- Combining the $WZ + E_T^{miss}$ and $W h_1 + E_T^{miss}$ searches using **dedicated tools**, e.g. FastLim, will further improve reach

Apologies to CMS for showing mainly ATLAS plots, thanks to collaborators Federico von der Pahlen, Sven Heinemeyer, Andreas Goudelis, Moritz McGarrie, Alexander Belyaev, Veronica Sanz, Werner Porod, Daniele Barducci

On a heavier note..

EW corrections to DM annihilation

- If the LSP mass M_χ >LHC reach, only possibilities are direct and **indirect detection**: search for cosmic rays (e,p,ν,γ) from DM annihilation
- As hierarchy between M_χ and M_W increases, EW corrections log-enhanced
- Further EW corr lifts suppression of Majorana LSPs annihilating to fermion
- Require flux at annihilation point:

  Standard: Tree-level cross-section+Pythia (e.g. MicrOmegas)

  More Recent: 3 body (+Z/W) cross sections +splitting functions +Pythia (PPPC4ID)

SCET provides a convenient framework to calculate these corrections to the 2 to 2 cross-section above cut off in energy~M_W, use Pythia

Provides accurate calculation of flux easily adaptable to different models.

For NLL: need LO high scale coeff, anomalous dim +low scale matching

Results to come in 2014…. Resummation of EW logarithms for dark matter annihilation, Martin Beneke, AB, Tanja Geib, and Torsten Pfoh

DM EW corrections: Ciafaloni et al. arXiv:1009.0224, arXiv:1104.2996, arXiv:1202.0692, arXiv:1305.6391, Cirelli, Pramana arXiv:1202.1454

SCET EW corrections: Chiu, Kelley, (Golf) and Manohar, 0709.2377, arXiv:0712.0396, arXiv:0806.1240, arXiv:0909.0012, arXiv:0909.0947

The Higgs mass in the MSSM

The scalar potential in SUSY takes the form:

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

Reminder: SM scalar potential looks like: $V = m_H^2|H|^2 + \lambda|H|^4$

Limit tanβ large, $m_{H_u} < m_{H_d}$

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2)$$

The tree-level Higgs mass in the MSSM is: $m_{Higgs}^2 = M_Z^2 \cos 2\beta$

Do not want tuning in (Higgs mass)^2

$$\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

Higgsinos

1loop $\delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$

stops, sbottom$_L$

2loop $\delta m_H^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$

gluino

See: A Supersymmetry primer, Stephen P. Martin , Kane, G.L. (ed.): Perspectives on supersymmetry II 1-153 , hep-ph/9709356

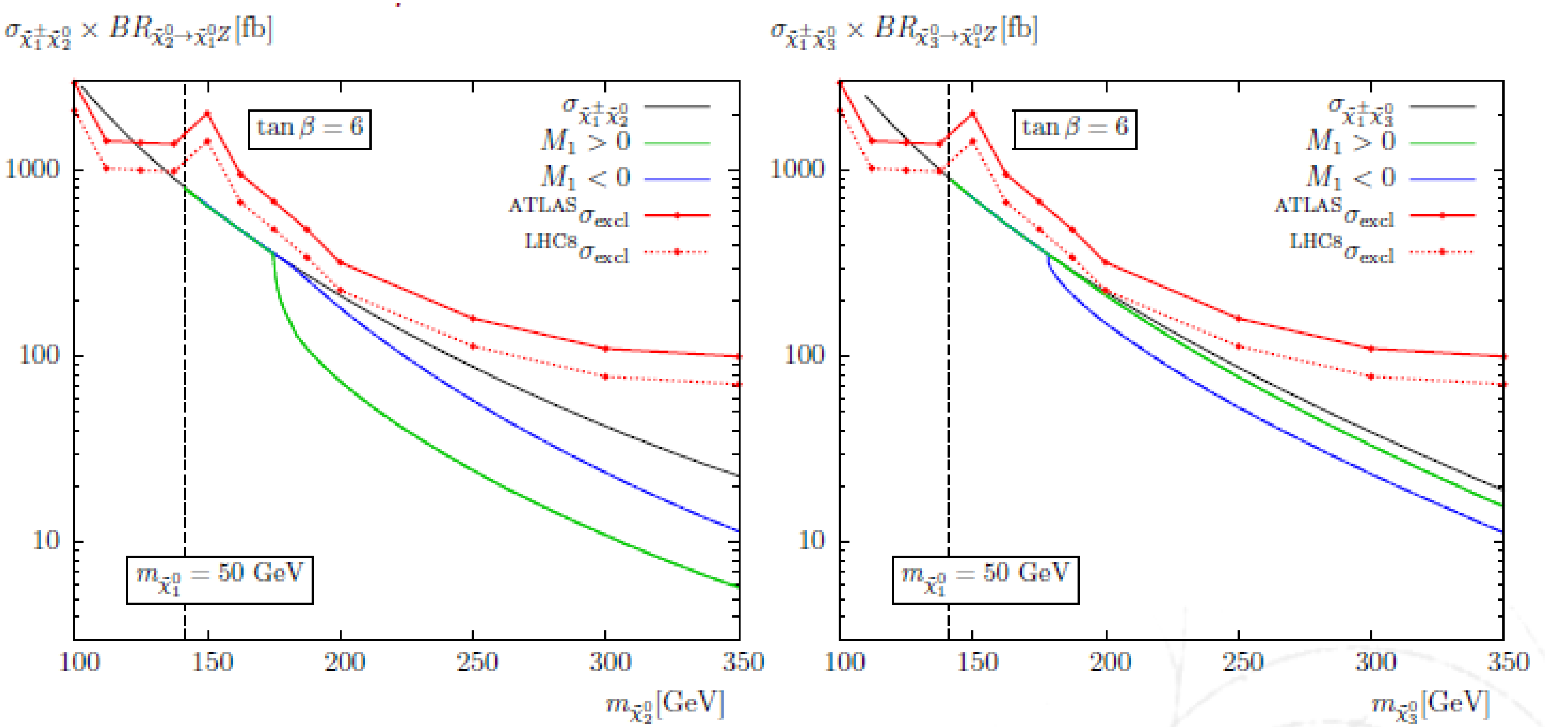
Thanks to Andreas Weiler

Impact of Loop corrections

$$\Delta\Gamma^{\text{loop}} := \frac{\Gamma^{\text{NLO}} - \Gamma^{\text{tree}}}{\Gamma^{\text{tree}}}\,, \quad \Delta\text{BR}^{\text{loop}} := \frac{\text{BR}^{\text{NLO}} - \text{BR}^{\text{tree}}}{\text{BR}^{\text{tree}}}\,.$$

Scenario	$\|M_1\|$	M_2	φ_{M_1}	μ	$\tan\beta$	M_{SUSY}	$M_{\tilde{\tau}_R}$	$\Delta\text{BR}^{\text{loop}}$	$\Delta\Gamma^{\text{loop}}$
S_{ATLAS}	100	250	0	1000	6	2000	M_{SUSY}	8%	$<1\%$
S_{ATLAS}	100	250	π	1000	6	2000	M_{SUSY}	4%	1%
$S^{\varphi_{M_1}}_{\text{ATLAS}}$	100	250	$\pi/2$	1000	6	2000	M_{SUSY}	8%	$<1\%$
$S^{\tan\beta}_{\text{ATLAS}}$	100	250	0	1000	20	2000	M_{SUSY}	8%	$<1\%$
$S^{\tan\beta}_{\text{ATLAS}}$	100	250	π	1000	20	2000	M_{SUSY}	4%	1%
S^{μ}_{ATLAS}	100	250	0	2000	6	2000	M_{SUSY}	7%	-5%
$S^{\text{SUSY}}_{\text{ATLAS}}$	100	250	0	1000	6	1200	M_{SUSY}	12%	-4%
$S^{\text{SUSY}}_{\text{ATLAS}}$	100	250	π	1000	6	1200	M_{SUSY}	11%	-2%
S^{DM}	100	250	0	1000	6	2000	$\|M_1\|$	5%	-1%
S^{DM}	100	250	π	1000	6	2000	$\|M_1\|$	5%	-1%
$S_{\text{low}-\mu}$	100	500	0	250	6	2000	M_{SUSY}	-1%	2%
$S_{\text{low}-\mu}$	100	500	0	350	6	2000	M_{SUSY}	-1%	4%

Natural SUSY: the low μ scenario



Notice green and blue lines swap: complementarity of production of neutralinos 2 and 3 (opposite CP behaviour)
Suppressed production cross-section (couplings) only partially overcome by combining channels: No limit so far