Electroweakino Searches at the LHC

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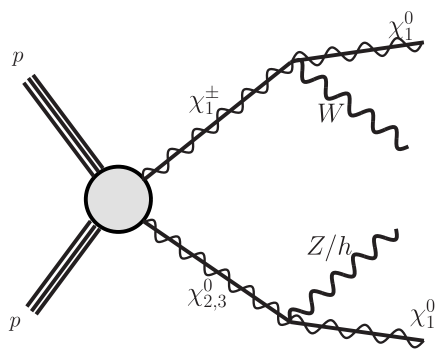
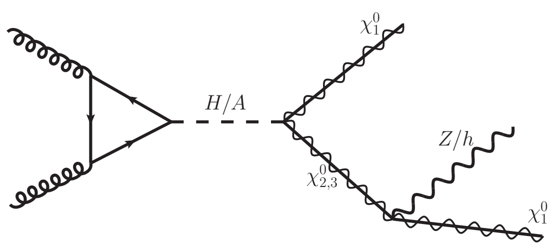
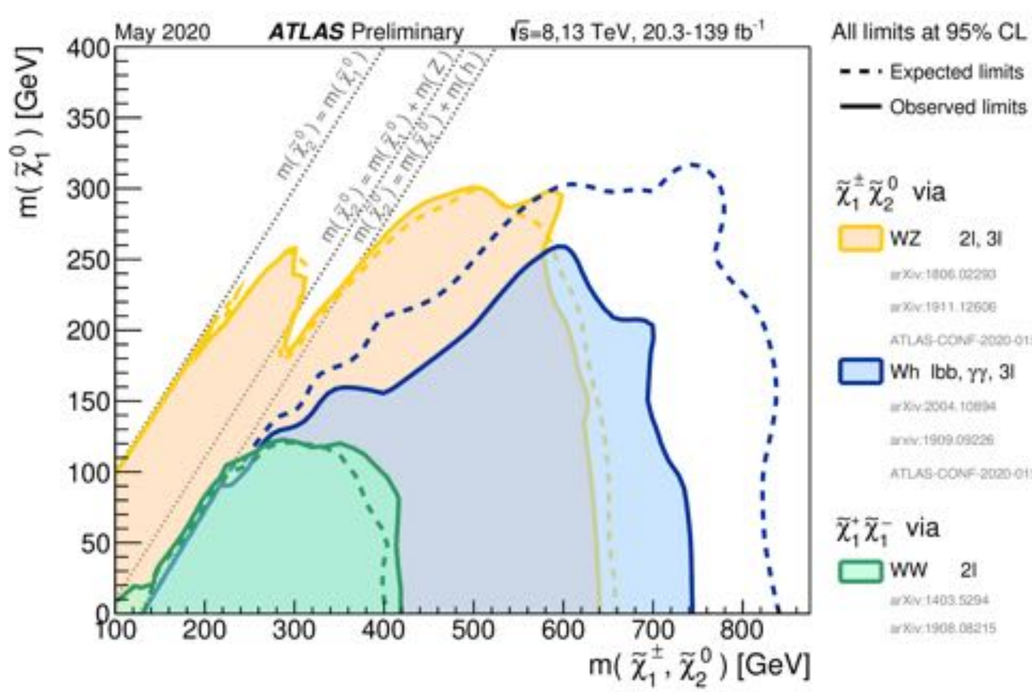


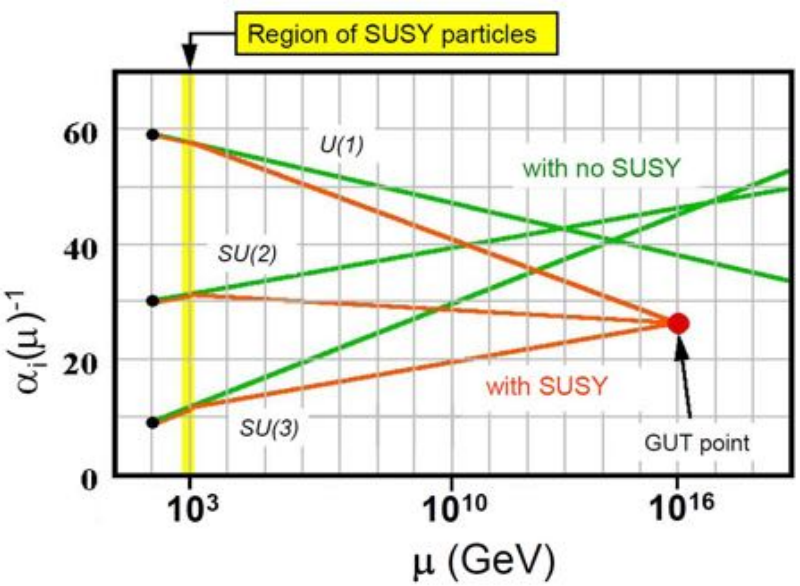




NTU Pheno Workshop,
Energy Frontier in Particle Physics : LHC and Future Colliders
National Taiwan University, 10.06.20

Consequences of SUSY

Unification



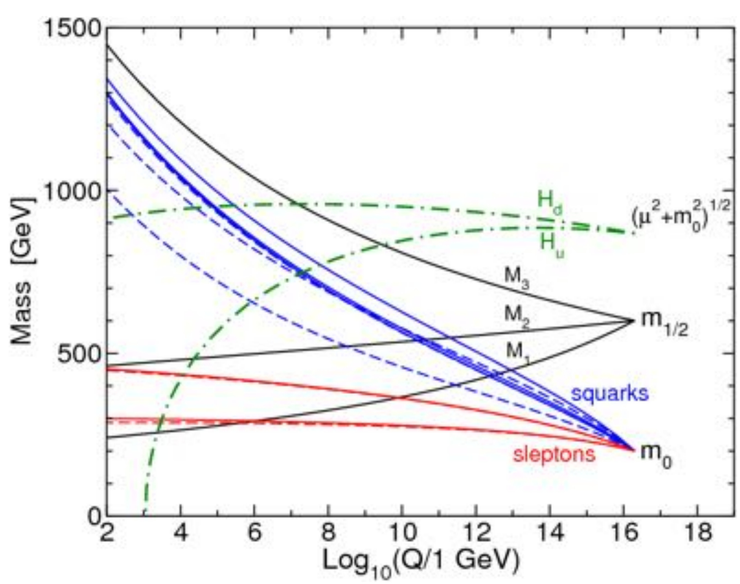
SUSY Algebra

$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0$$

Quantum Gravity ?

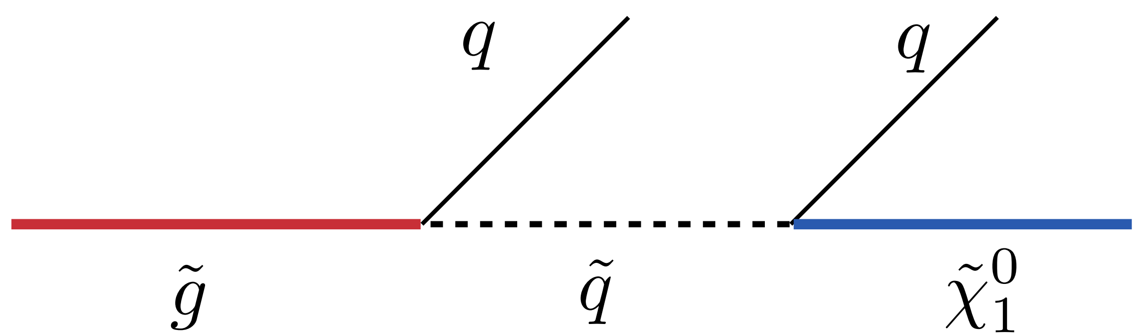
Electroweak Symmetry Breaking



If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

Searches for Supersymmetric Particles at the LHC

Gluino Decays (Simplified Scenario)



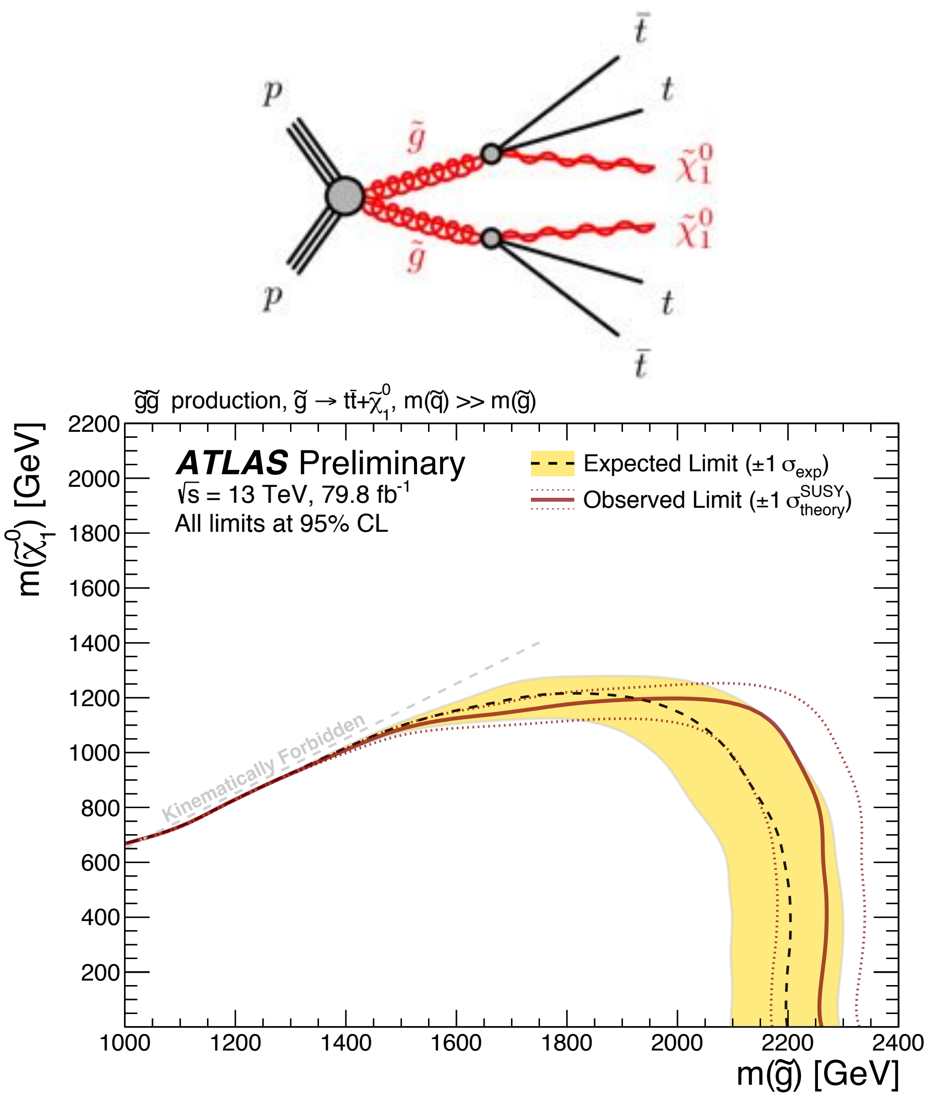
- Due to RG running of mass parameters, the gluinos tend to get large masses at low energies. Squark masses are pushed up by gluino effects.

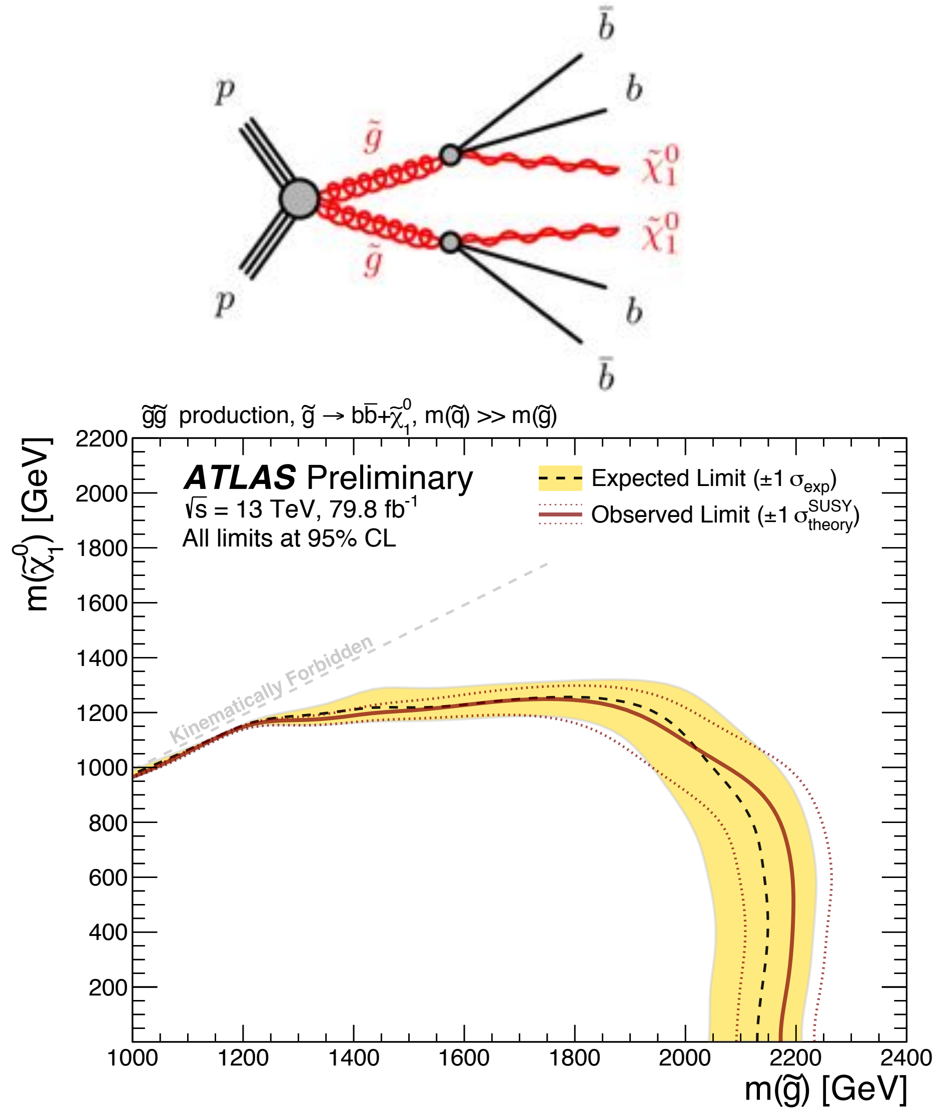
- Gluino decay rate tends to be prompt.

- Assuming R-Parity, LSP is stable at collider scales, implying large missing energy.

- Lightest squark dominates the decay. Due to Yukawa effects in the RG running and mixing, they tend to be the third generation squarks.

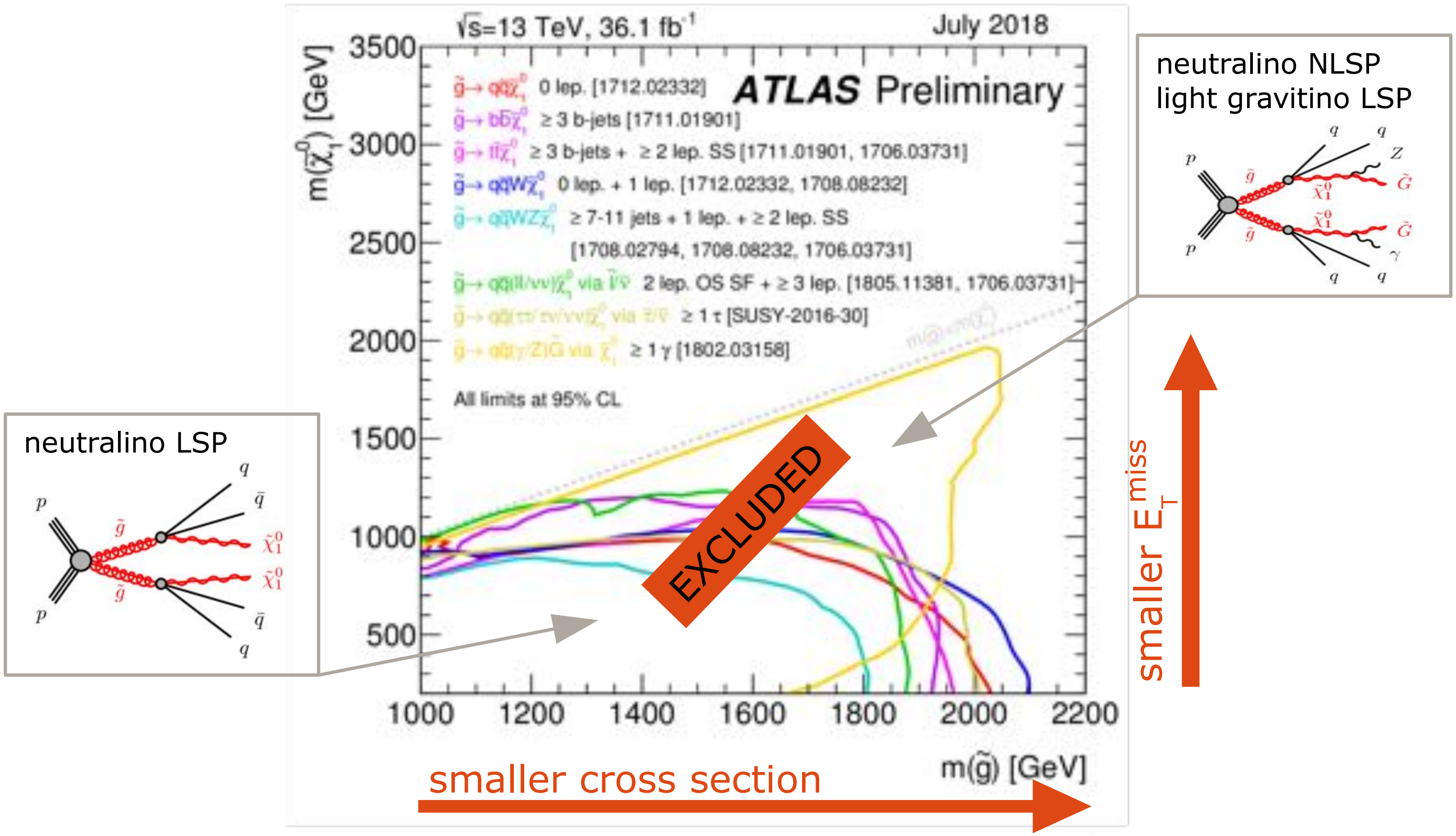
Recent ATLAS Results





If they decay directly to third generation quarks, gluinos must be heavier than about 1.5 to 2.2 TeV

Gluino Searches in more complicated Cascade Decays



Channels with cascade decays into intermediate chargino/neutralino states and compressed spectrum present the weakest limits, and the bound falls short of 2 TeV for non-compressed spectrum. Bound of 2.2 TeV in the most extreme case. Hard to evade the TeV bound.

Stop Masses : MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

- CP-odd Higgs mass m_A
- tan beta $= \frac{v_u}{v_d}$
- the top quark mass
- the stop masses and mixing

$$M^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t. [and on sbottom/stau sectors for large tan beta]

For moderate to large values of tan beta and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$$

$X_t = A_t - \mu/\tan\beta \rightarrow$ LR stop mixing

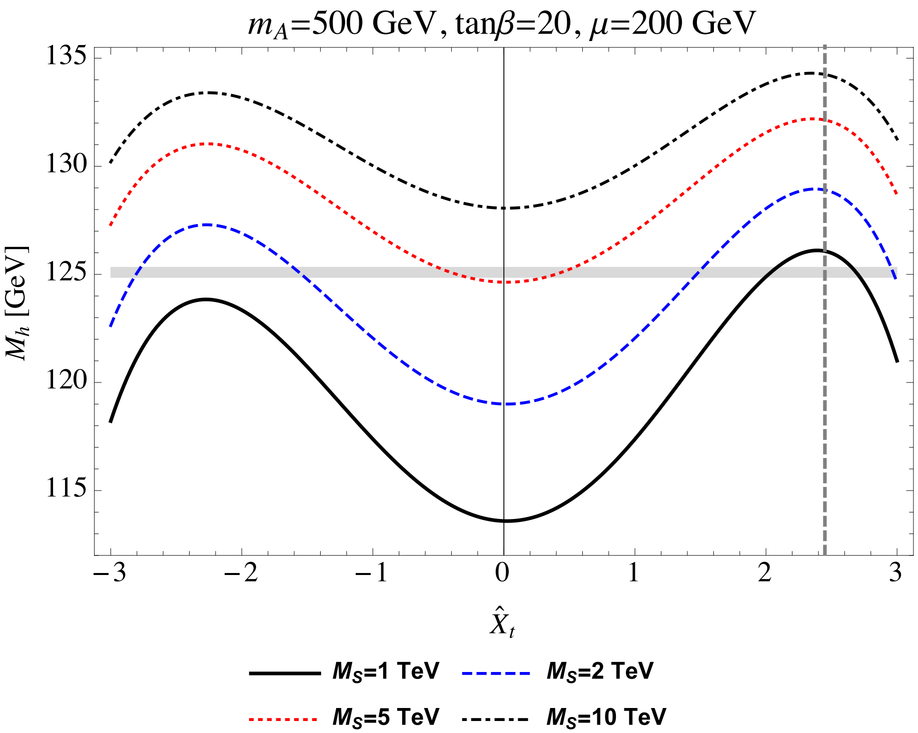
Carena, Espinosa, Quiros, C.W.'95,96

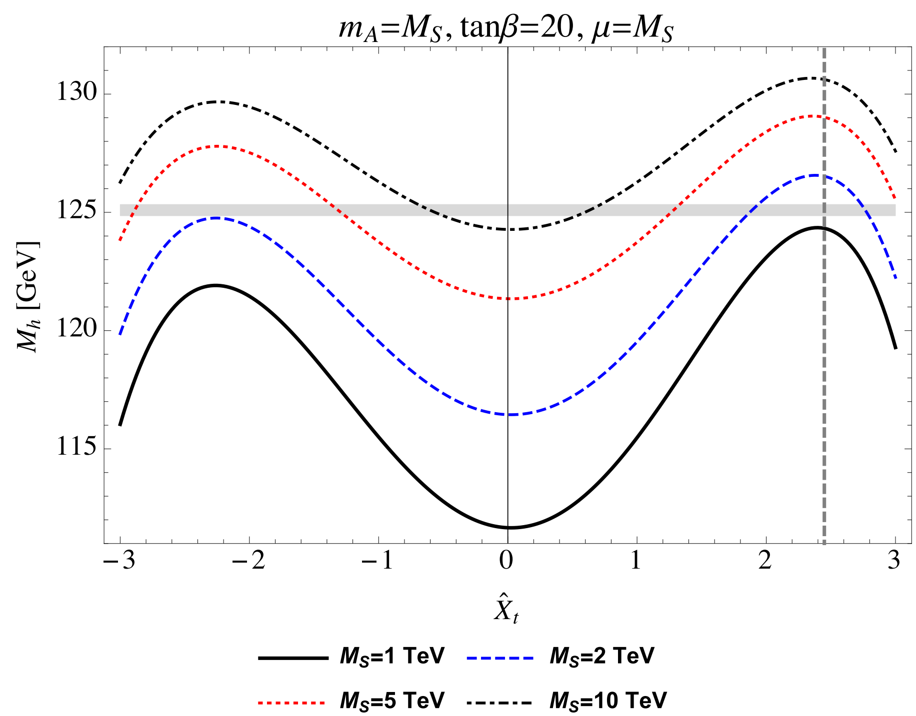
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

G. Lee, C.W. arXiv:1508.00576

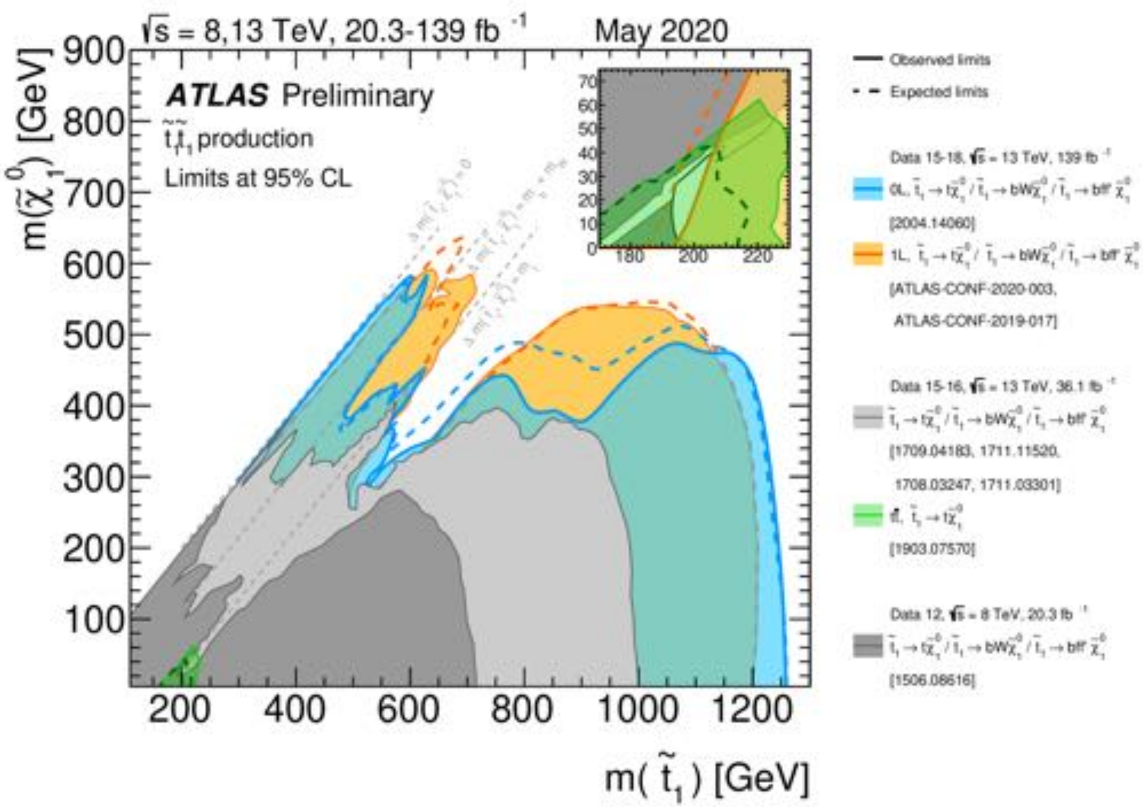


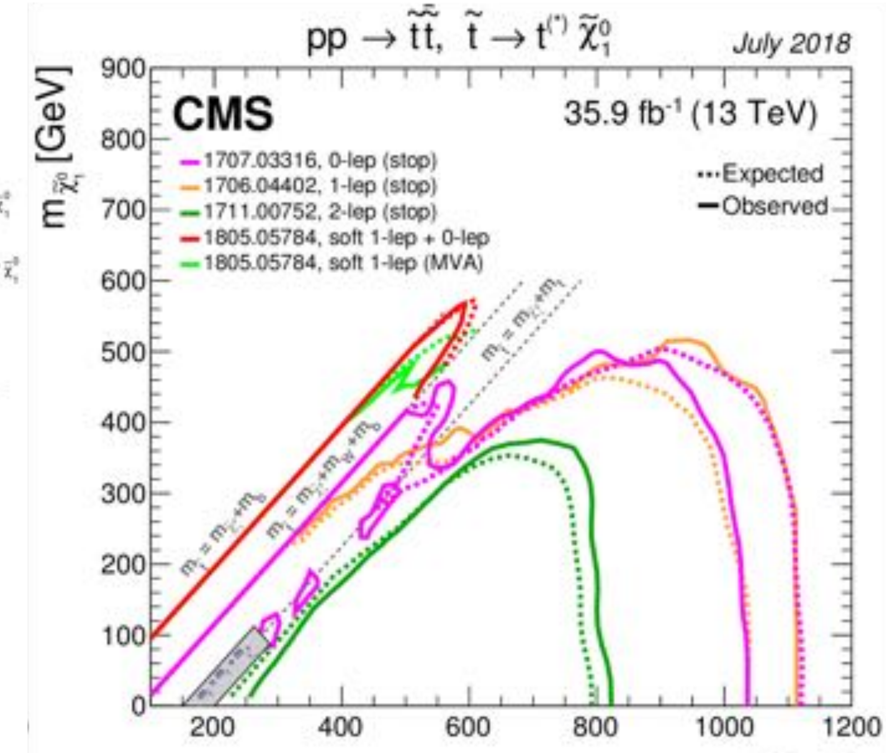


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

Stop Searches

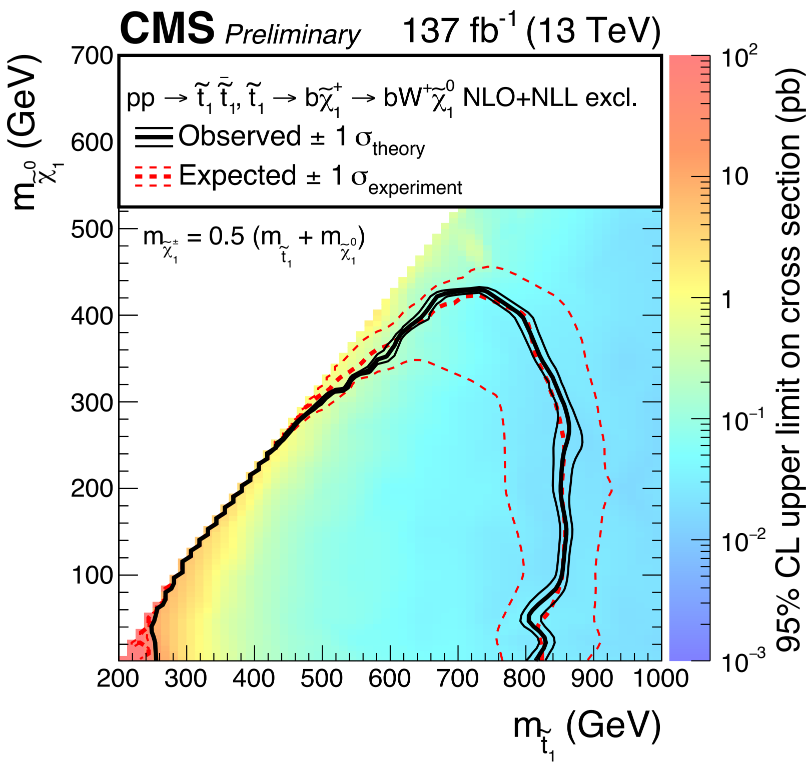


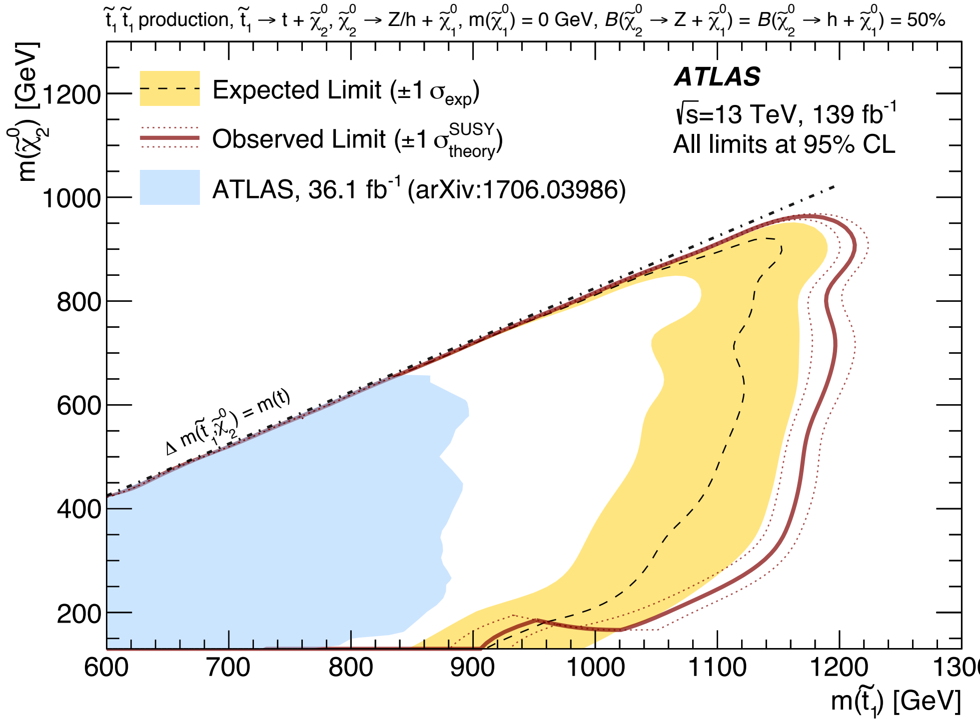


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints 600 GeV—1.2 TeV for stops, if it decays directly to top quarks and neutralinos.

We are just starting to explore the mass region suggested by the Higgs mass determination !

Cascade Decays may lead to weaker bounds



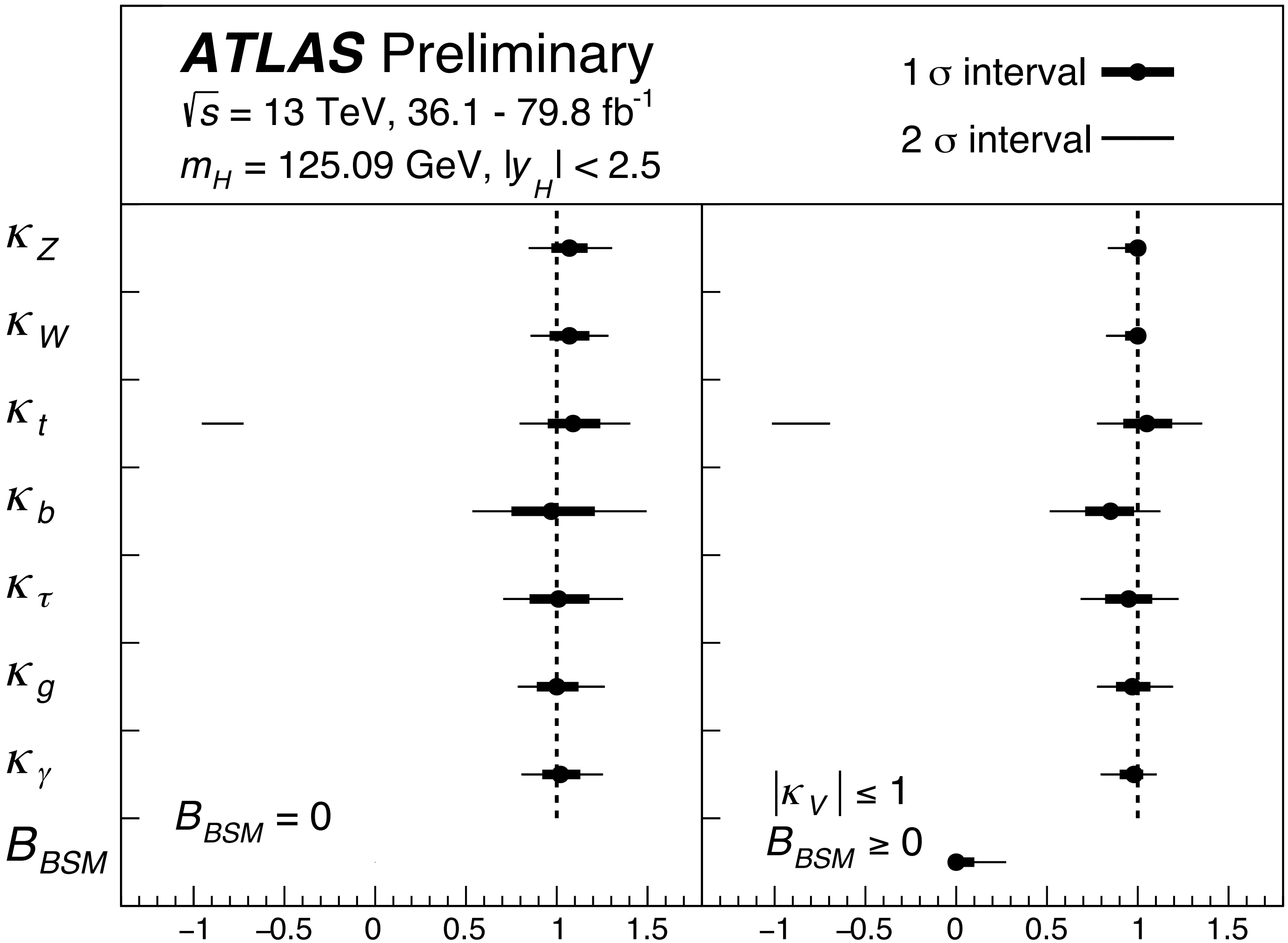


For heavier stop masses, it is natural to expect the presence of other electroweakino states the stop may decay to.

Above searches optimize the pT values. Limits may be significantly weaker than the ones shown above.

Guidance from Higgs Couplings

Departure from SM predictions of the order of few tens of percent allowed at this point



Modifying the top and bottom couplings in two Higgs Doublet Models

- Modification of about ten (or fifteen) percent are still possible
- Large modifications are certainly ruled out, with the exception of an inversion of the sign of the bottom Yukawa coupling.

$$h = -\sin\alpha H_d^0 + \cos\alpha H_u^0$$
$$H = \quad \cos\alpha H_d^0 + \sin\alpha H_u^0$$

$$\kappa_t = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\kappa_b = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$
$$\kappa_V = \sin(\beta-\alpha) \simeq 1$$

$$\tan\beta = \frac{v_u}{v_d}$$

- Alignment condition : $\cos(\beta-\alpha) = 0$ J. Gunion, H. Haber '02
- In the MSSM, it can only be achieved for large values of μ

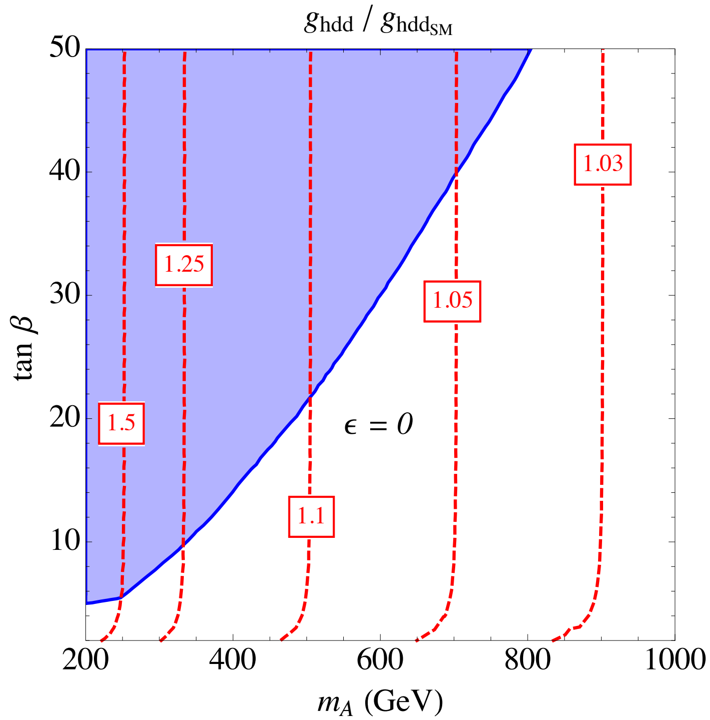
Down Couplings in the MSSM for low values of μ

- Higgs Decay into bottom quarks is the dominant one

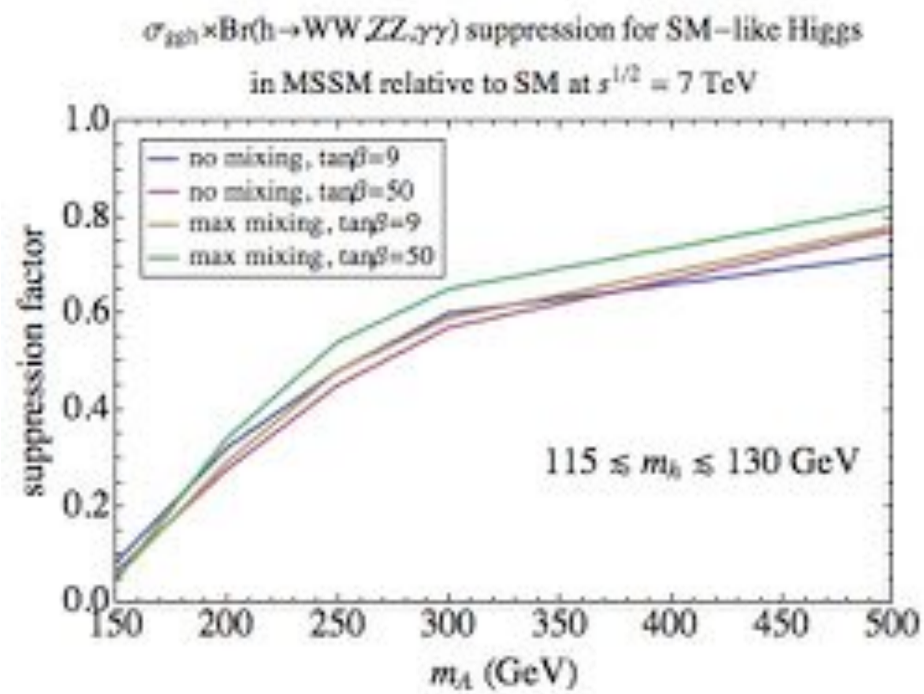
- A modification of the bottom quark coupling affects all other decays

$$t_\beta \, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta \left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2 \left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

Carena, Haber, Low, Shah, C.W. '14



Carena, Low, Shah, C.W.'13



Enhancement of bottom quark and tau couplings independent of tan β

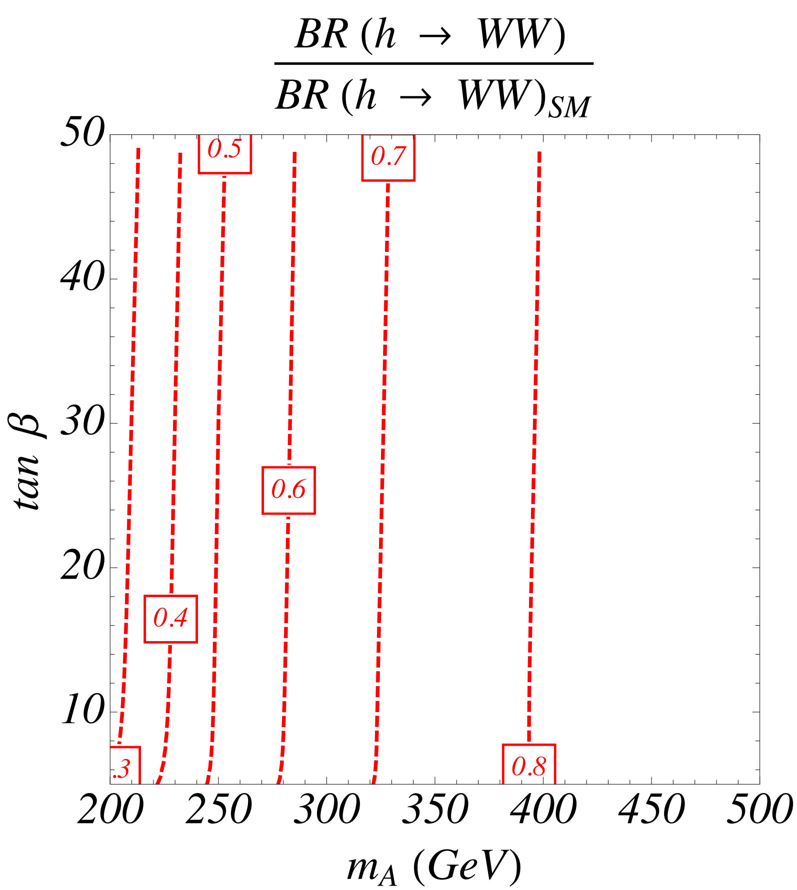
Carena, Haber, Low, Shah, C.W.'14

M. Carena, I. Low, N. Shah, C.W.'13

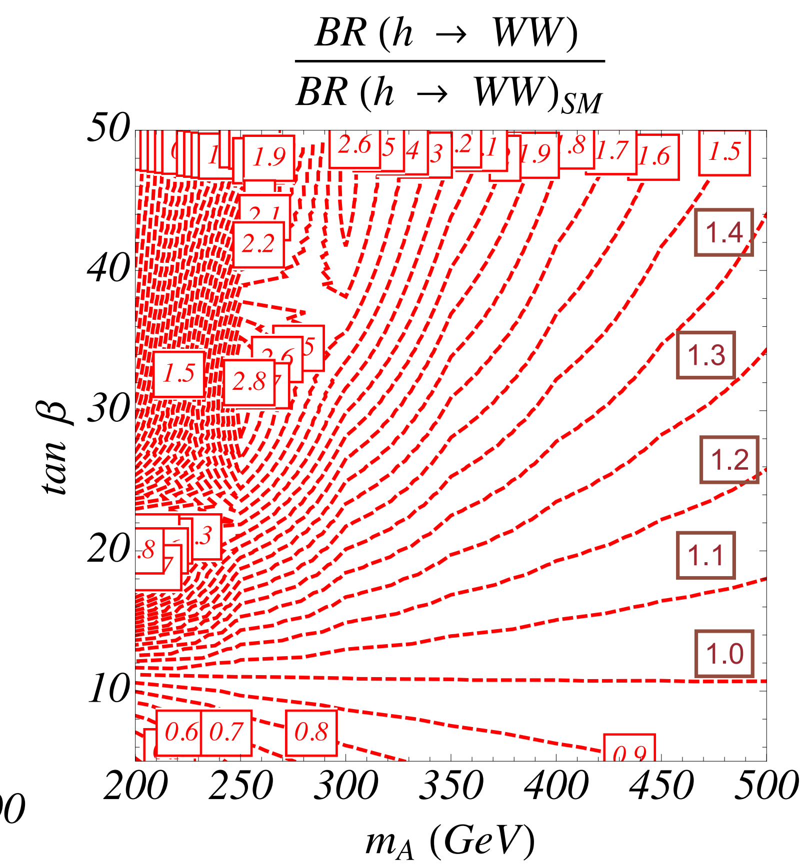
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



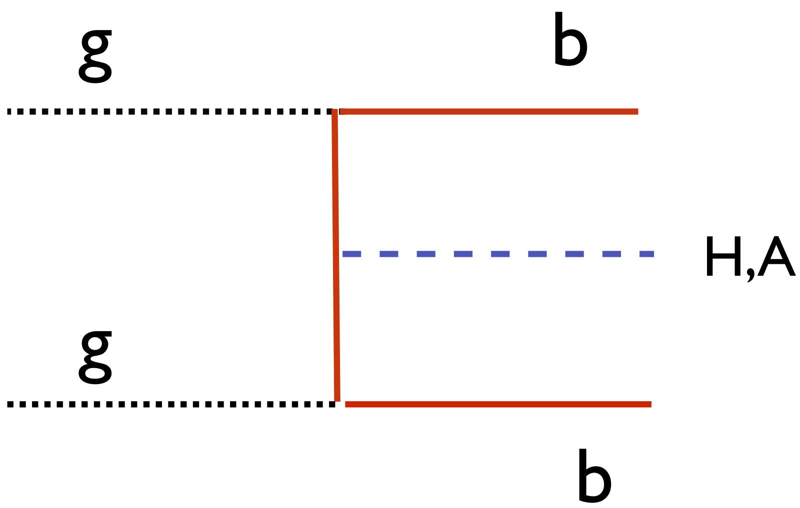
$\mu/M_{\rm SUSY} = 2, \quad A_t/M_{\rm SUSY} \simeq 3$



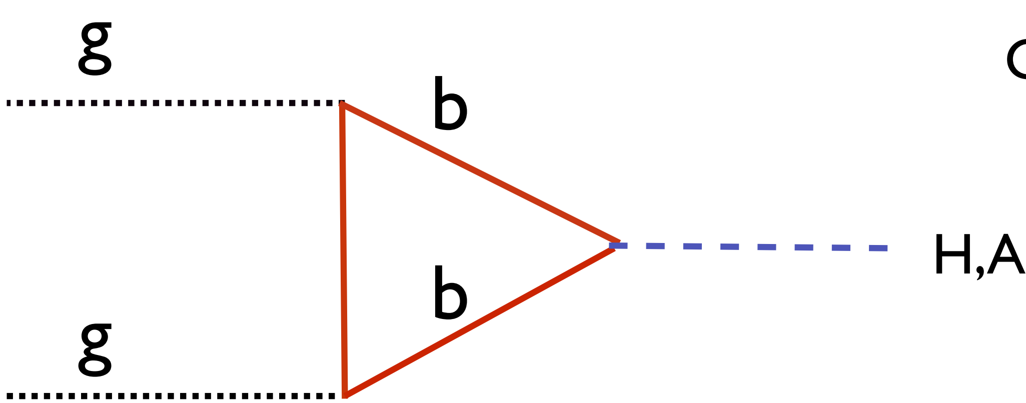
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



Associated Production



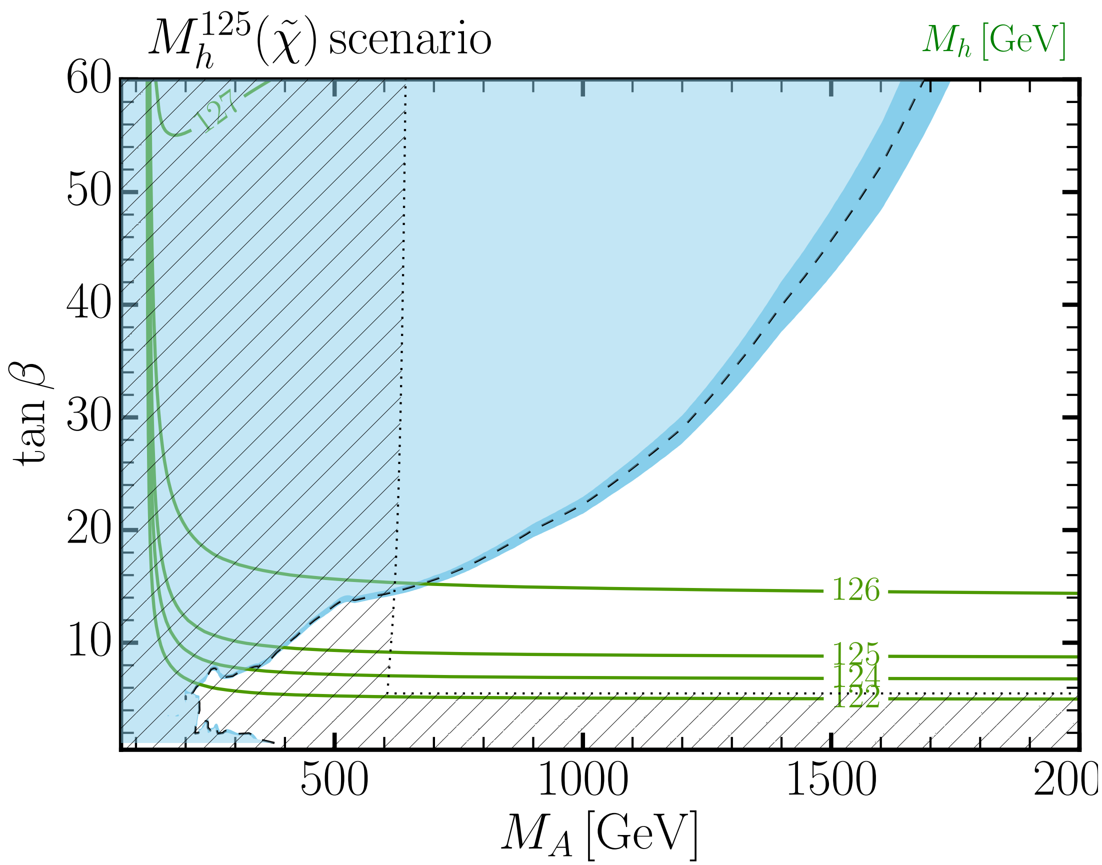
Gluon Fusion

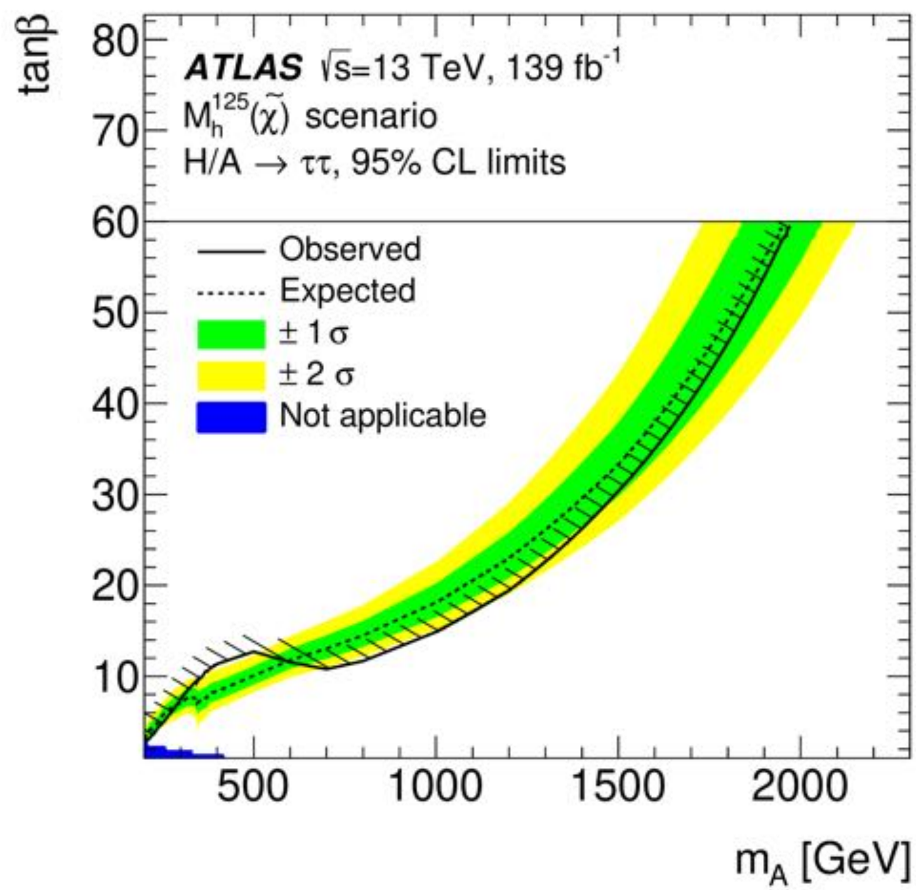
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Complementarity of Direct and Indirect Bounds

Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Weiglein, C.W. arXiv:1808.07542

Dashed area, constrained by precision measurements.
Low values of the Higgsino Mass assumed in this Figure.





Electroweak Sector

- Situation here is far less well defined than in the strongly interacting sector
- Sleptons, in particular staus are only weakly constraint beyond the LEP limits
- Winos as NLSP's are the strongest constrained particles.
- Sensitivities in the search for these particles will increase only at high luminosities, but bounds on Higgsinos will remain weak.
- In general, a scenario with large cascade decays with light electroweakinos is the most natural one and the highest hope for SUSY at the weak scale.

MSSM charginos and neutralinos

Mass matrices

charginos

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2}m_W c_\beta \\ \sqrt{2}m_W s_\beta & \mu \end{pmatrix}$$

neutralinos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

M_2 real, $\quad M_1 = |M_1| e^{i\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

At tree level:

charginos $\quad M_2, \mu, \tan\beta$

neutralinos $\quad +M_1$

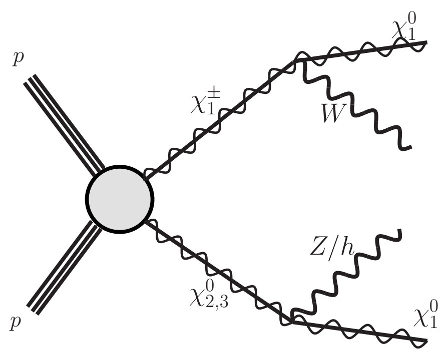
Expected to be among the lightest sparticles

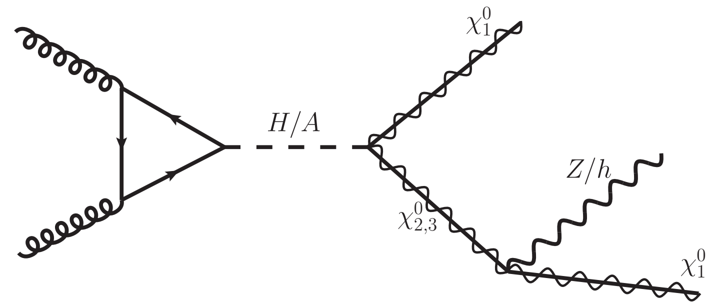
Φ_μ, Φ_1

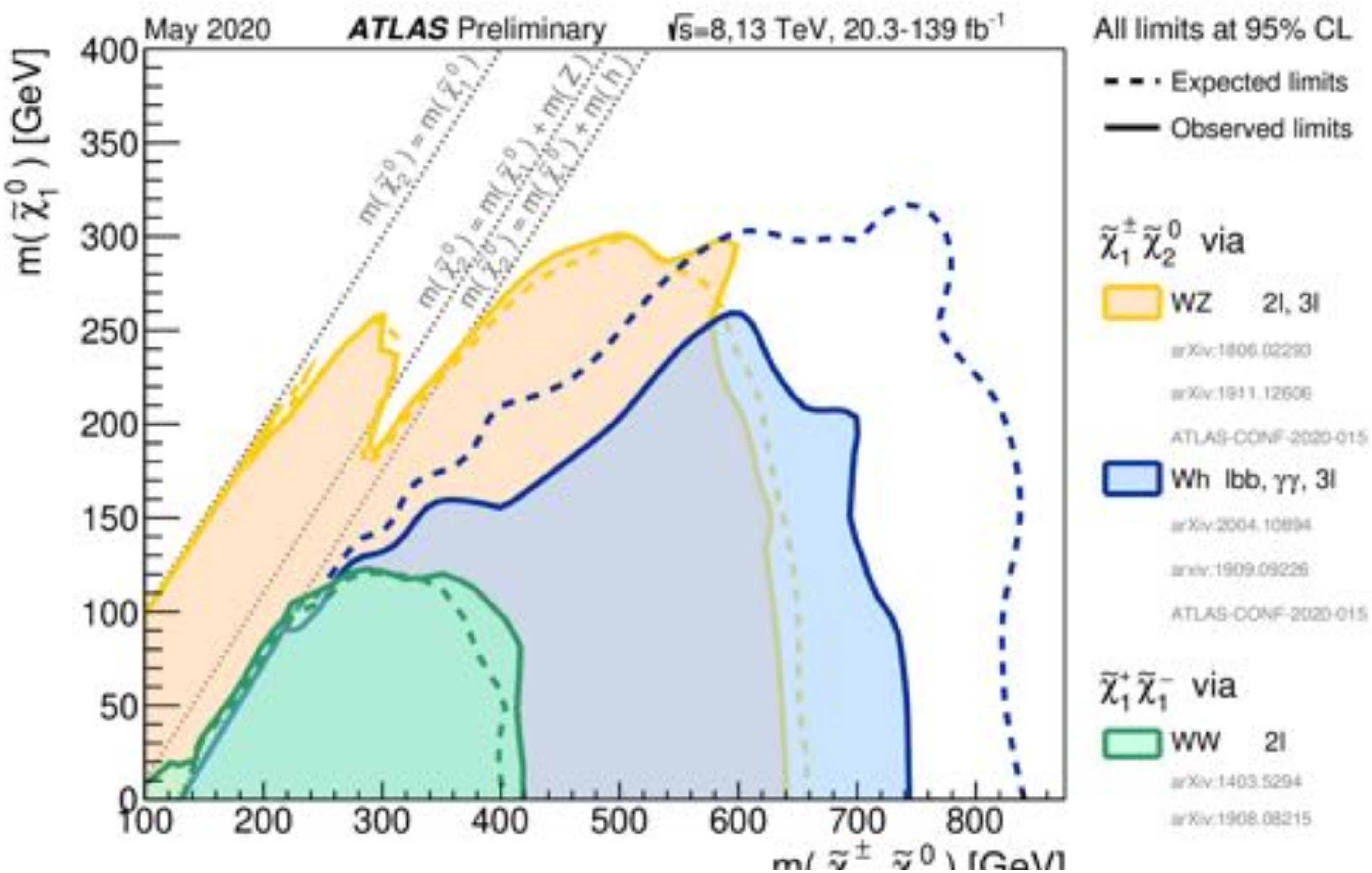
CP phases

→ A good starting point towards SUSY parameter determination

Current Electroweakino Mass Bounds
Wino NLSP (BR = 1)







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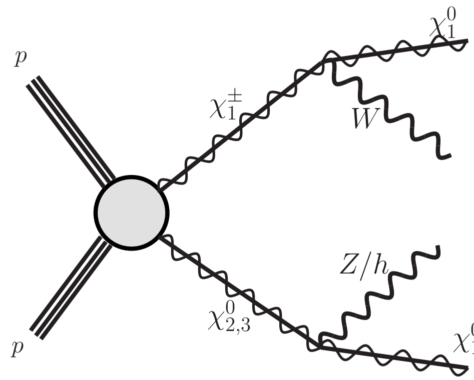
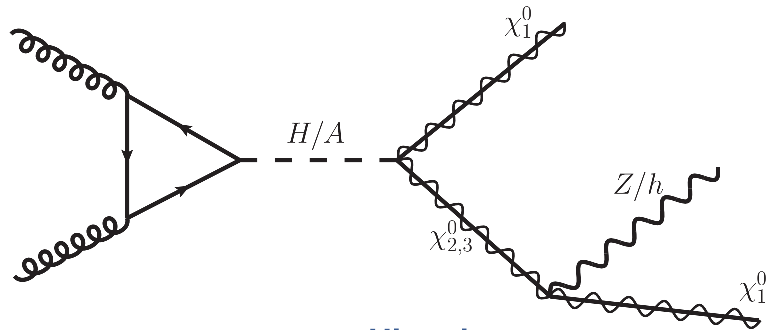
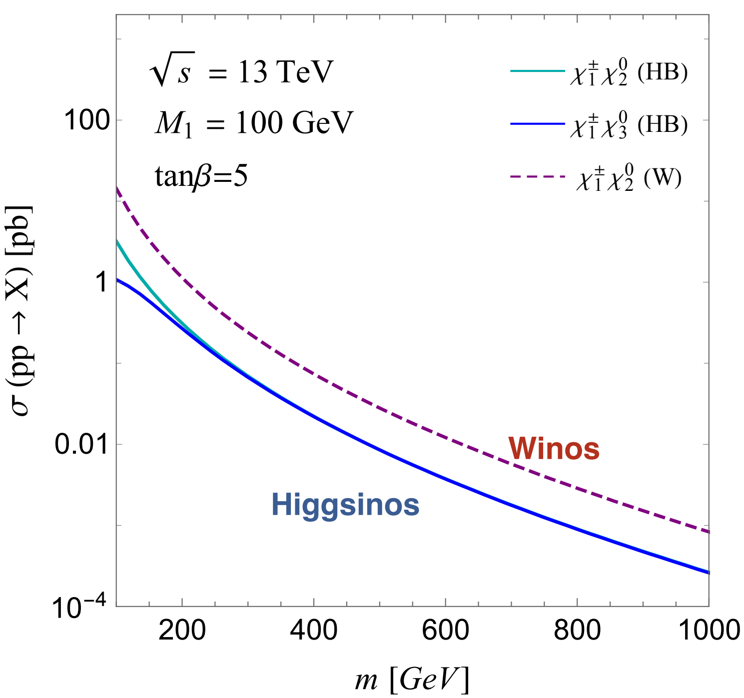
Relevant Electroweakino Production and Decay at the LHC (Bino LSP)

Baum, Freese, Shah, Shakya'17,
Gori, Liu, Shakya'18, Bahl, Liebler, Stefaniak'19,
Adhikary, Bhattacherjee, Godbole, Kahan, Kulkarni'20
Canepa, Han, Wang'20

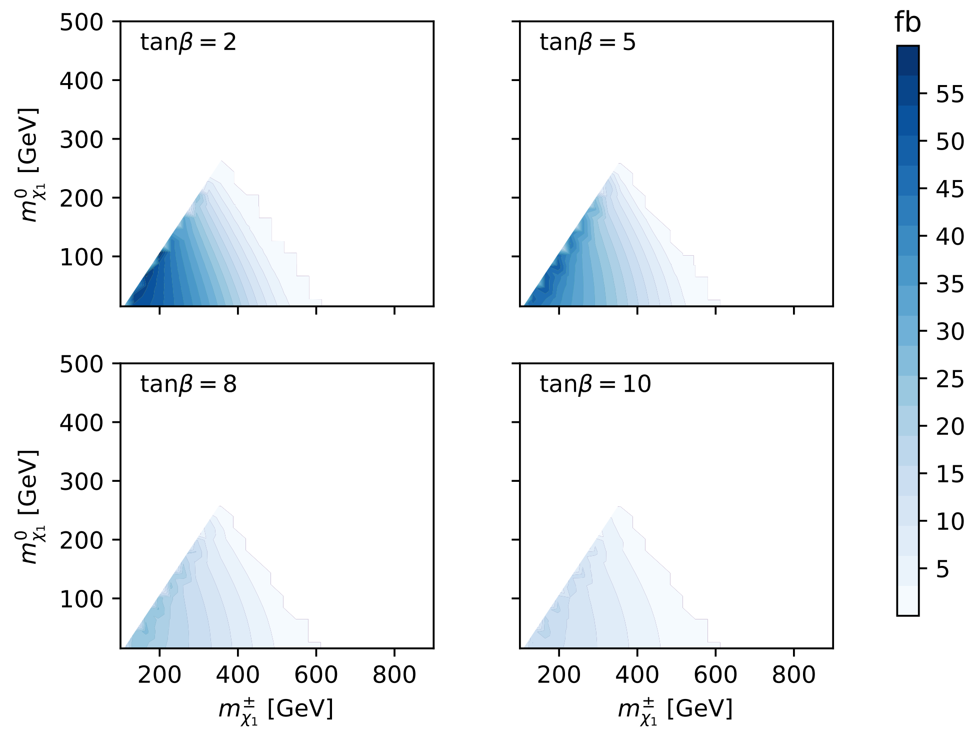




Higgsinos



$\sigma(H/A \to \chi_{2,3}^0 + \chi_1^0 \to Z + 2\chi_1^0)$, $M_A = 600$ GeV



Neutral Higgsino Decays

At low masses, at some point Higgsinos cannot decay into Higgs bosons due to kinematic restrictions

At sufficiently large mass values, the Goldstone equivalent theorem applies and the decays are approximately 50 percent into Higgs and into the Z gauge boson.

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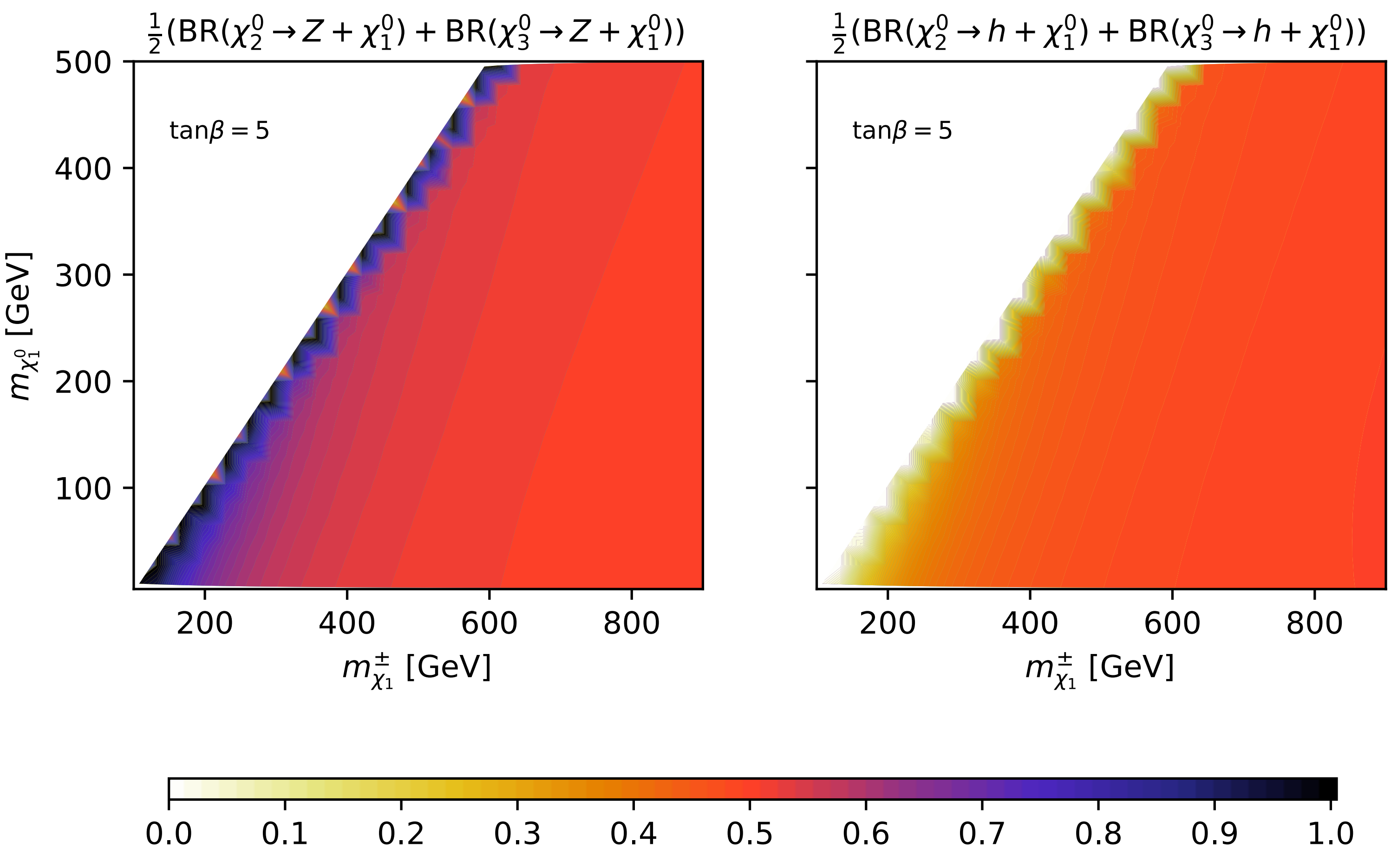

Heavy Winos : Higgsino-Bino LHC Probes

Results from a recast of current CMS and ATLAS bounds.

Due to lower cross sections, the reach is weaker than in the Wino case.

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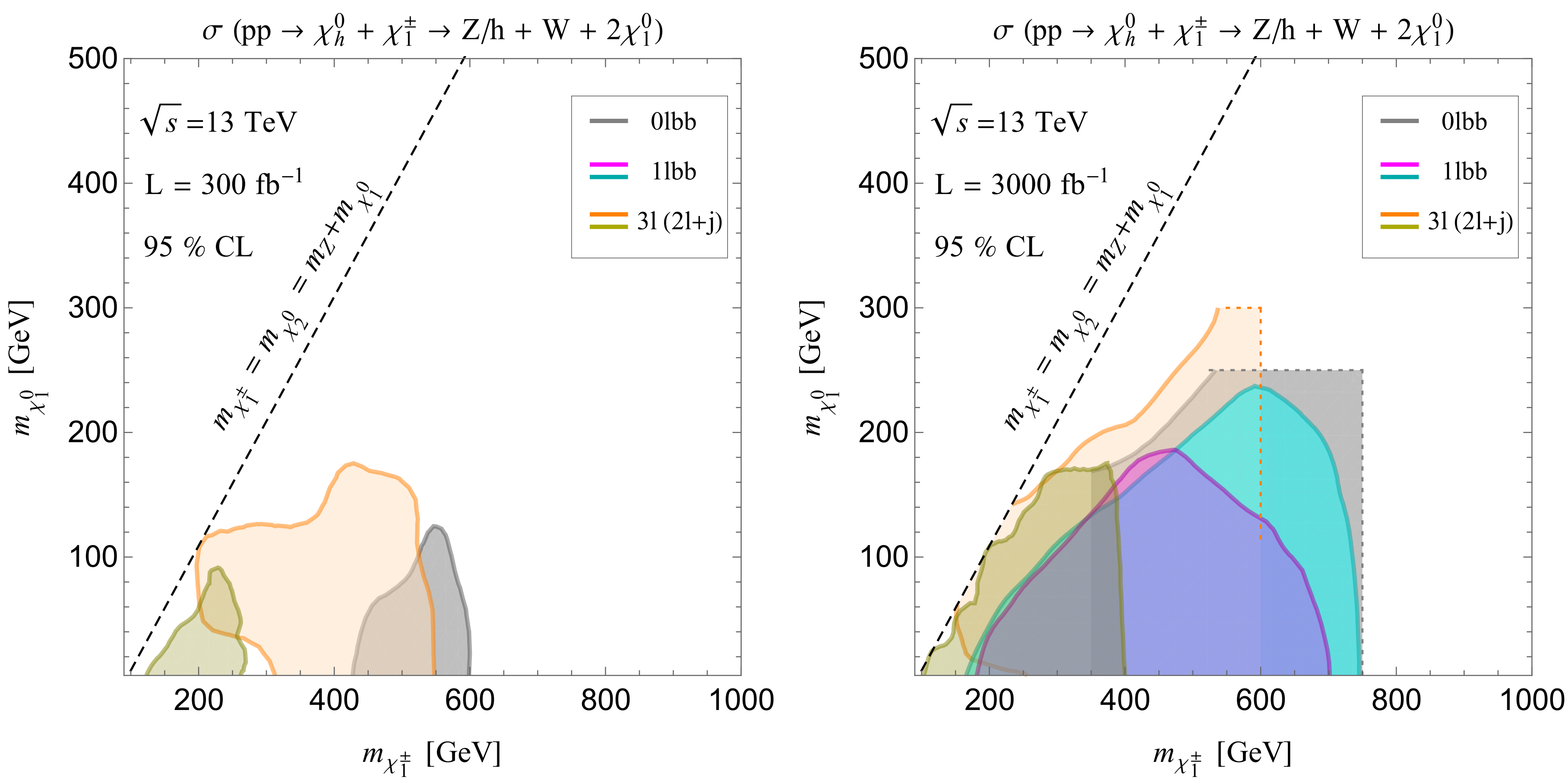

Compressed Region hard to Probe in direct production

Heavy Winos : Higgsino-Bino
Current Exclusion and Discovery Reach

Current sensitivity is even weaker than at 300 fb-1.

Clear discovery opportunity for reasonable values of the electroweakino masses not yet explored by the LHC.

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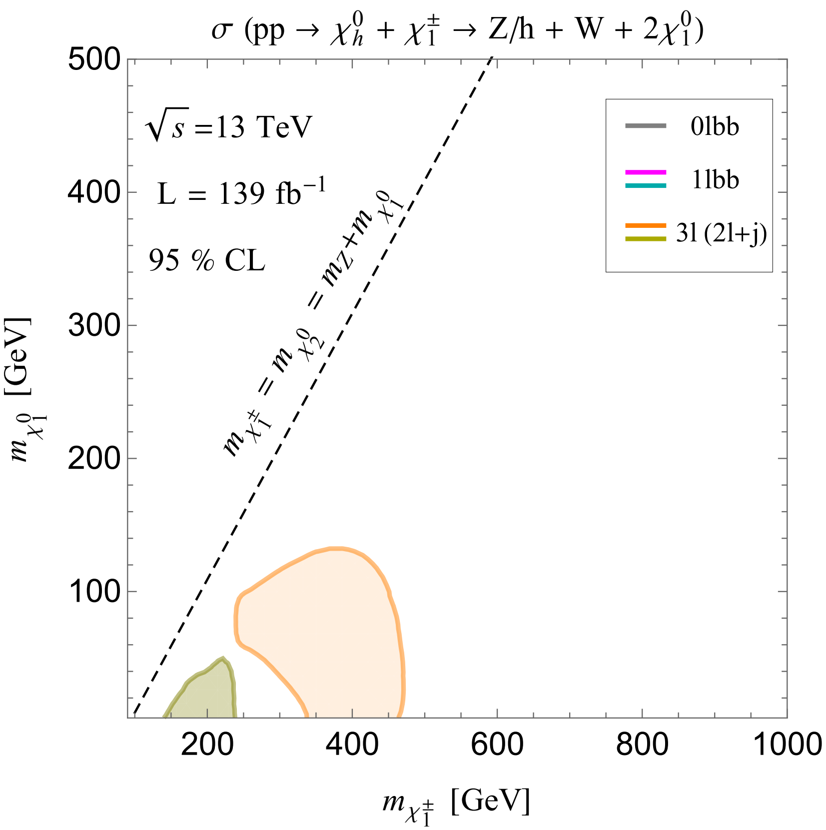
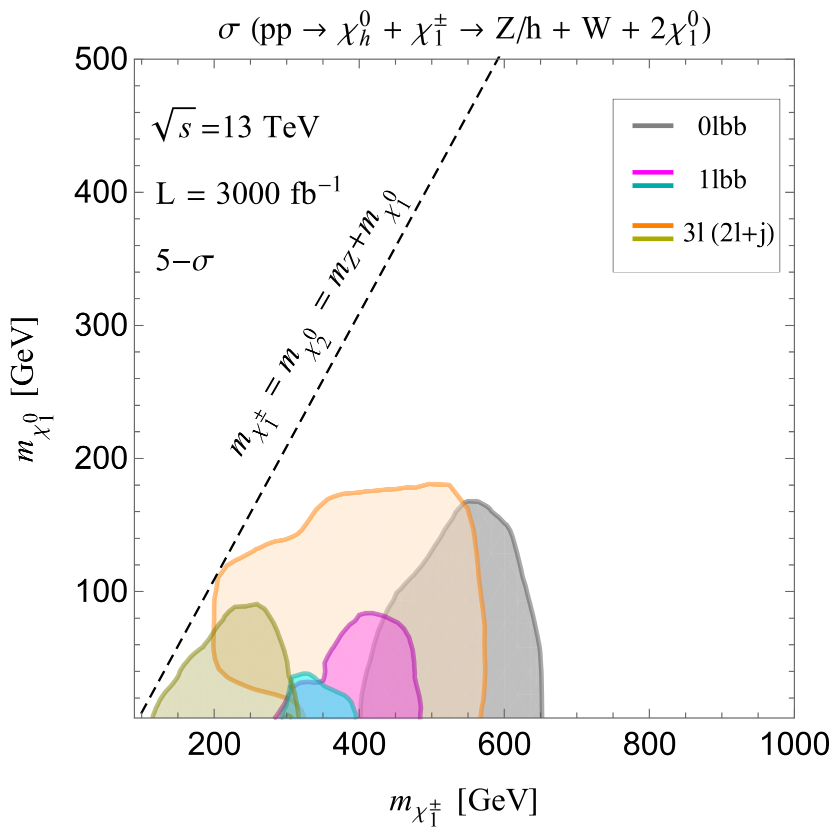
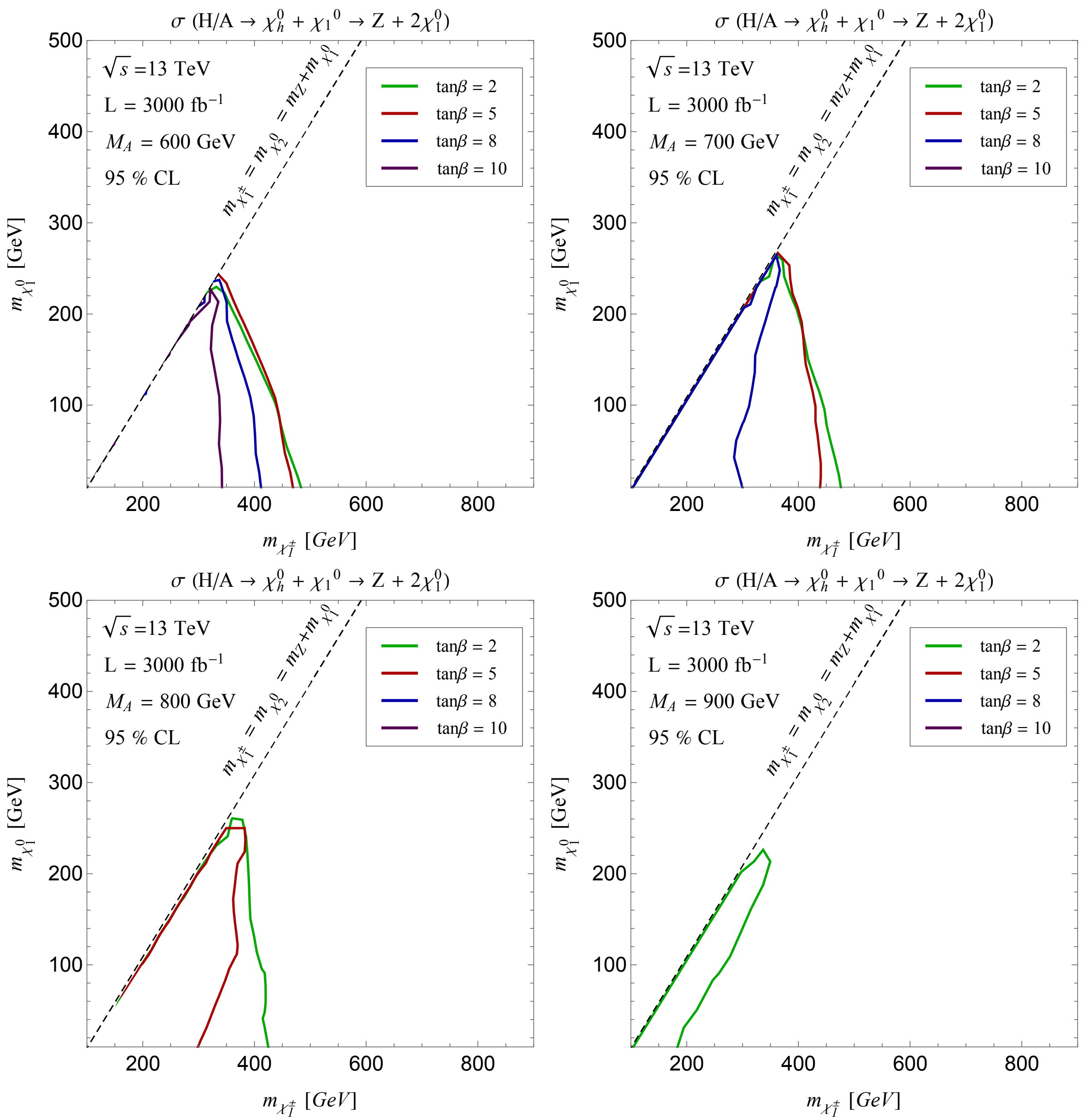




Reach from heavy Higgs Production

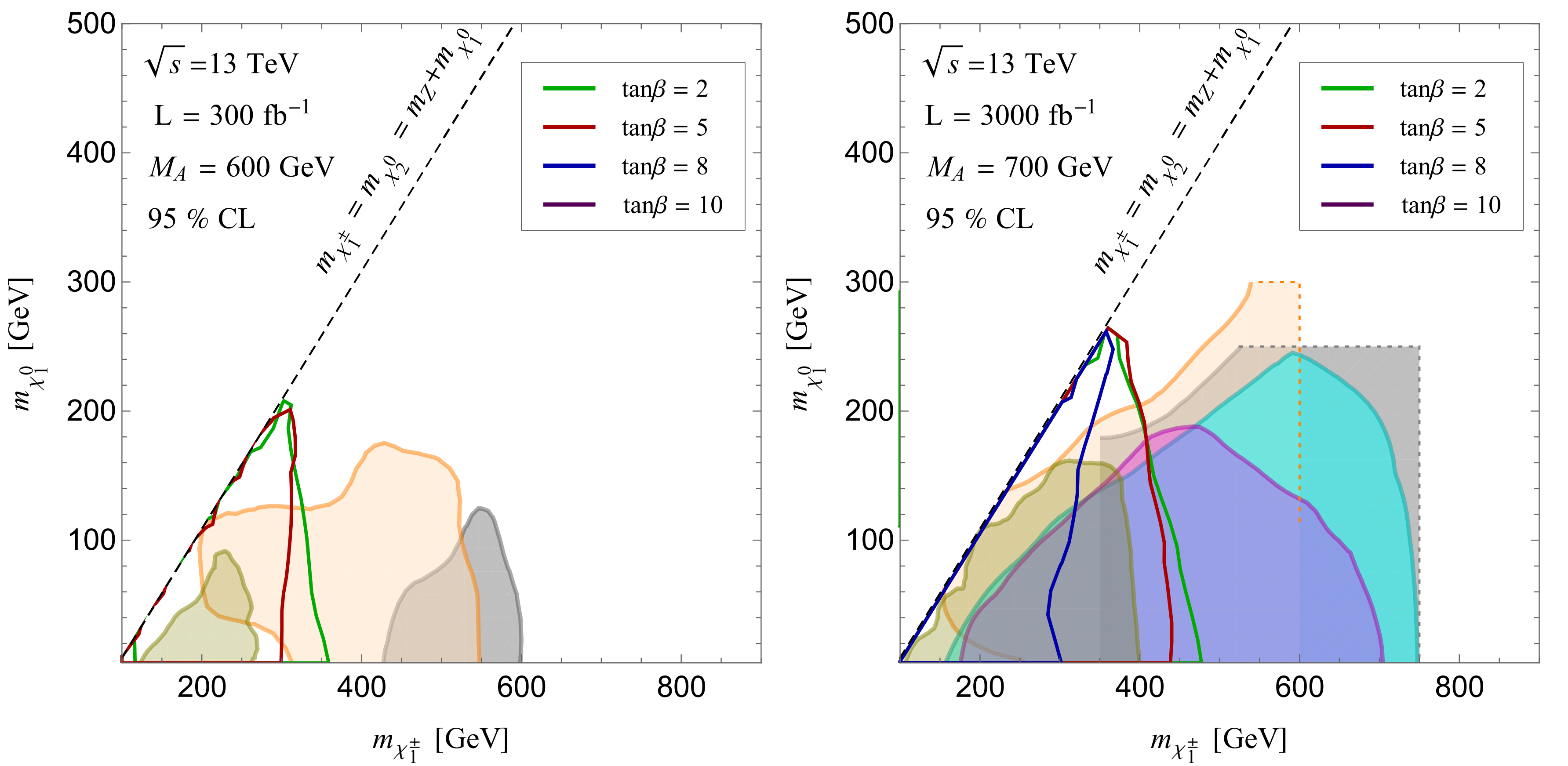
J. Liu, N. McGinnis, X. Wang, C.W. ‘20



Larger transverse momentum coming from Higgs decays allow to probe the compressed region.

Complementarity of Direct and Higgs Decay Production

J. Liu, N. McGinnis, X. Wang, C.W. '20



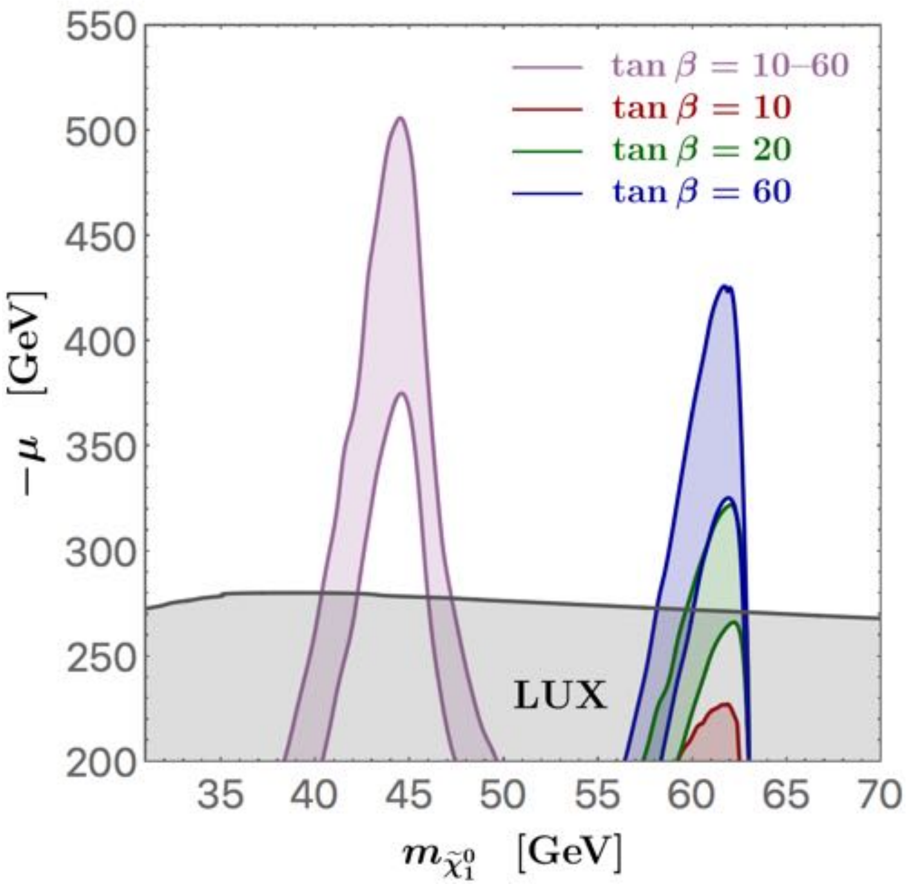
For certain region of parameters, discovery of Supersymmetry plus a heavy Higgs via electroweakino production possible.

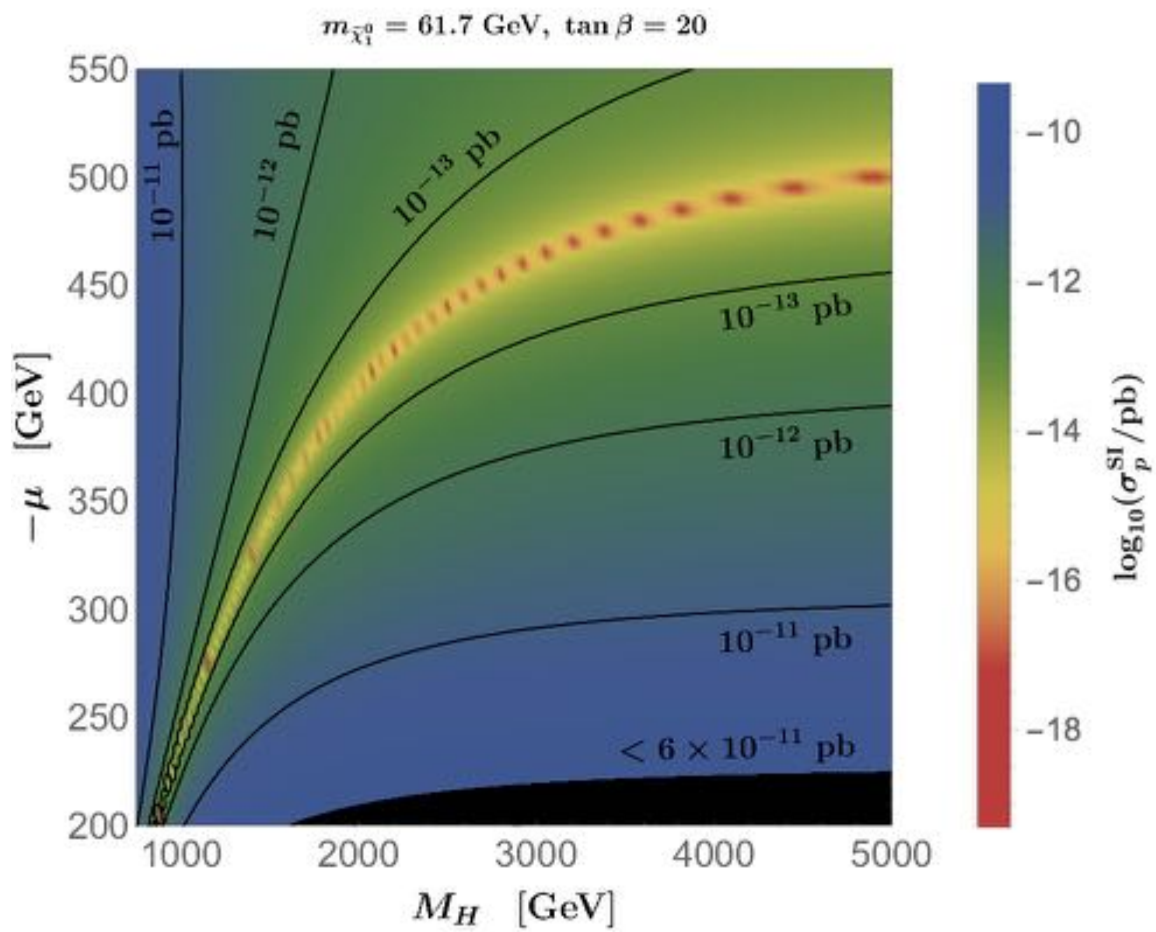
Carena, Osborne, Shah, C.W. ’18'19

Dark Matter Phenomenology

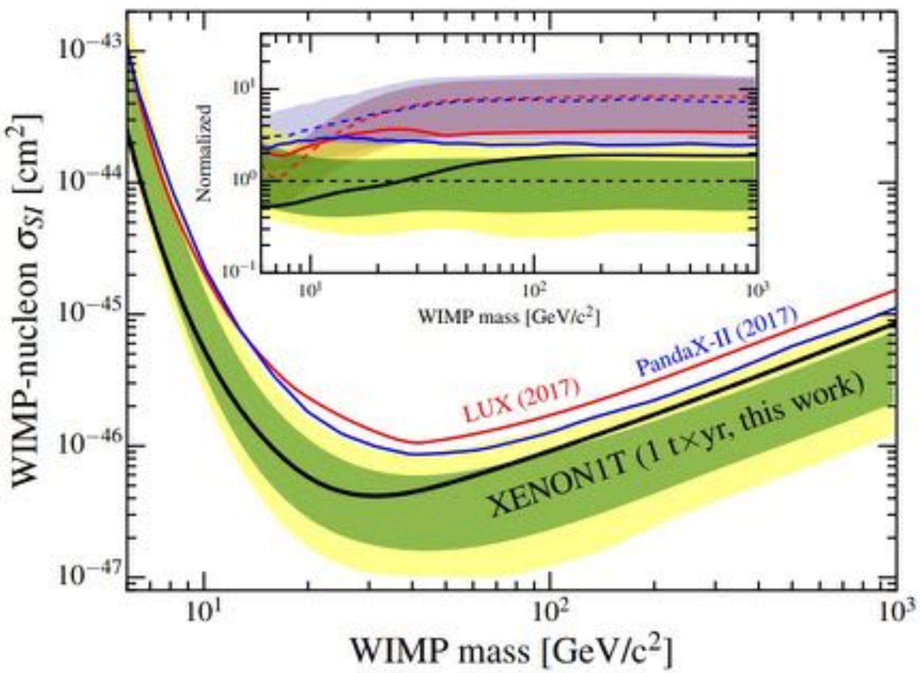
Higgs and Z Resonant Annihilation Regions
SD Cross Section Bounds satisfied
provided $|\mu| > 270$ GeV

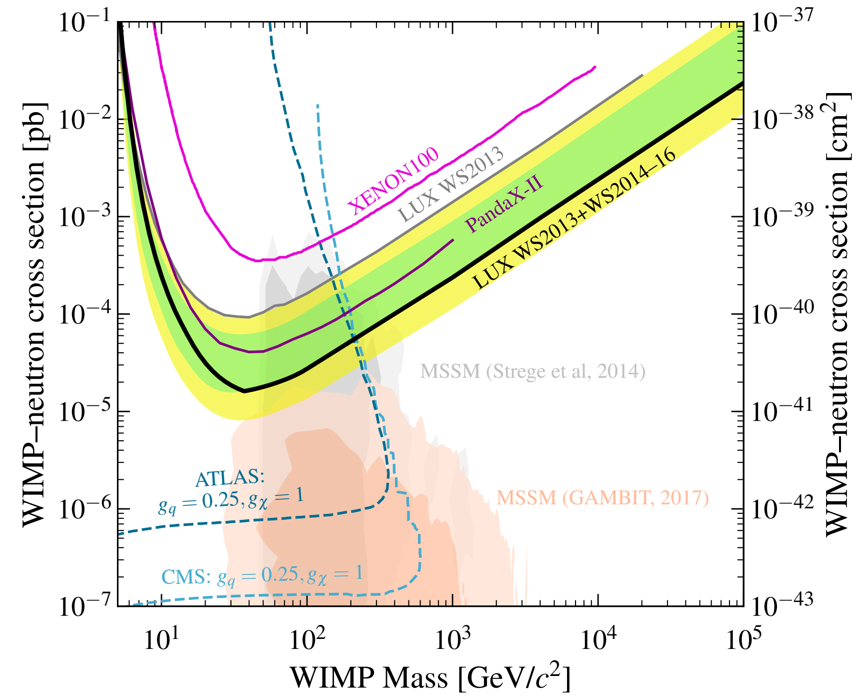
Existence of Blind Spot Regions Suppresses the SI cross section below the current limits in most of the parameter space.





DM : Direct Detection Bounds





$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde{\chi}_1^0} + 2\mu/\tan\beta)\frac{1}{m_h^2} + \mu\tan\beta\frac{1}{m_H^2} + (m_{\tilde{\chi}_1^0} + \mu\tan\beta/2)\frac{1}{m_{\tilde{Q}}^2}\right]^2$$

Blind Spot :

$$2\left(m_{\tilde{\chi}_1^0} + 2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2} + \frac{1}{2m_{\tilde{Q}}^2}\right)$$

$$\mu \times m_{\tilde{\chi}^0} < 0$$
$$m_{\tilde{\chi}^0} \simeq M_1$$

Cheung, Hall, Pinner, Ruderman'12, Huang, C.W.'14, Cheung, Papucci, Shah, Stanford,Zurek'14, Han,Liu,Mukhopadhyay,Wang'18

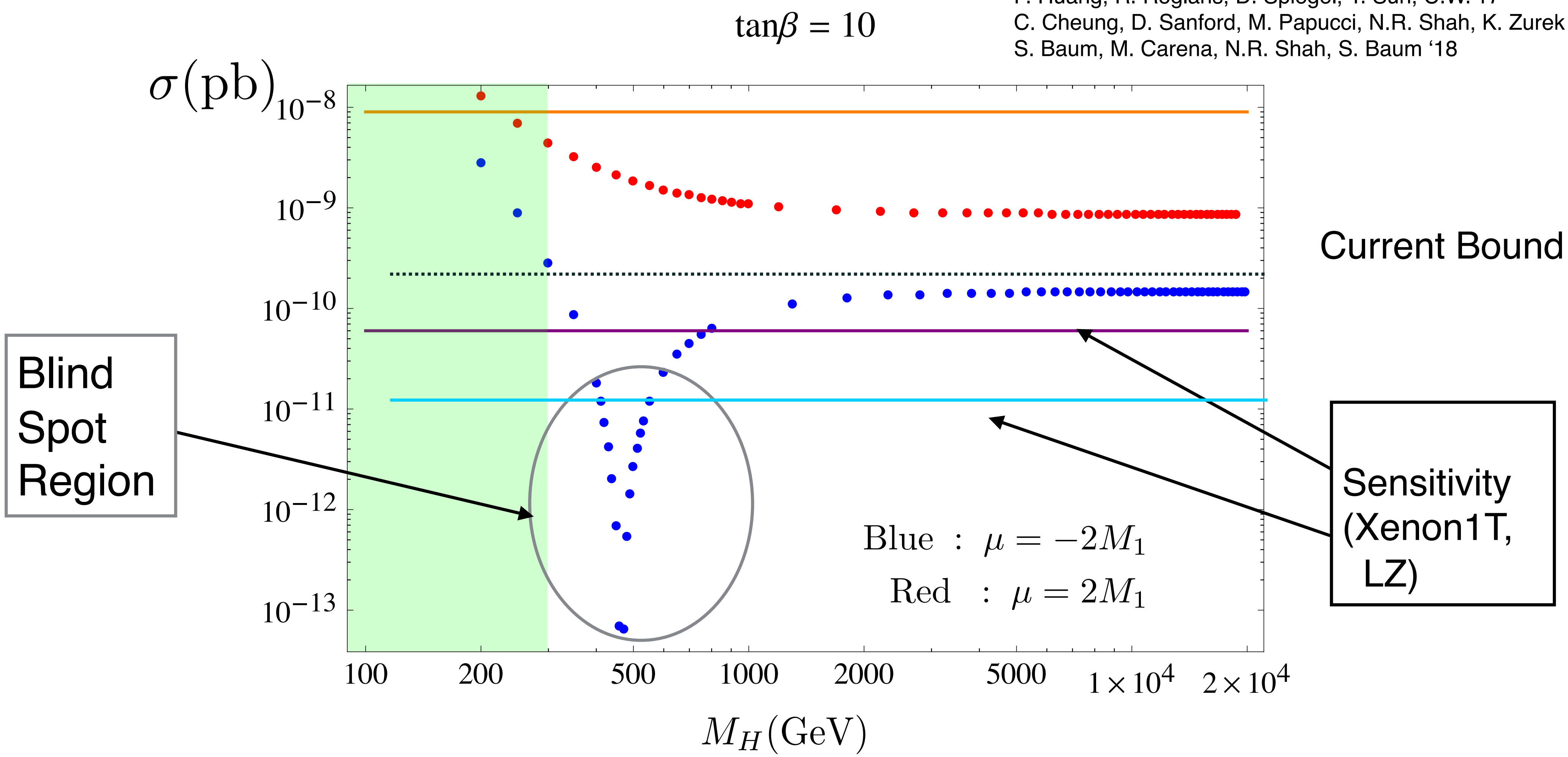
$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

Dependence of the cross section on the heavy Higgs mass

Negative values of μ : Much weaker direct spin-independent detection bounds

Blind Spots : $$2\left(m_{\chi^0} + \mu \sin 2\beta\right)\frac{1}{m_h^2} = -\mu \tan\beta \frac{1}{M_H^2}$$

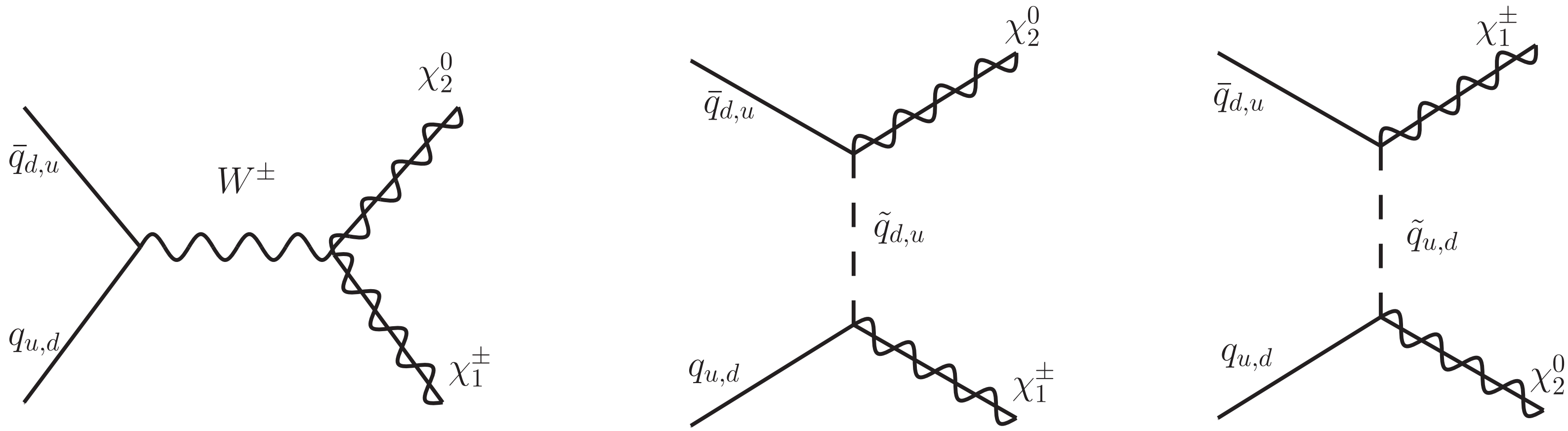
C. Cheung, L. Hall, D. Pinner, J. Ruderman'12
P. Huang, C.W.'14
P. Huang, R. Roglans, D. Spiegel, Y. Sun, C.W.'17
C. Cheung, D. Sanford, M. Papucci, N.R. Shah, K. Zurek '1
S. Baum, M. Carena, N.R. Shah, S. Baum '18

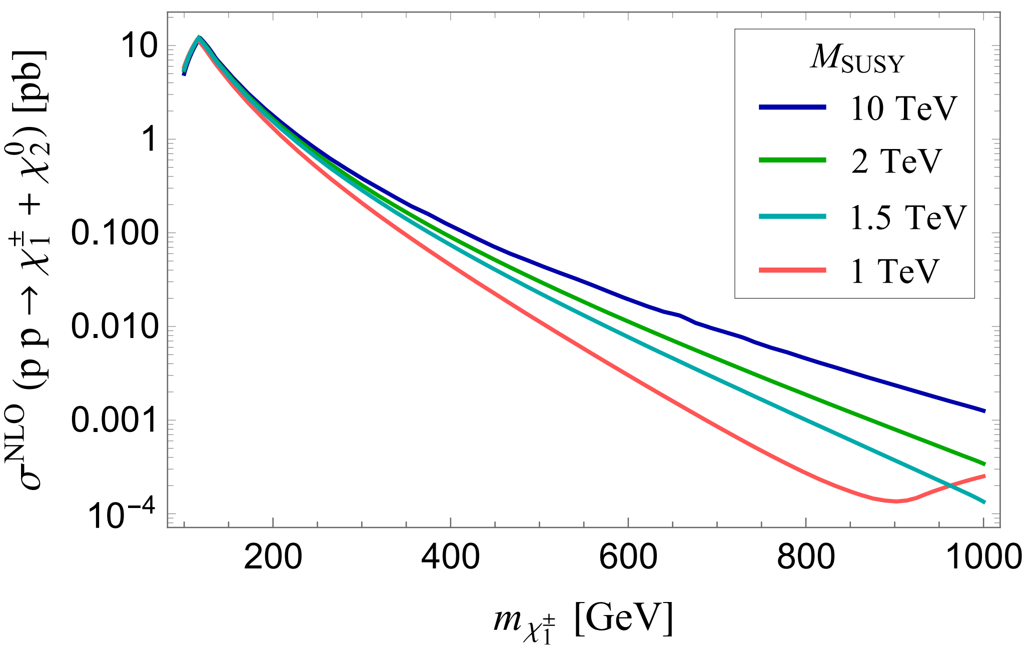


$$m_{\chi^\pm} = |\mu|, \quad m_\chi^0 = M_1, \quad M_1 = 200 \text{ GeV}$$

Heavy Higgsinos and Light Winos : Squark t- and u-channel contributions become relevant

(Direct Detection Suppressed by the large values of μ : Suppression of Higgs coupling)





$$M_{\mathrm{SUSY}} = m_{\tilde{q}} = |\mu|$$

Variation of production cross section comes mostly from the squark mass spectrum.

Relevant destructive interference.

Higgs coupling dominant (induced by direct Bino-Higgsino mixing)

Z-coupling can only appear via both Bino and Wino-Higgsino mixing

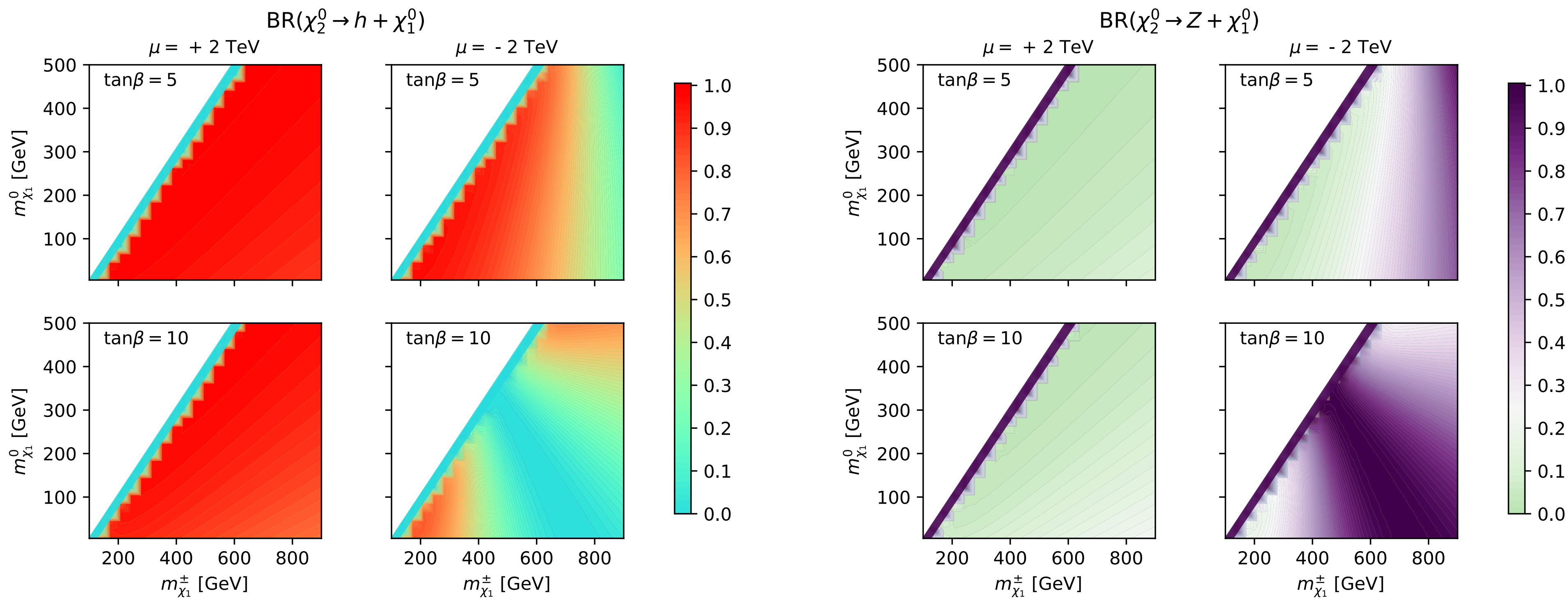
$$g_{h\chi_1^0\chi_2^0} = -\frac{em_Z}{\mu}\left[s_{2\beta} + \frac{m_{\chi_1^0}+m_{\chi_2^0}}{2\mu} + \frac{m_Z^2 s_{2\beta}^2 c_{2w}}{\mu\left(m_{\chi_2^0}-m_{\chi_1^0}\right)}\right]$$

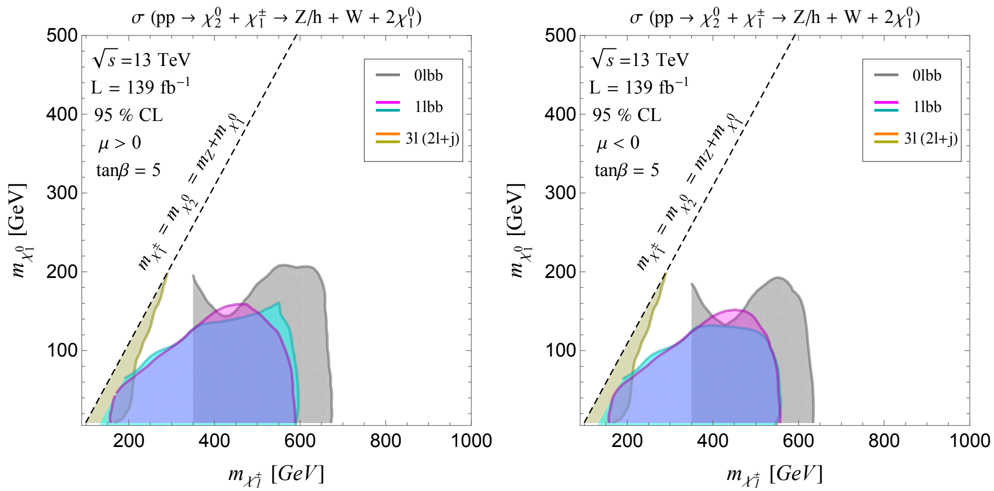
$$g_{Z\chi_1^0\chi_2^0} = -\frac{em_Z^2}{2\mu^2}\left[c_{2\beta} + \frac{m_Z^2 s_{4\beta} c_{2w}}{2\mu\left(m_{\chi_2^0}-m_{\chi_1^0}\right)}\right].$$

Blind Spot $(g_{h\chi_1^0\chi_2^0}=0)$ for

$$\mu\ s_{2\beta} = -\frac{m_{\chi_1^0}+m_{\chi_2^0}}{2}$$

Higgs Decay is the dominant BR

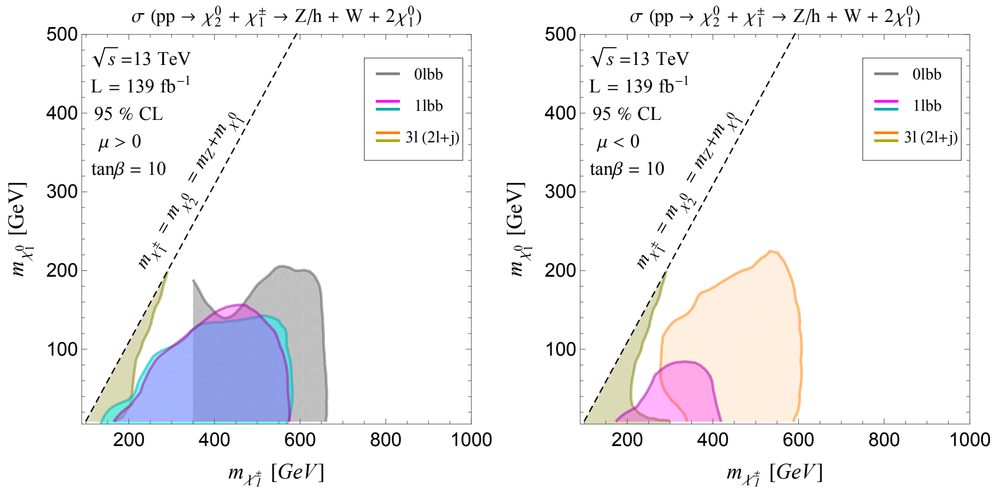




$|\mu| = 2$ TeV

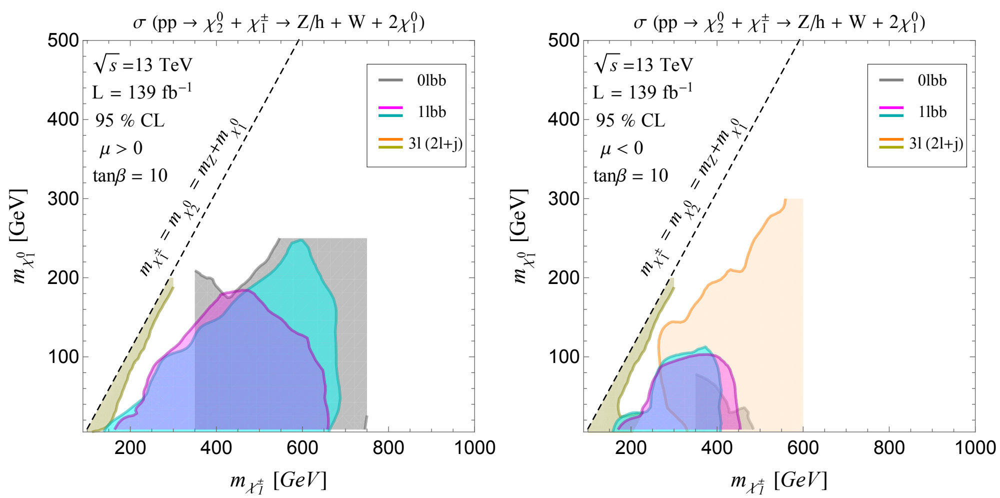
$m_{\tilde{q}} = 2$ TeV

Far from the Blind Spot, Higgs decay dominates, independently of the sign of the μ mass.



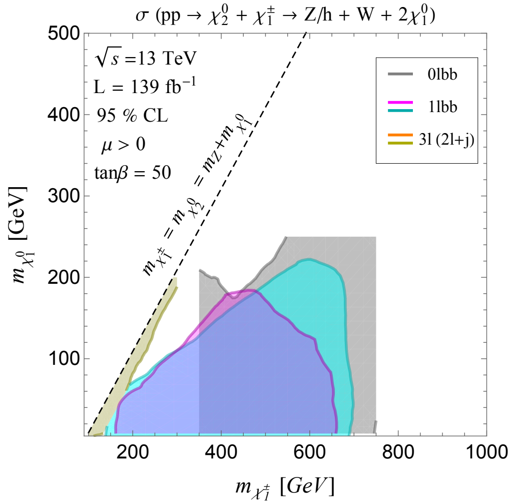
$m_{\tilde{q}} = 2$ TeV

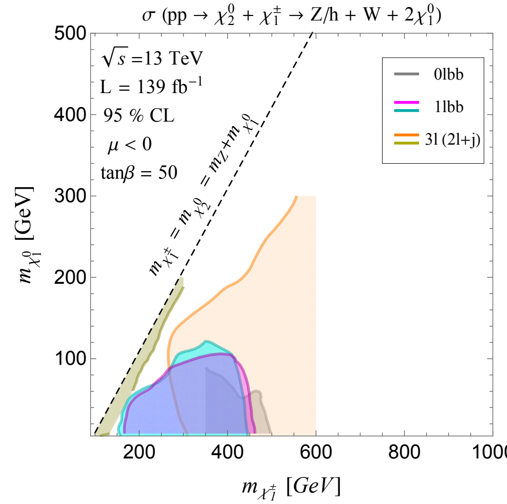
For μ negative, we see the emergence of the Blind Spot Higgs decay condition.



$m_{\tilde{q}} = 10$ TeV

Cross section increases and therefore the reach.

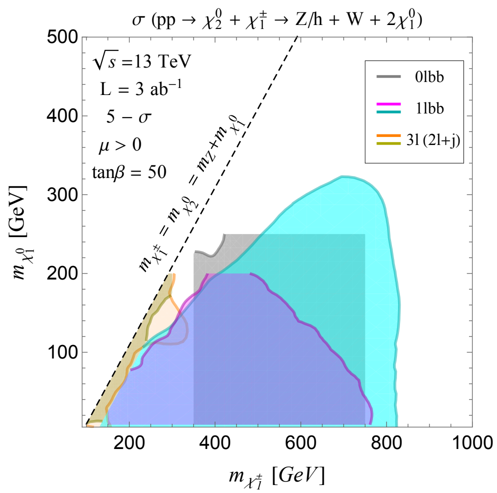


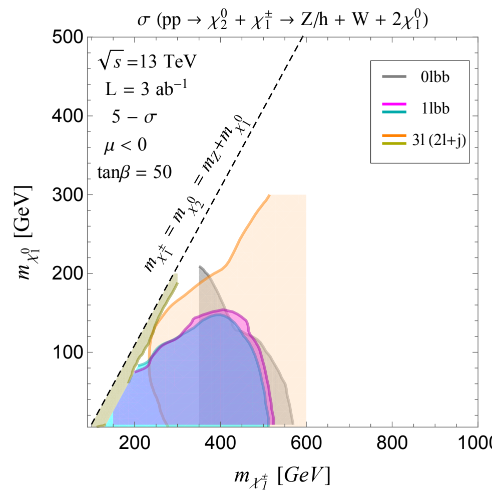


$$|\mu| = 10 \text{ TeV}$$

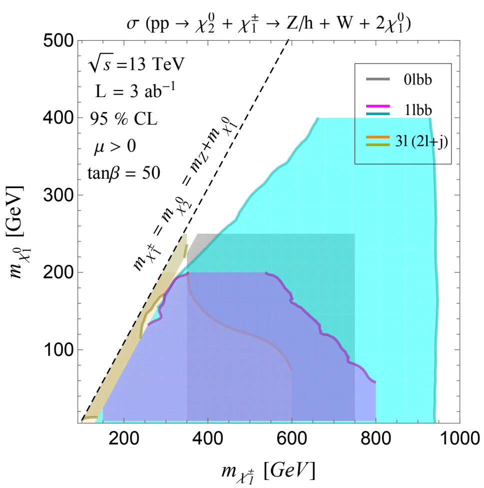
$$m_{\tilde{q}} = 10 \text{ TeV}$$

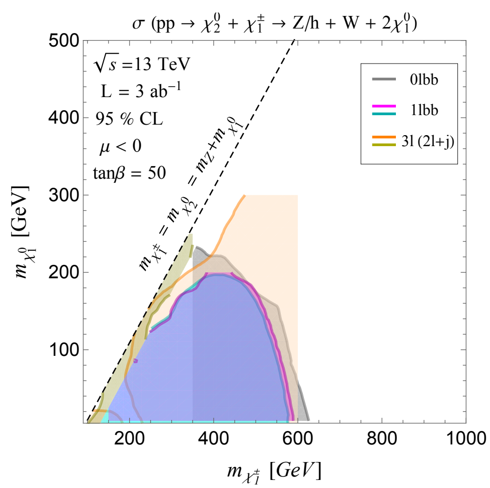
Reach increase due to increase of cross section. Result almost equivalent to the previous case for heavy squark masses.





Discovery potential is less impressive than in the Higgsino case, but yet one can clearly go to larger masses than the ones so far explored (if analysis preformed with full run 2 luminosity in all channels)

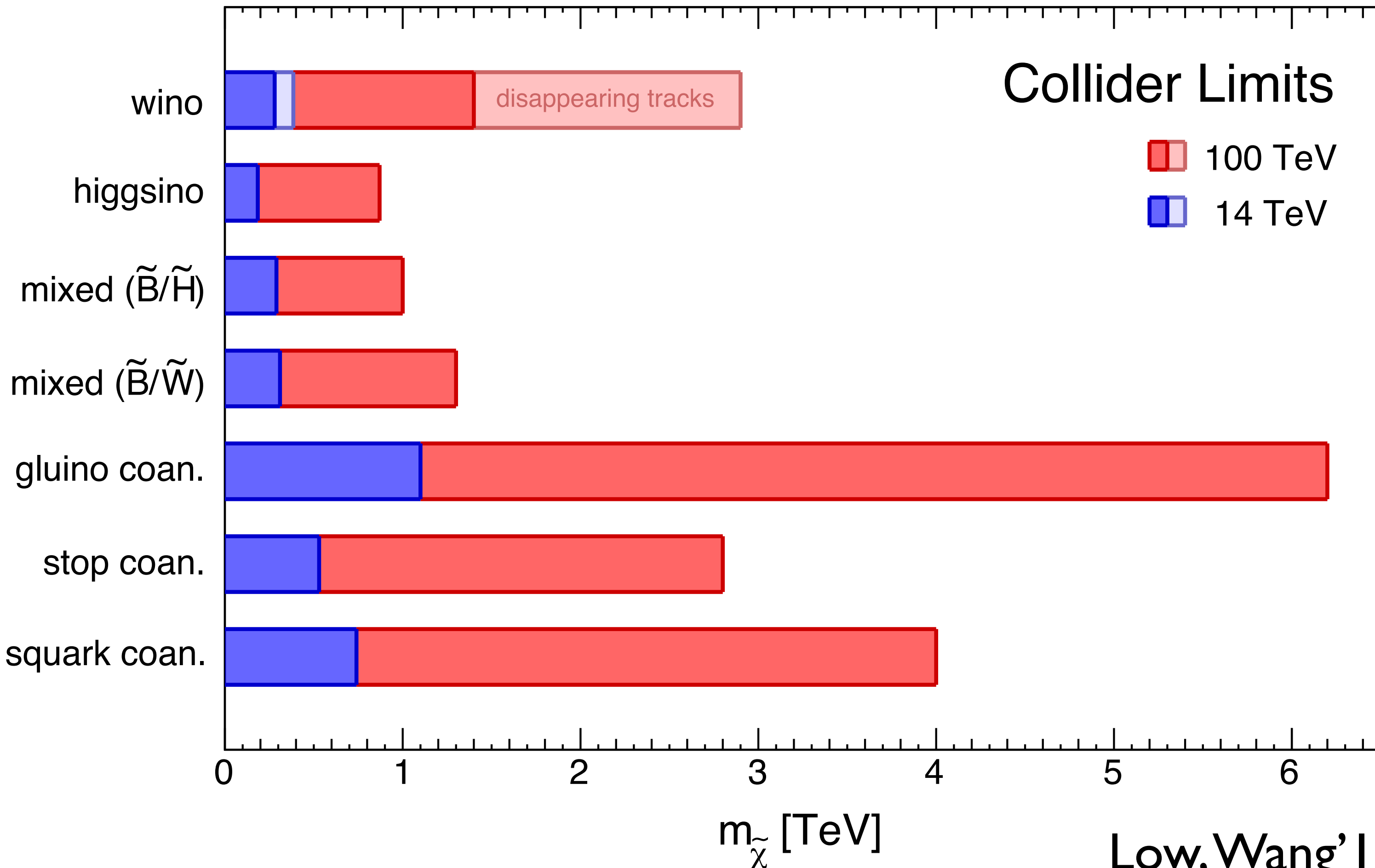




Exclusion Reach clearly larger than the current exclusion limits, reaching the 900 GeV region (or more) for a large range of the lightest neutralino masses.

Dark Matter in SUSY Theories is a neutral partner of either the Higgs or Gauge Bosons

Future Colliders : Direct Production Limits



Low, Wang'14

100 TeV collider will probe most promising regions

Conclusions

- Strongly interacting particles are restricted to be heavier than about 1 TeV
- We are just starting to constrain the region of stop masses consistent with the MSSM Higgs mass determination !
- No clear deviation of Higgs coupling from SM expectations :
  Alignment or Decoupling ?
- Electroweakino sector :
  Several channels, including direct and Higgs decay production.
- If Electroweakinos are at the weak scale, they could lead to a solution of the DM problem. Tensions with current direct detection data could be highly ameliorated for negative values of μ.
- There is still clear room for discovery at the LHC.

Backup

Carena, Haber, Low, Shah, C.W.'15

Naturalness and Alignment in the (N)MSSM

see also Kang, Li, Li,Liu, Shu'13,   Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

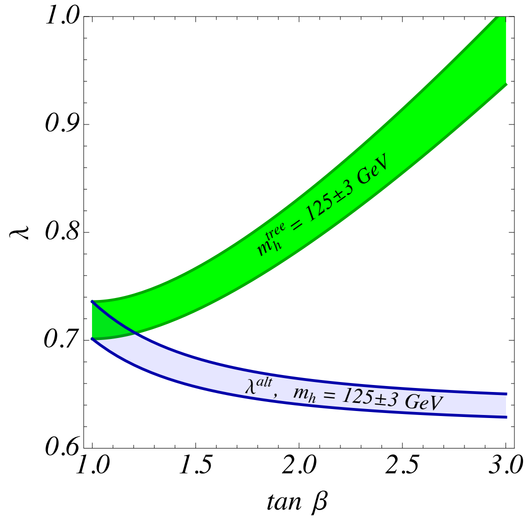
- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to $\Delta\lambda_4 = \lambda^2$)

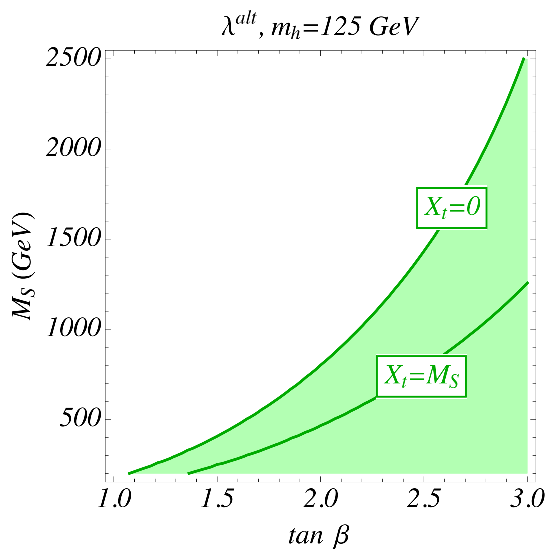
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}} \right)$$

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for all values of tan(beta), that are the values that lead to naturalness with perturbativity up to the GUT scale

$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

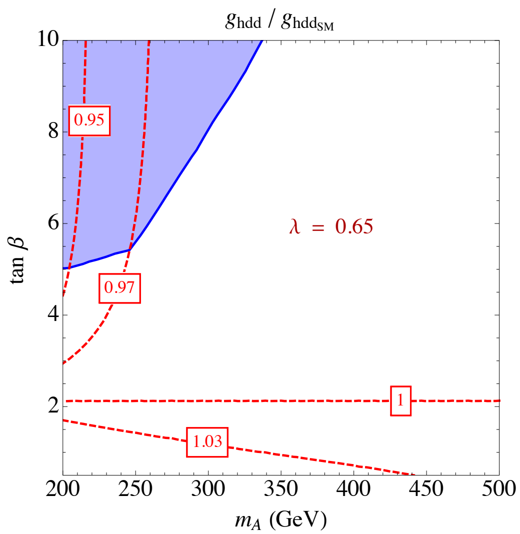
Alignment in the NMSSM (heavy or Aligned singlets)

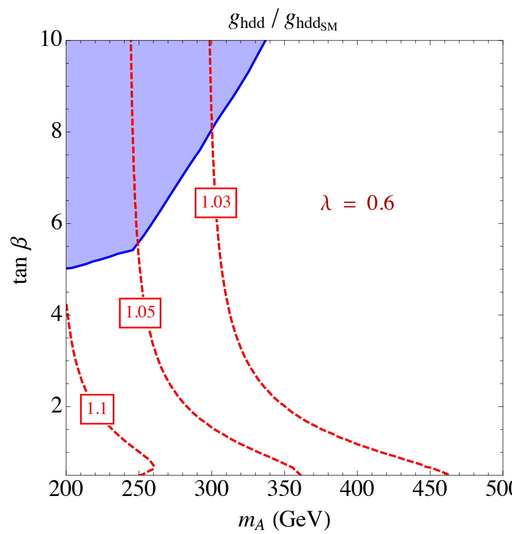




Carena, Low, Shah, C.W.'13
Carena,Haber,Low,Shah,C.W.'15

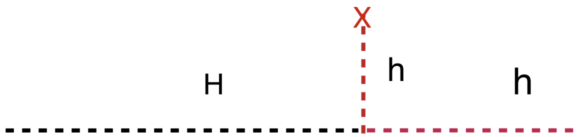
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided $\lambda \sim 0.65$





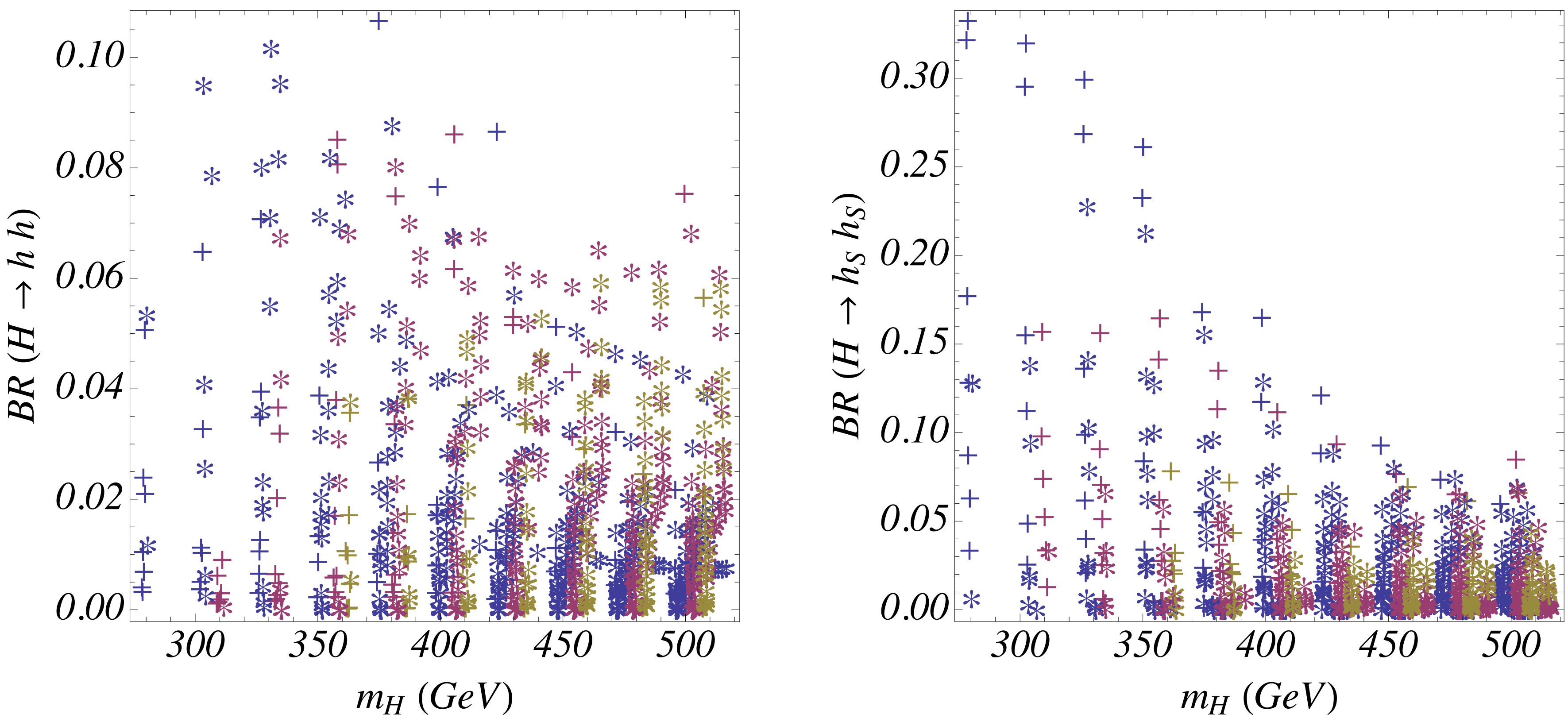
Decays into pairs of SM-like Higgs bosons suppressed by alignment

Carena, Haber, Low, Shah, C.W.'15



Crosses : H1 singlet like
Asterix : H2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$



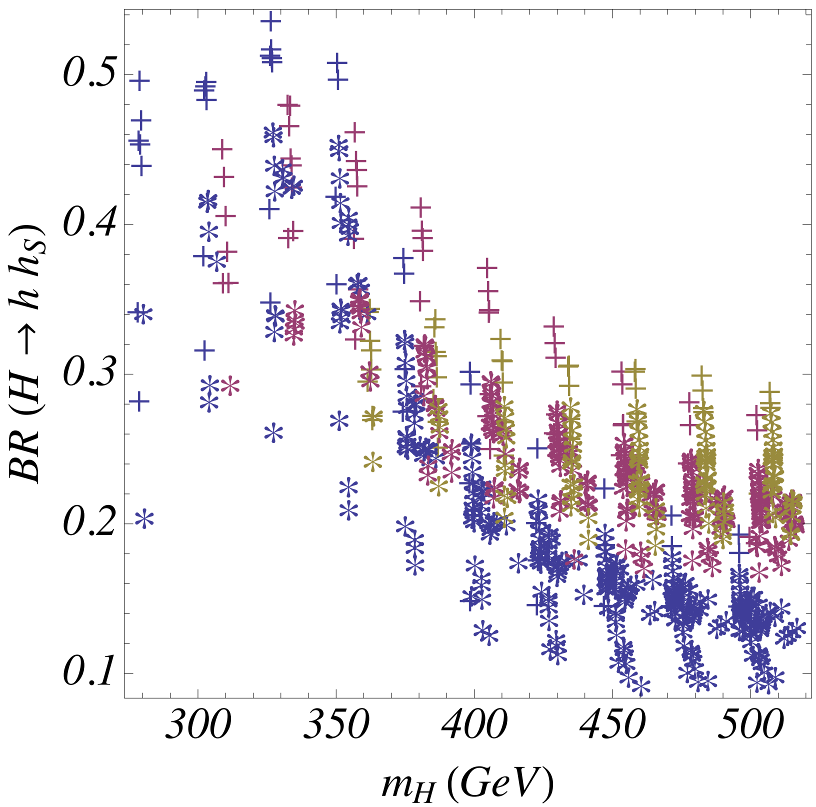
Significant decays of heavier Higgs Bosons into lighter ones and Z's

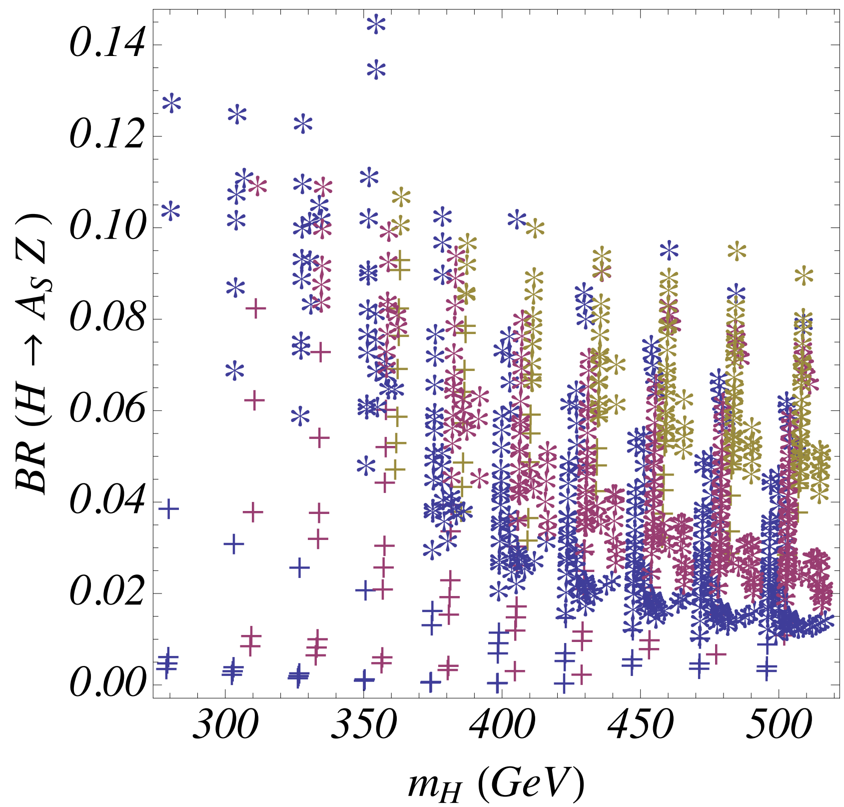
Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$

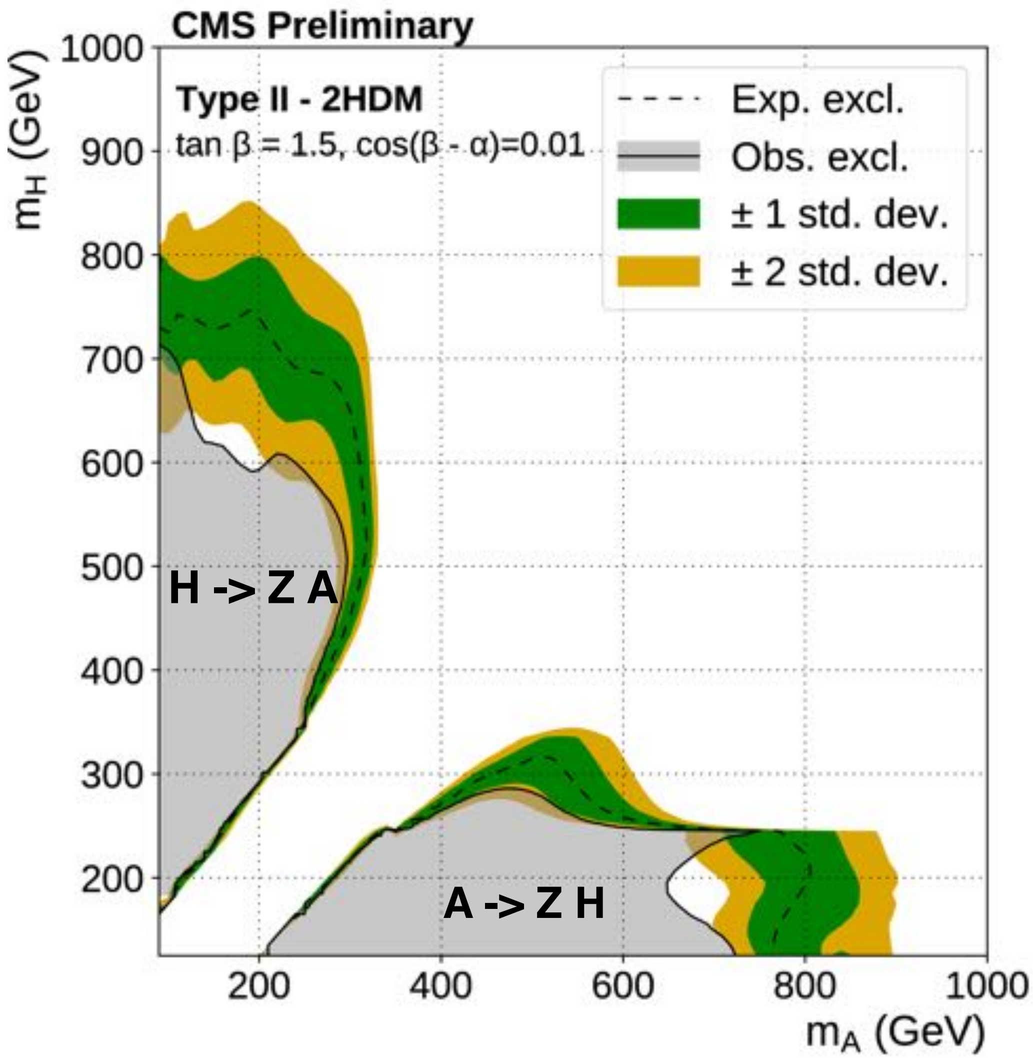
Carena, Haber, Low, Shah, C.W.'15





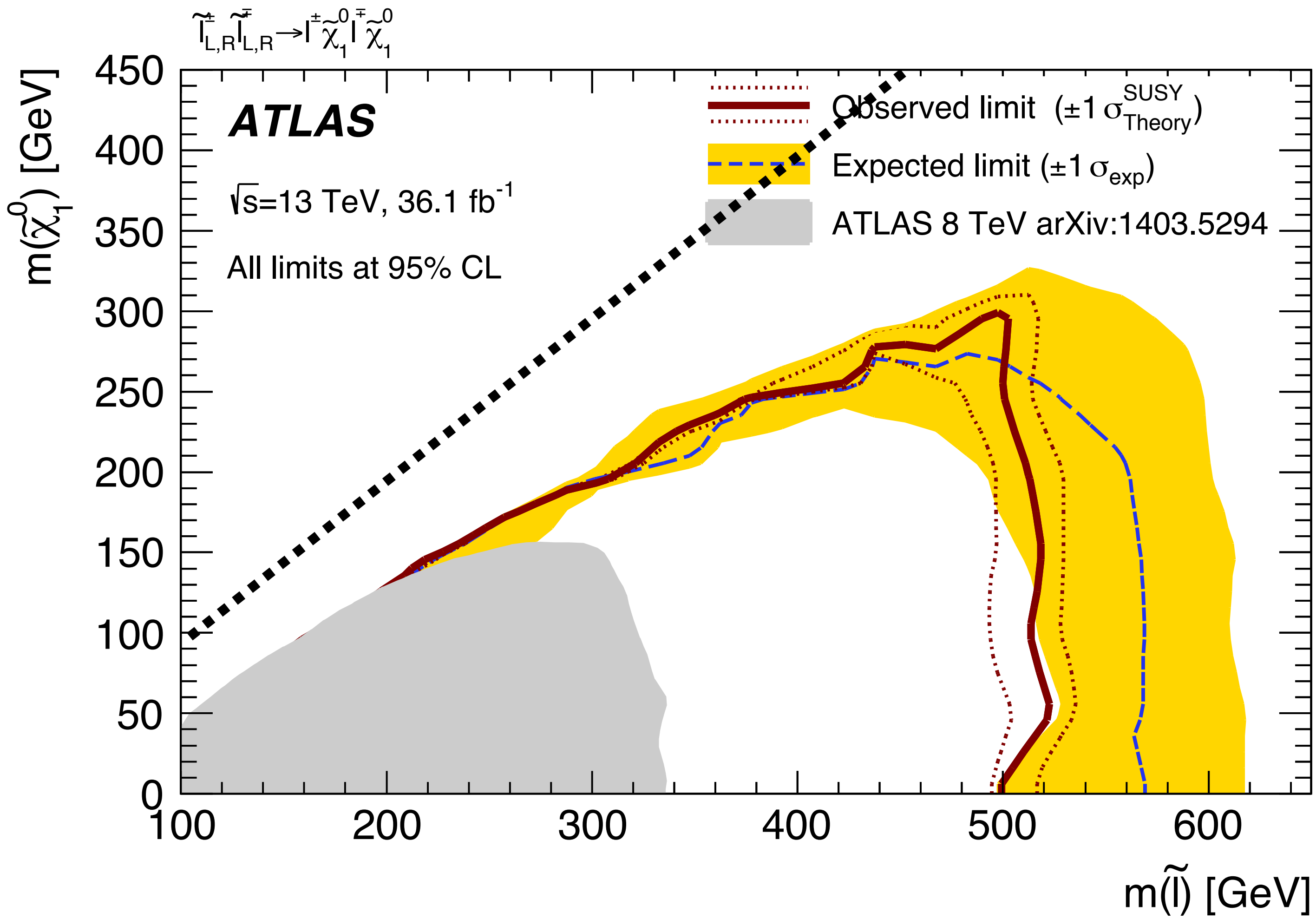
Search for (psudo-)scalars decaying into lighter ones

CMS-PAS-HIG-18-012



It is relevant to perform similar analyses replacing
the Z by a SM Higgs (and changing the CP property of the Higgs)

Slepton production
All four light generation leptons mass degenerate



Limits may be different in the case of cascade decays of the leptons into lighter electroweakino states.

Stop bound may be somewhat relaxed in complex cascade decays