Supersymmetry and LHC Physics

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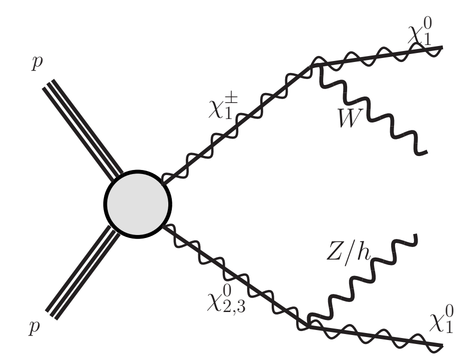
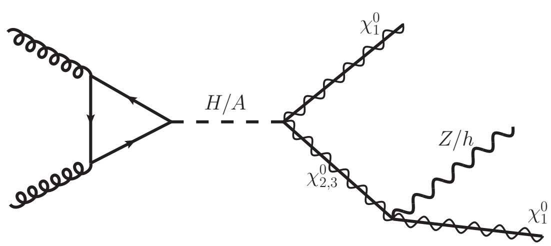
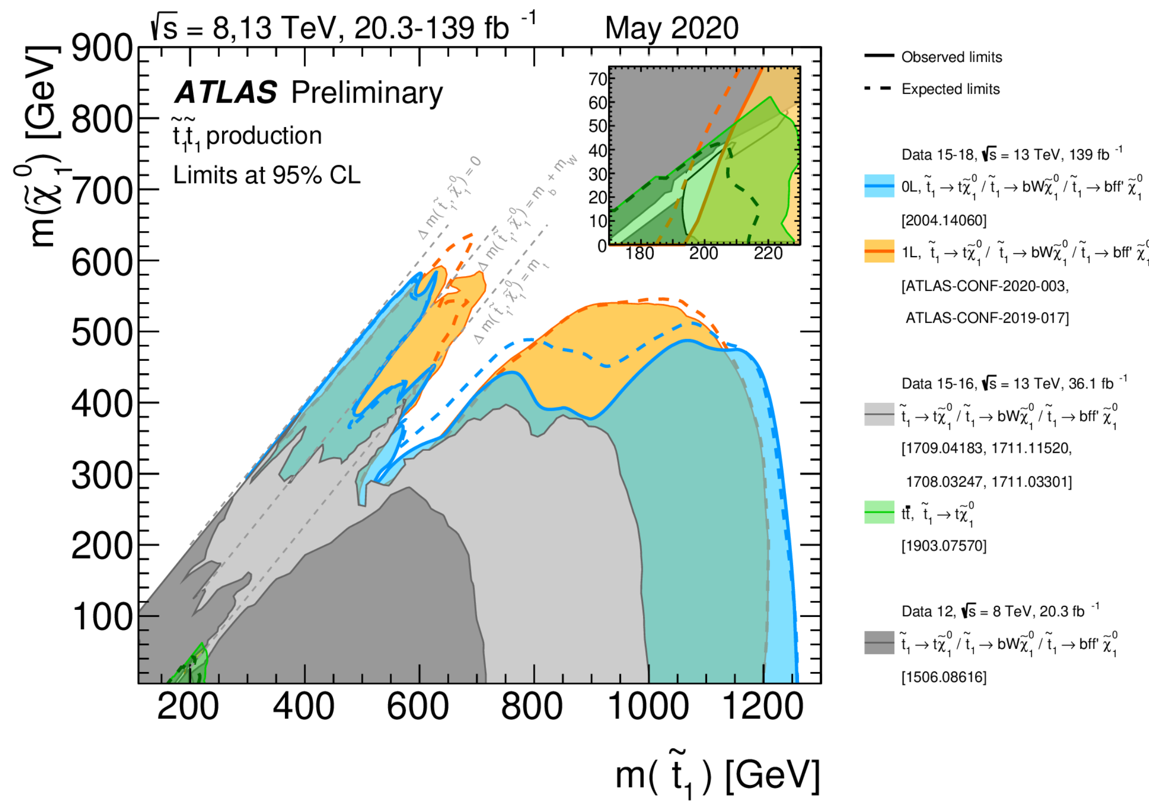


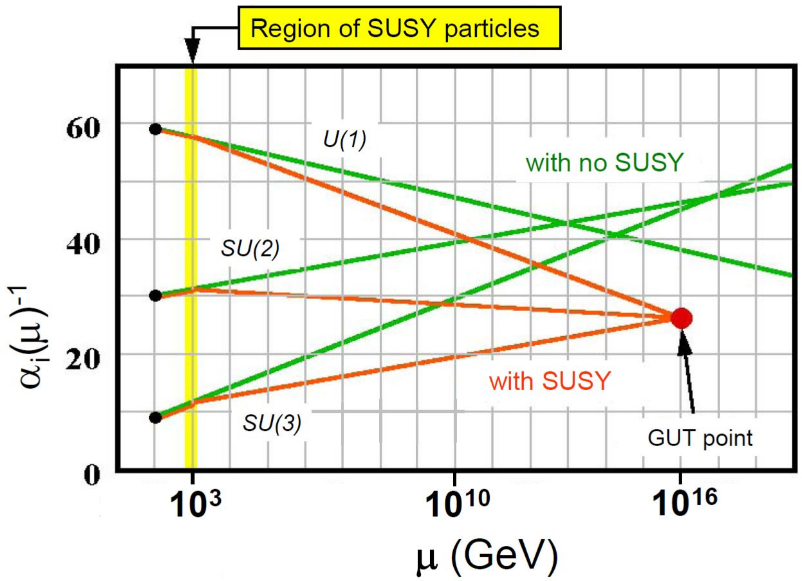




Snowmass-EF08 Working Group, 06.25.20

Consequences of SUSY

Unification



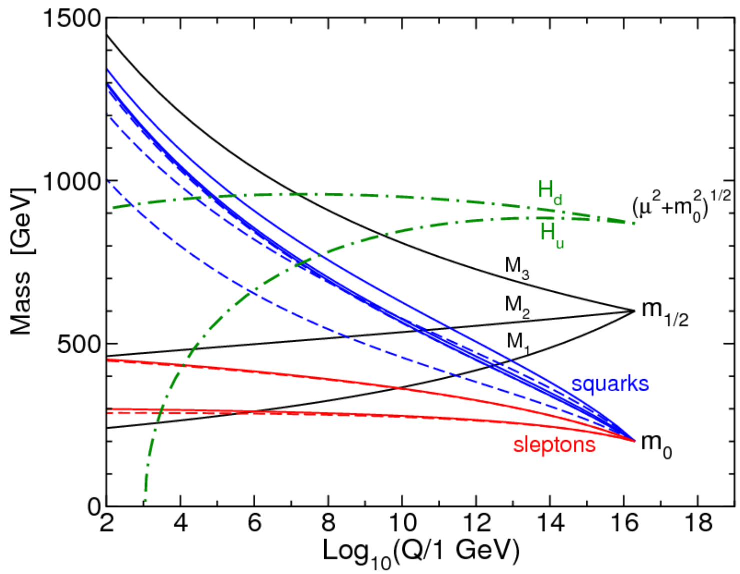
SUSY Algebra

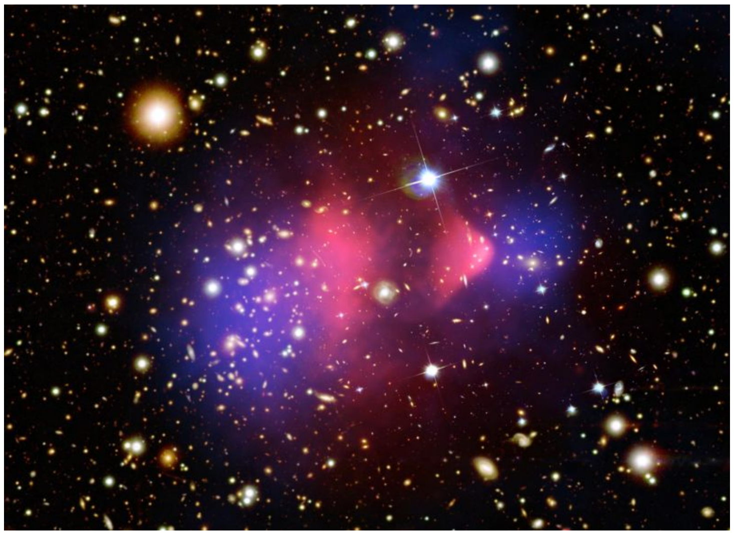
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

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

Quantum Gravity ?

Electroweak Symmetry Breaking





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

Supersymmetric Spectrum

Theoretical Prejudice

- Due to RG running of mass parameters, heavier gluinos tend to push up the squark masses

- The third generation SUSY breaking masses receive large negative corrections in the RG running (related to the ones driving the Higgs mass parameter negative) and tend to be the lightest.

- Due to its large coupling to the Higgs sector, stops are particularly relevant and have important phenomenological effects at low energies.

Barbieri, Giudice '88, Carena, Olechowski, Pokorski, C.W.'94

RG running from universal soft supersymmetry breaking masses at the Grand Unification Scale

$$m_{H_1}^2 = m_0^2 + 0.5 M_{1/2}^2 \quad , \quad m_{H_2}^2 = m_{H_1}^2 + \Delta m^2 \ ,$$

Left-handed stop

$$m_Q^2 = 7.2 M_{1/2}^2 + m_0^2 + \frac{\Delta m^2}{3} \quad , \quad m_U^2 = 6.7 M_{1/2}^2 + m_0^2 + 2\frac{\Delta m^2}{3},$$

Right-handed stop

$$\Delta m^2 = -\frac{3m_0^2}{2}\frac{Y_t}{Y_f} + 2.3 A_0 M_{1/2}\frac{Y_t}{Y_f}\left(1 - \frac{Y_t}{Y_f}\right) - \frac{A_0^2}{2}\frac{Y_t}{Y_f}\left(1 - \frac{Y_t}{Y_f}\right) + M_{1/2}^2\left[-7\frac{Y_t}{Y_f} + 3\left(\frac{Y_t}{Y_f}\right)^2\right] .$$

$$\tan^2\beta \simeq \frac{\mu^2 + m_{H_1}^2 + M_Z^2/2}{\mu^2 + m_{H_2}^2 + m_h^2/2}$$

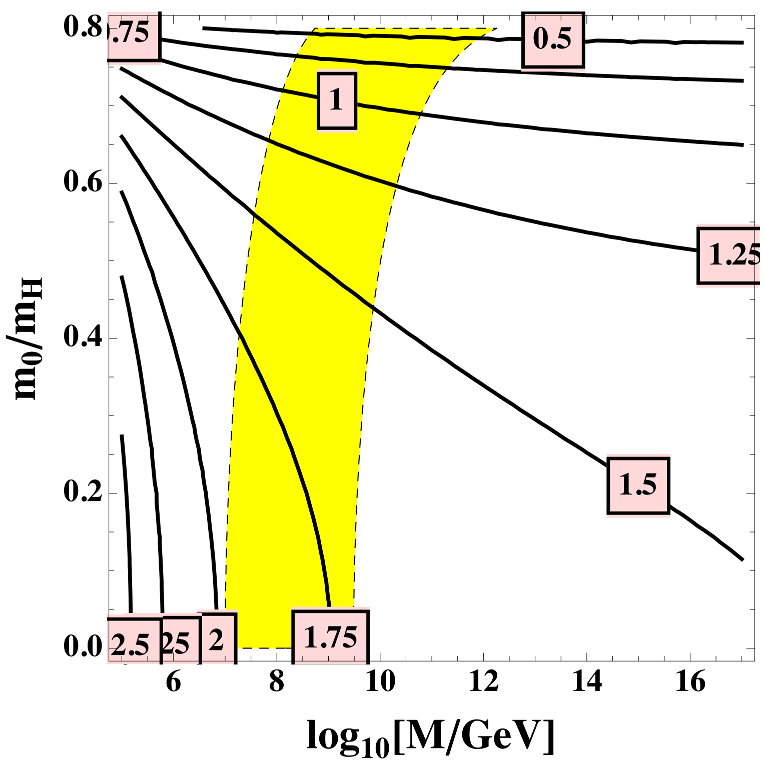
Y_t/Y_f is the ratio of the low energy Yukawa coupling to the IR fixed point value and ranges from values close to 1 at low values of $\tan\beta$ to values of order $2/3$ at large values of $\tan\beta$, for which the focus point solution develops.

Feng, Matchev, Moroi'99

But the dependence on the gluino mass is very strong and due to the current bounds, there must be correlations between the different parameters to ensure the proper Higgs scale, Certain correlations may assure the smallness of the Higgs soft breaking parameter at low energies. Electroweak symmetry breaking becomes more natural if the parameters are close to the ones that satisfy those correlations and if the supersymmetry breaking scale is reduced.

$$m_{H_u}^2(Q_{ew}) \simeq \quad 0 = m_{H_U}^2 + \eta_{Q_L}[\mathcal{Q}_0, \mathcal{M}](m_{Q_L}^2 + m_{U_R}^2 + m_{H_U}^2) + \sum_a \eta_a[\mathcal{Q}_0, \mathcal{M}]M_a^2$$
$$+ \sum_{a \neq b} \eta_{ab}[\mathcal{Q}_0, \mathcal{M}]M_a M_b + \sum_a \eta_{aA}[\mathcal{Q}_0, \mathcal{M}]M_a A_t + \eta_A[\mathcal{Q}_0, \mathcal{M}]A_t^2$$

Delgado, Quiros, C.W.'14



Non-Universal soft parameters

Berezsinski et al '95,
Nath and Arnowitt '95,
Carena et al '97
Anderson et al '99,
Profumo '03,
Baer et al'05, Ellis et al'05,
Martin'09

Values of $M_{\tilde{g}}/m_{\tilde{t}_L}$ needed to get the proper Higgs scale and a relatively light stop for different values of the ratio of the squark and Higgs masses at the SUSY breaking scale M.

Dine, Nelson, Nir, Shirman, '93—'95

Low Energy Supersymmetry Breaking ?

In this case, the gravitino tends to become the lightest SUSY particle

$$m_{\rm SUSY} \simeq \eta \frac{F}{M}$$

$$m_{\tilde{G}} = \frac{F}{\sqrt{3} M_{Pl}}$$

M : Messenger scale
η : Depends on Mediation mechanism

The lightest SM super partner tends to decay into a gravitino and a SM particle. For instance for neutralinos,

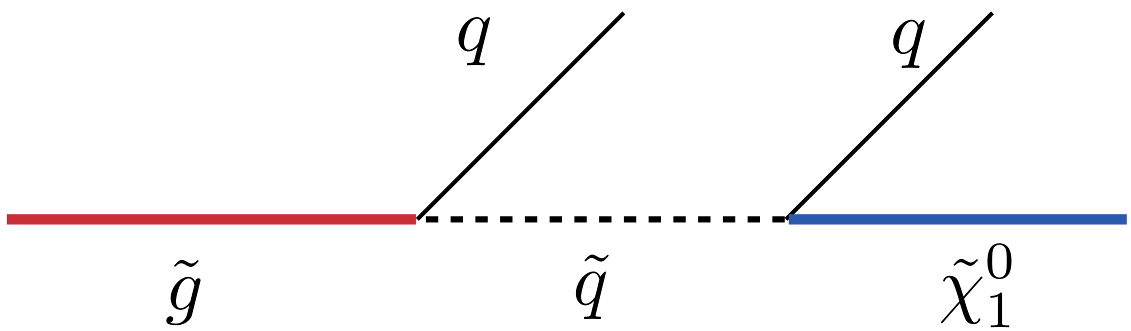
S. Ambrosanio et al'96
S. Martin ' 97

$$\Gamma(\widetilde{N}_1 \to \gamma \widetilde{G}) \; = \; 2 \times 10^{-3} \, \kappa_{1\gamma} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}} \right)^5 \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^{-4} \text{ eV}.$$

$$d = 9.9 \times 10^{-3} \, \frac{1}{\kappa_{1\gamma}} \, (E^2/m^2_{\widetilde{N}_1} - 1)^{1/2} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}} \right)^{-5} \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^4 \text{ cm},$$

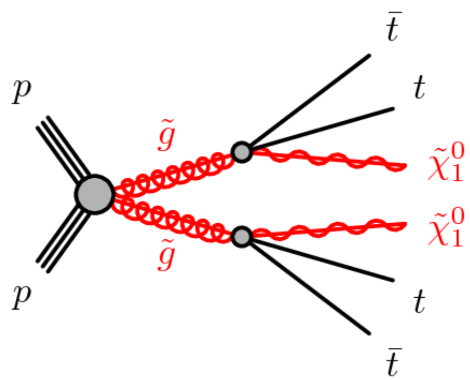
In this talk, I will not concentrate on this exciting possibility

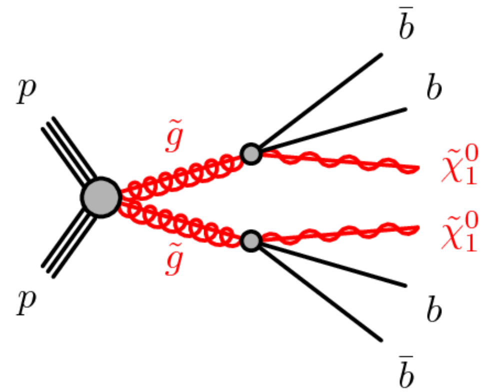
Gluino Decays (Simplified Scenario)

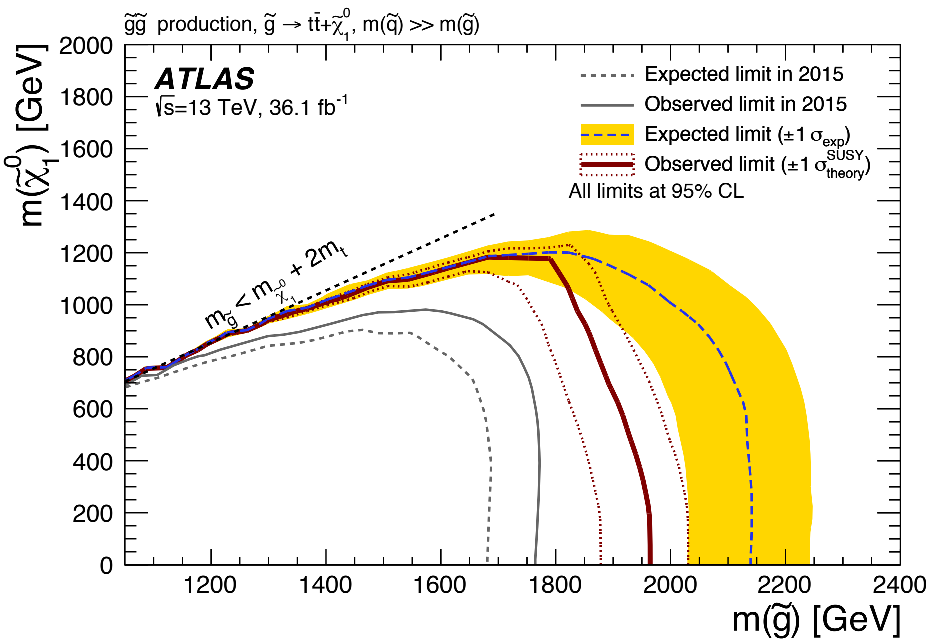


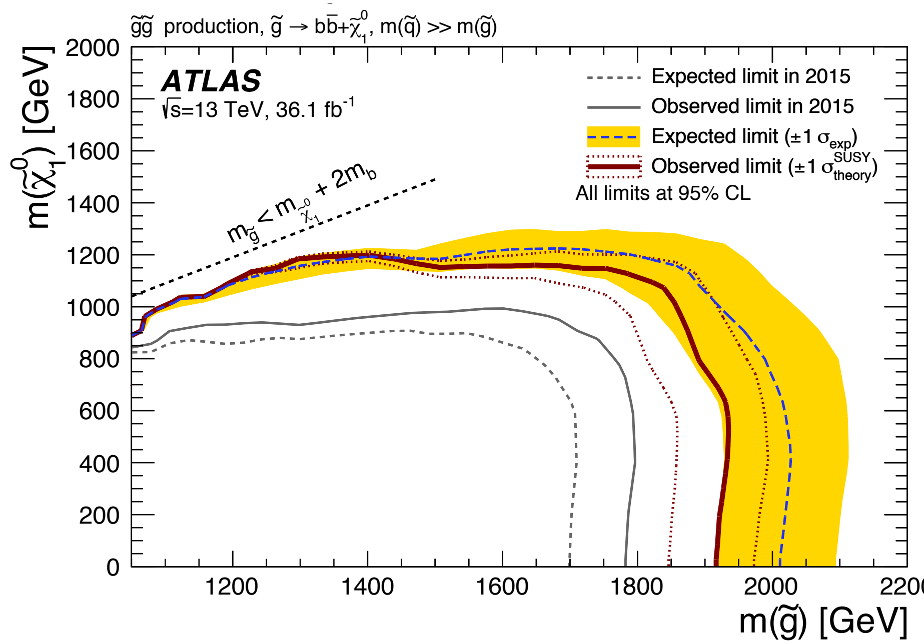
- Rate tends to be prompt.
- Assuming R-Parity, LSP is stable at collider scales, implying large missing energy.
- Although the gluino has no other way of decaying, the decay of squarks can be much more complicated
- Lightest squark dominates the decay.

Gluino Searches :
Gluino couples to SM via quark-squark vertices
Squarks can decay in a variety of ways







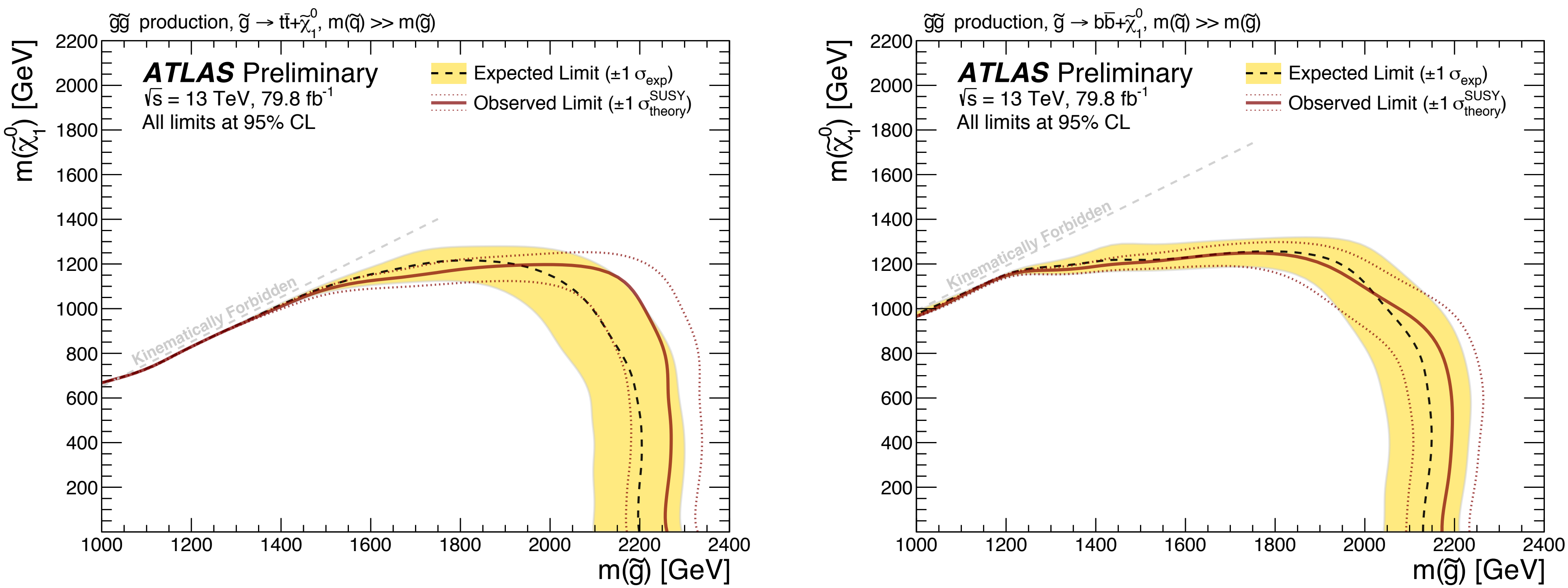


Excess in channel with four tops ?
Events with b's, jets, leptons and Missing ET

Events with b's and Missing Energy

CMS Analysis not sensitive to the Excess Region

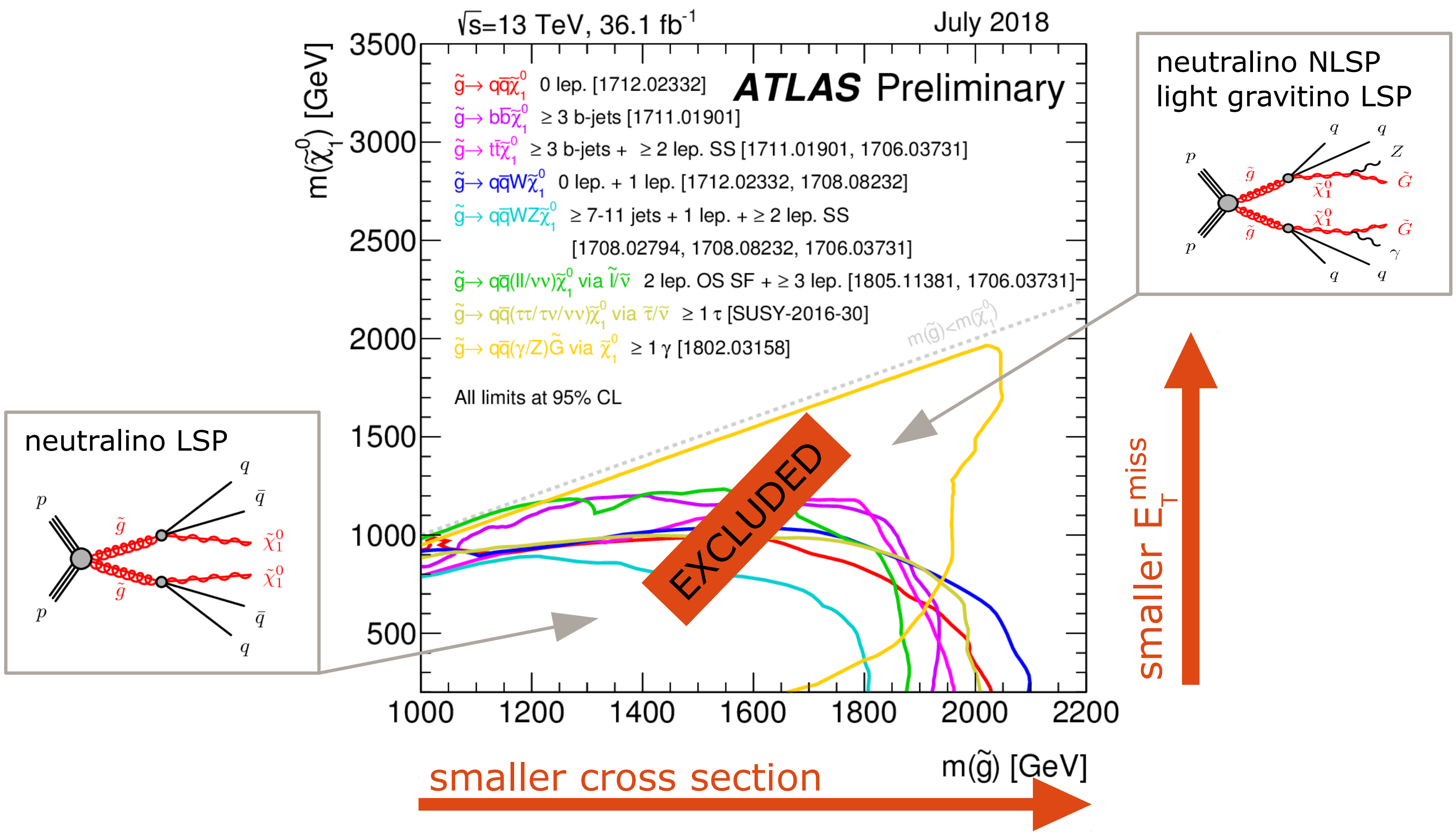
More recent ATLAS Results



(a) (b)

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

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_Q + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_U + m^2_t + D_R \end{pmatrix}$$

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

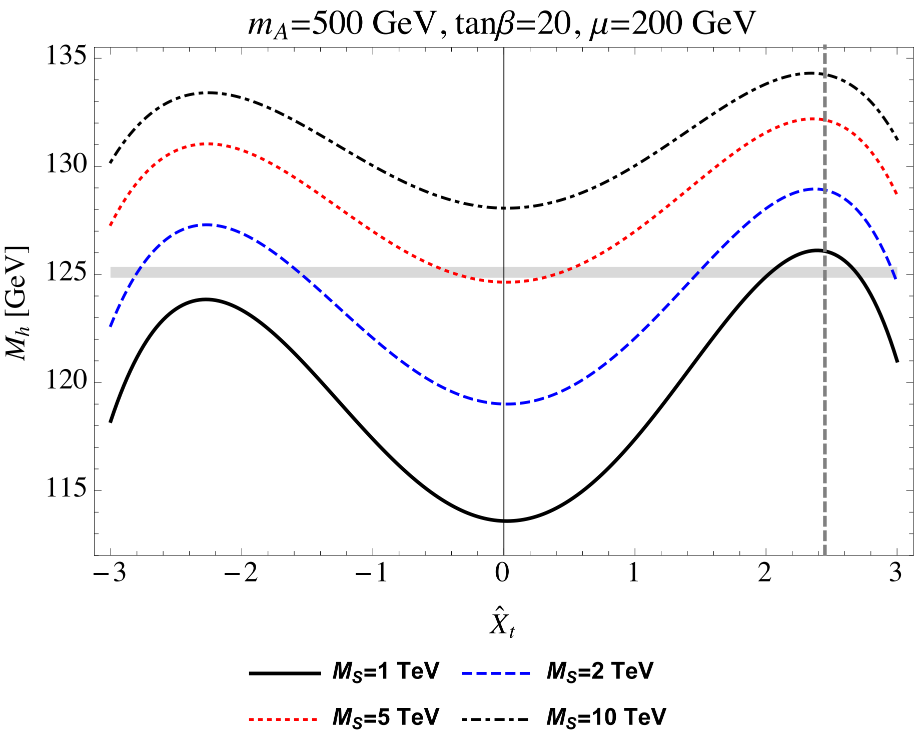
Carena, Espinosa, Quiros, C.W.'95,96

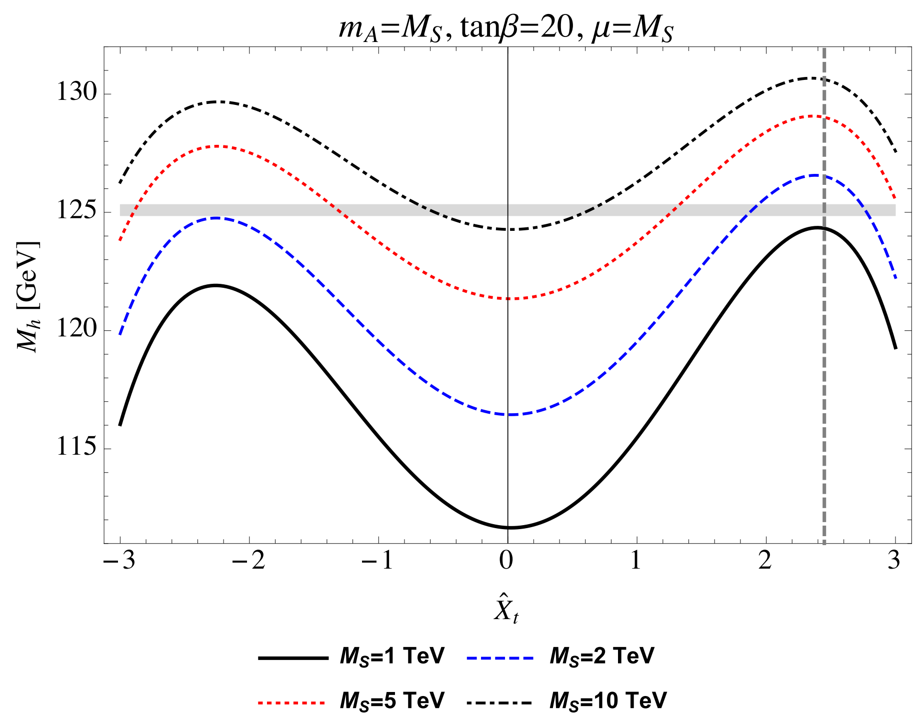
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

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

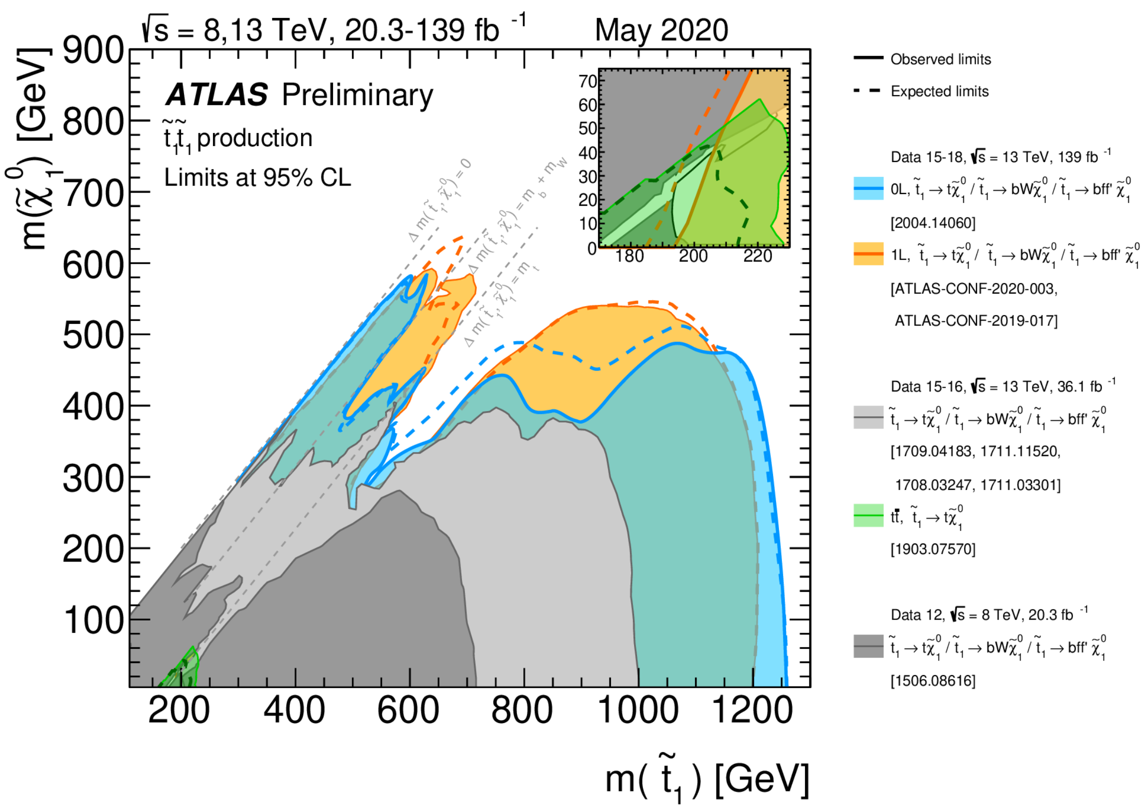


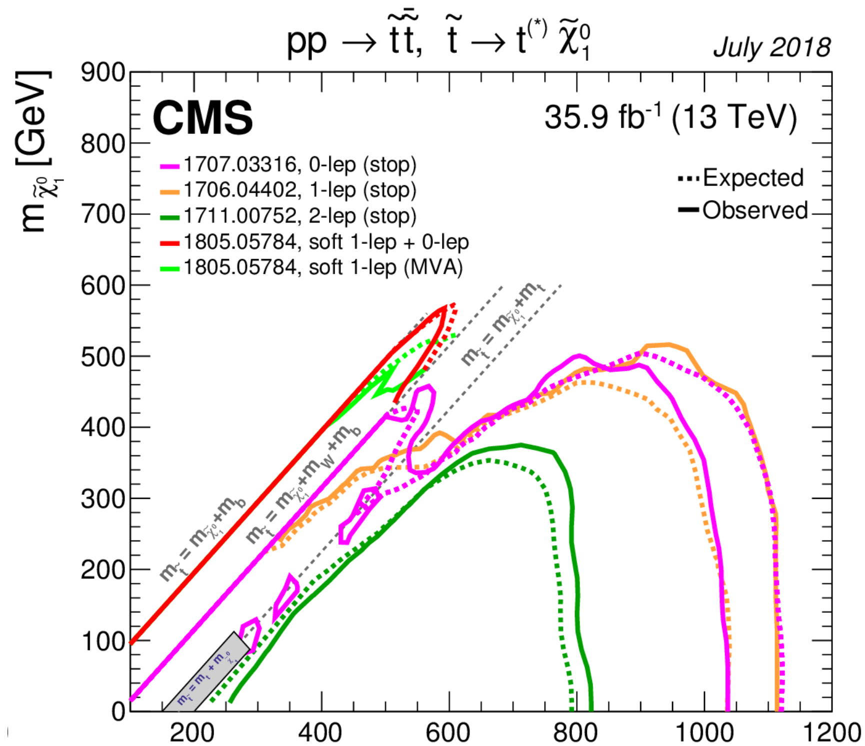


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

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

Stop Searches

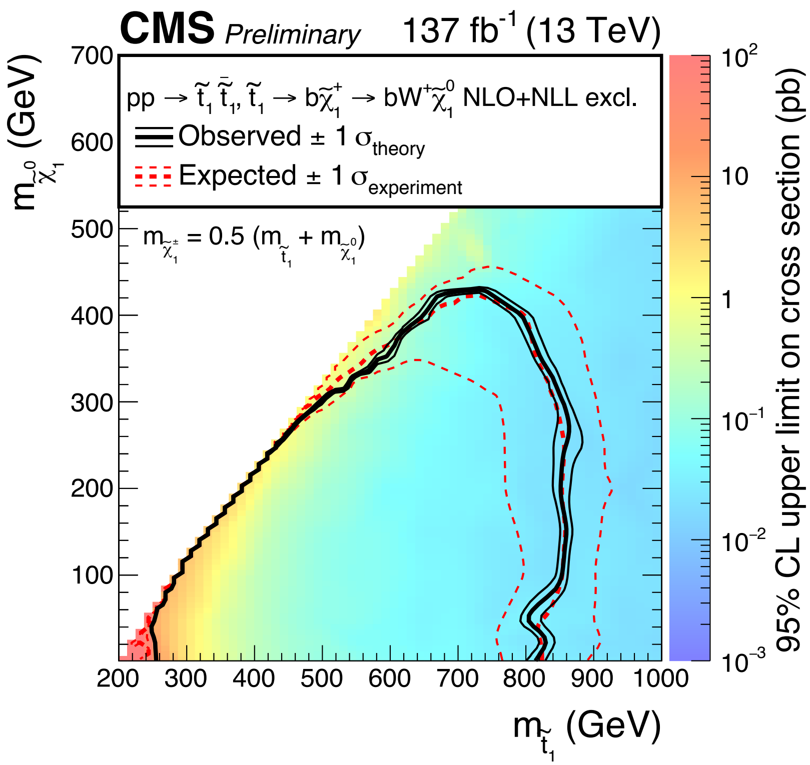


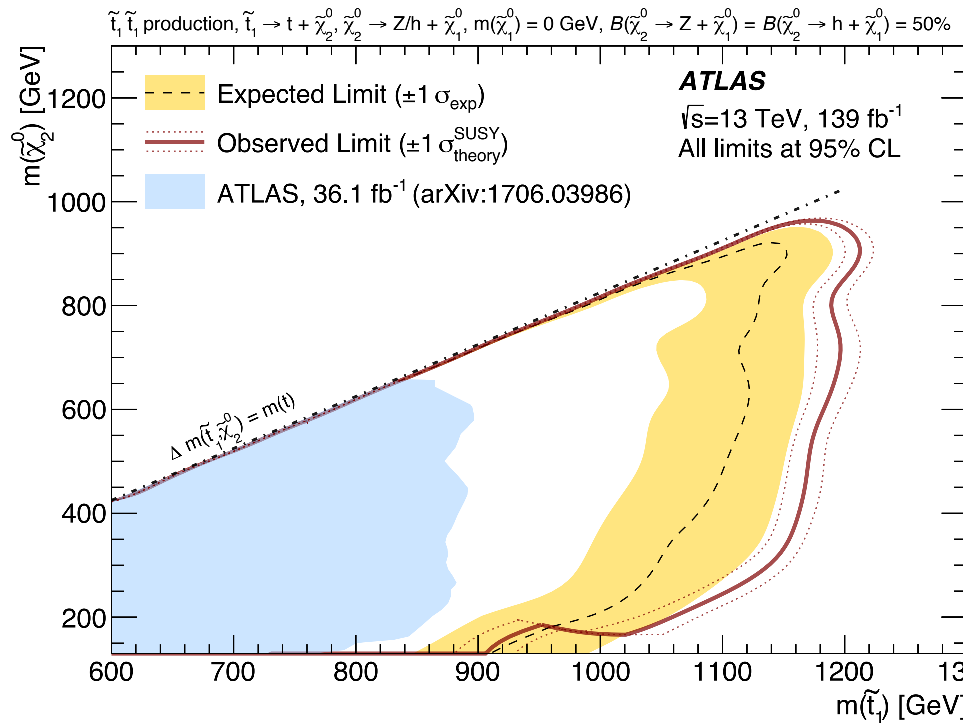


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints 600 GeV—1.2 TeV for stops, if it decays directly to top quarks and neutralinos.

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

Cascade Decays may lead to weaker bounds



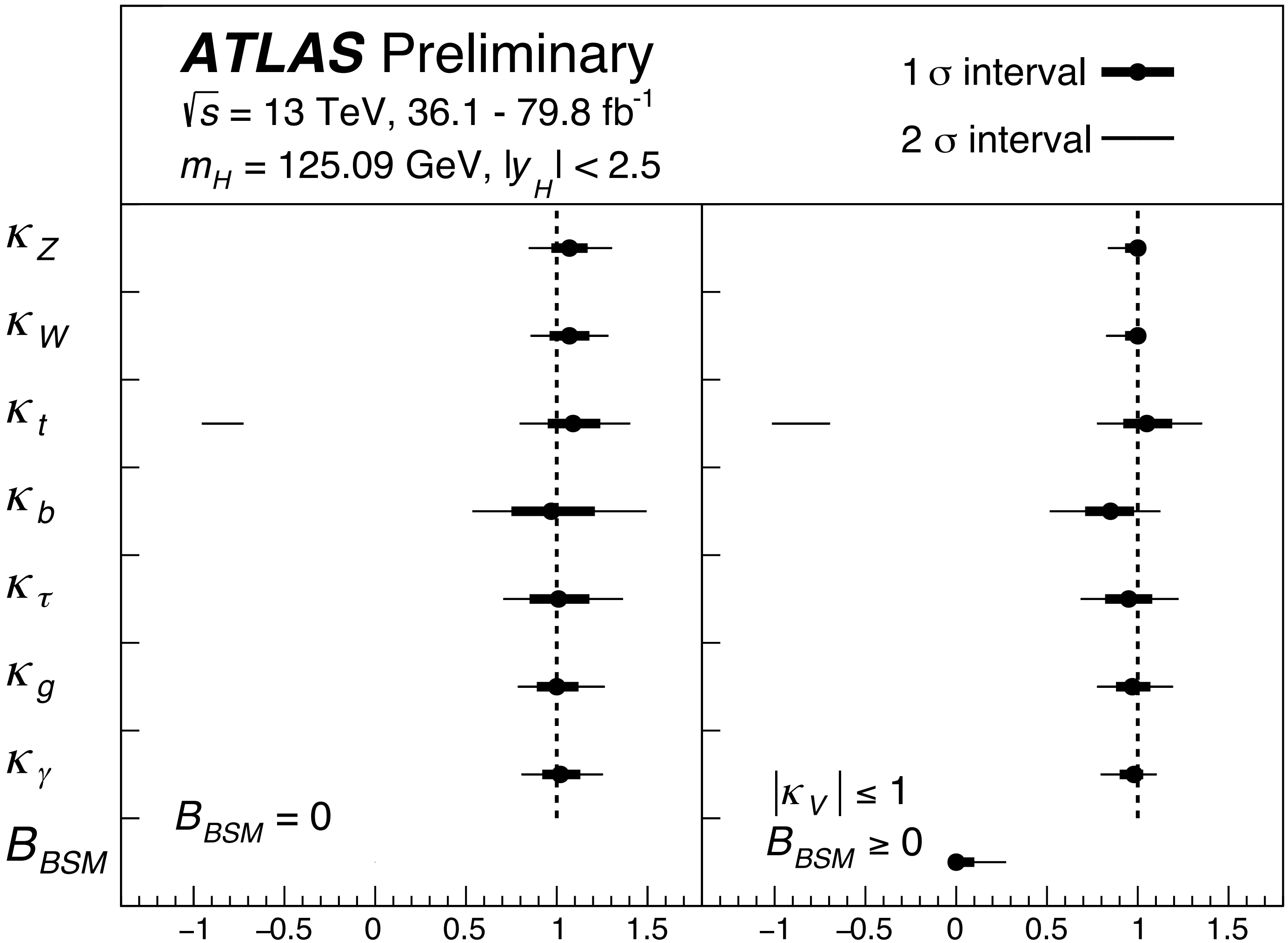


For heavier stop masses, it is natural to expect the presence of other electroweakino states the stop may decay to.

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.

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

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

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

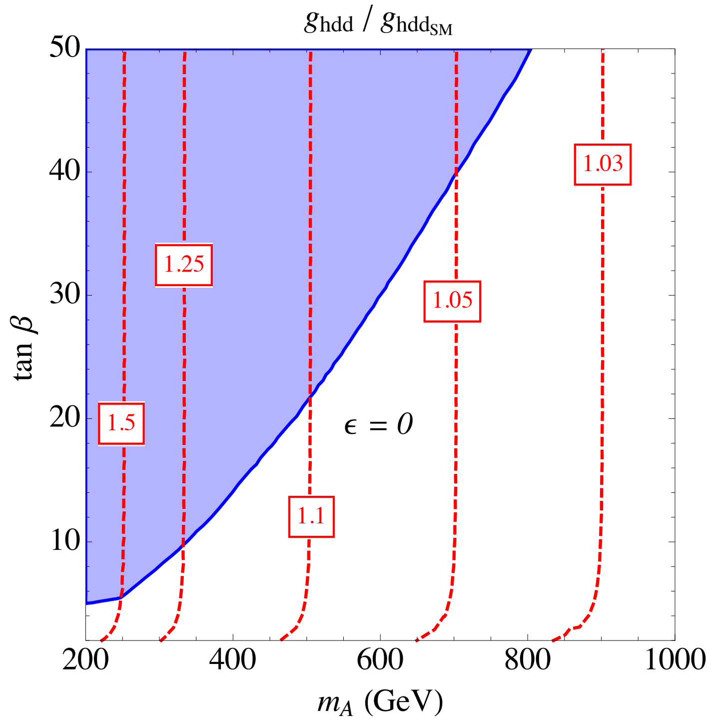
- Alignment condition : $\cos(\beta - \alpha) = 0$ J. Gunion, H. Haber '02
- In the MSSM, it can only be achieved for large values of μ

Down Couplings in the MSSM for low values of μ

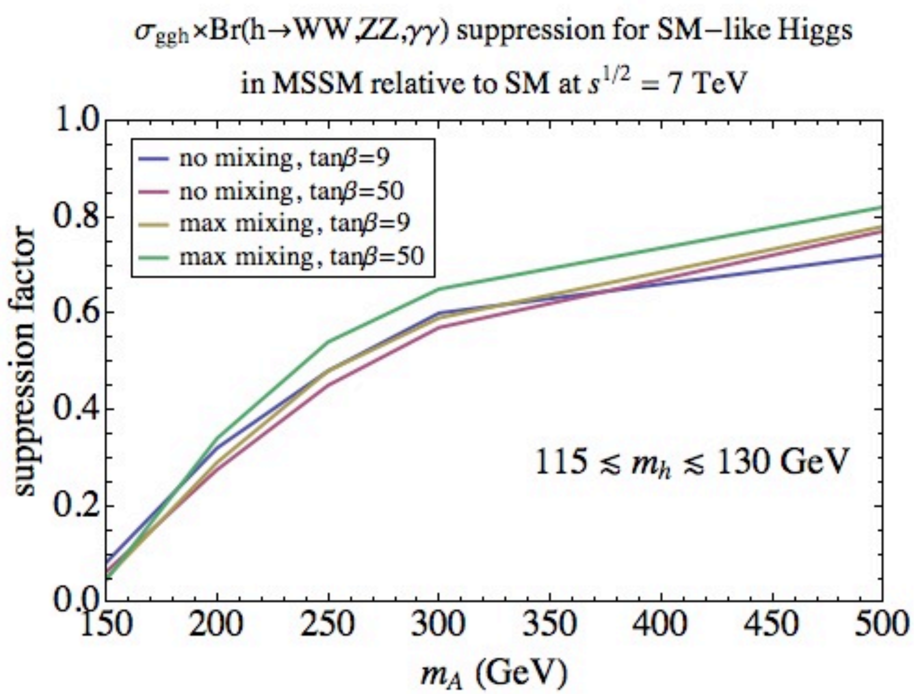
- Higgs Decay into bottom quarks is the dominant one
- A modification of the bottom quark coupling affects all other decays

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

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



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



Enhancement of bottom quark and tau couplings independent of $\tan\beta$

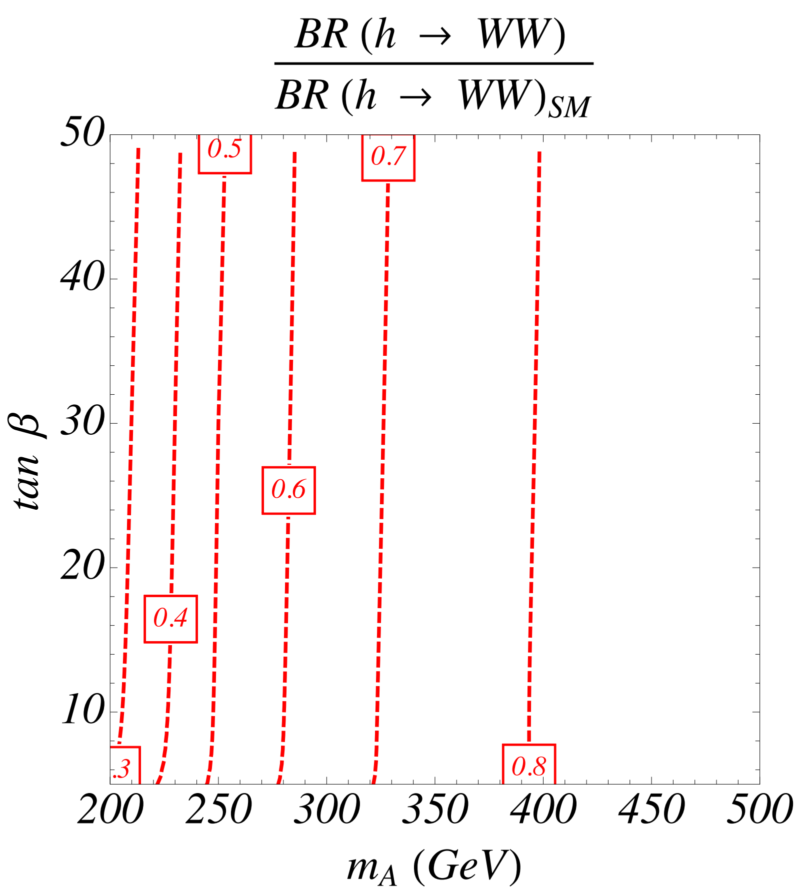
Carena, Haber, Low, Shah, C.W.'14

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

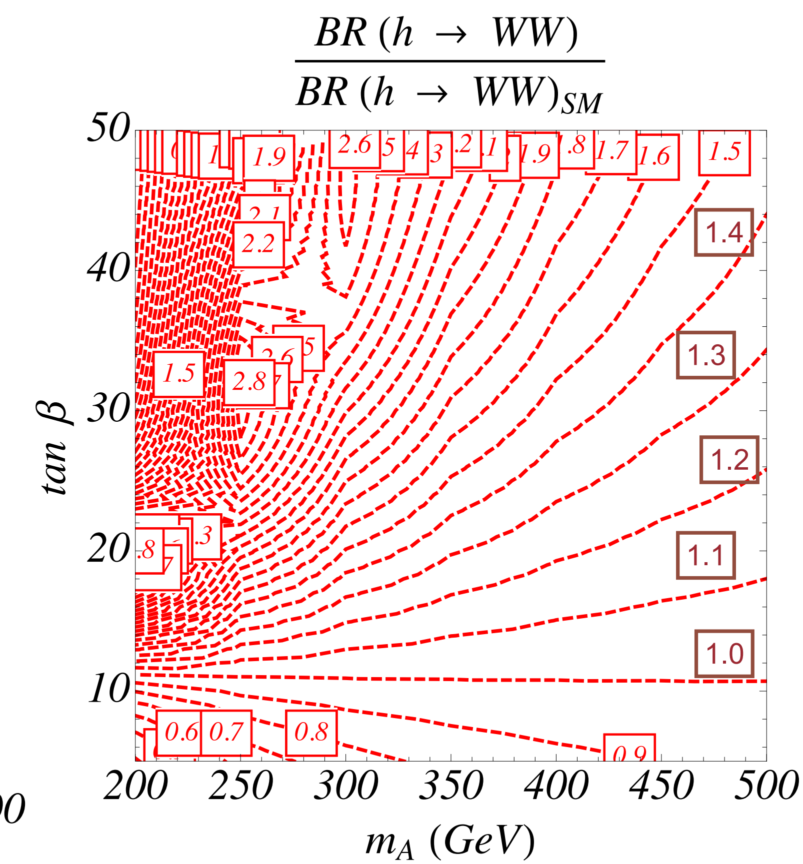
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



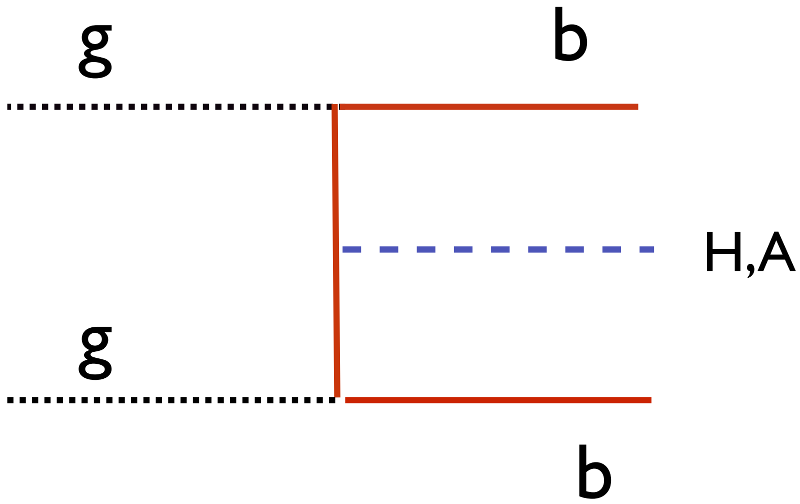
$\mu/M_{\rm SUSY} = 2, \qquad A_t/M_{\rm SUSY} \simeq 3$



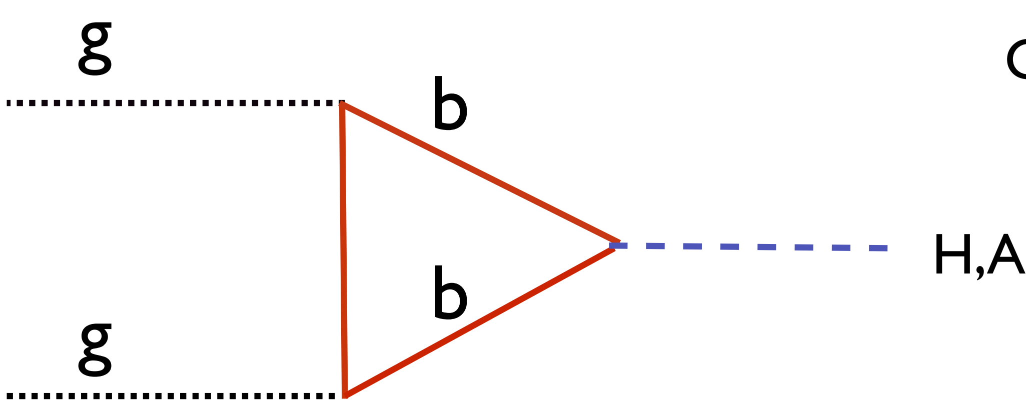
CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

Non-Standard Higgs Production

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



Associated Production



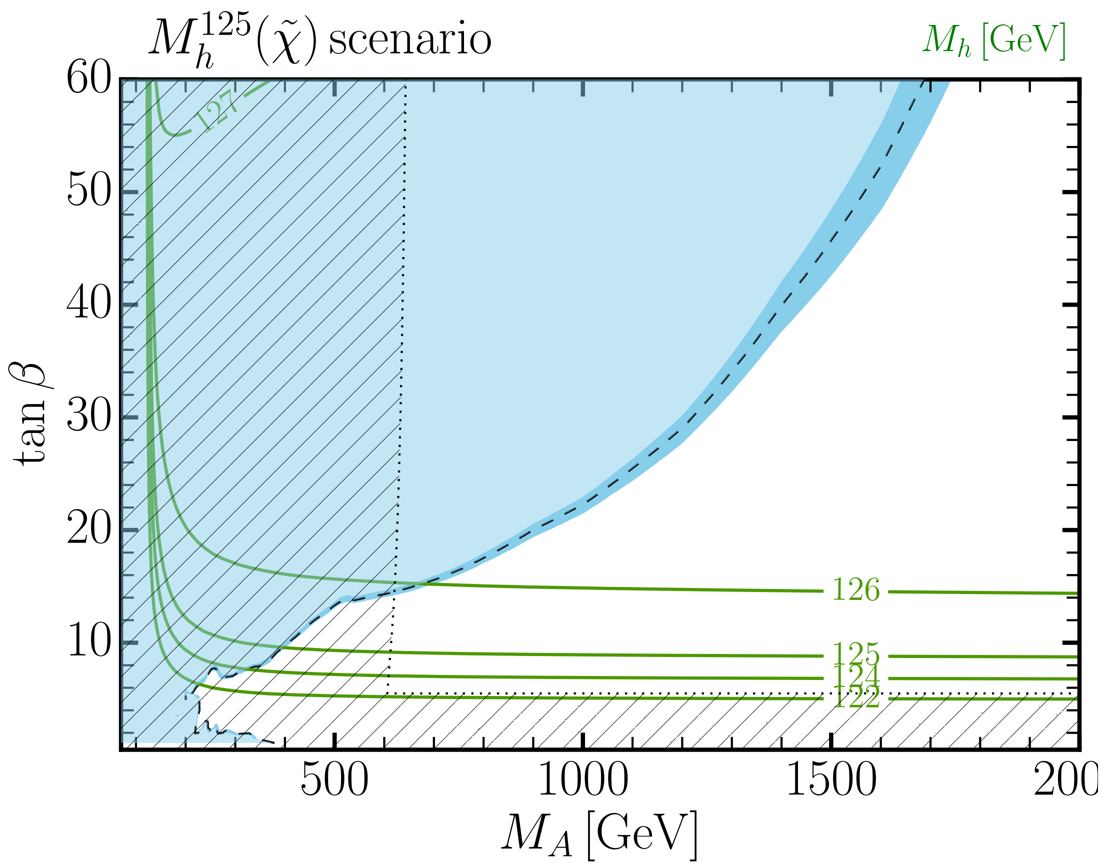
Gluon Fusion

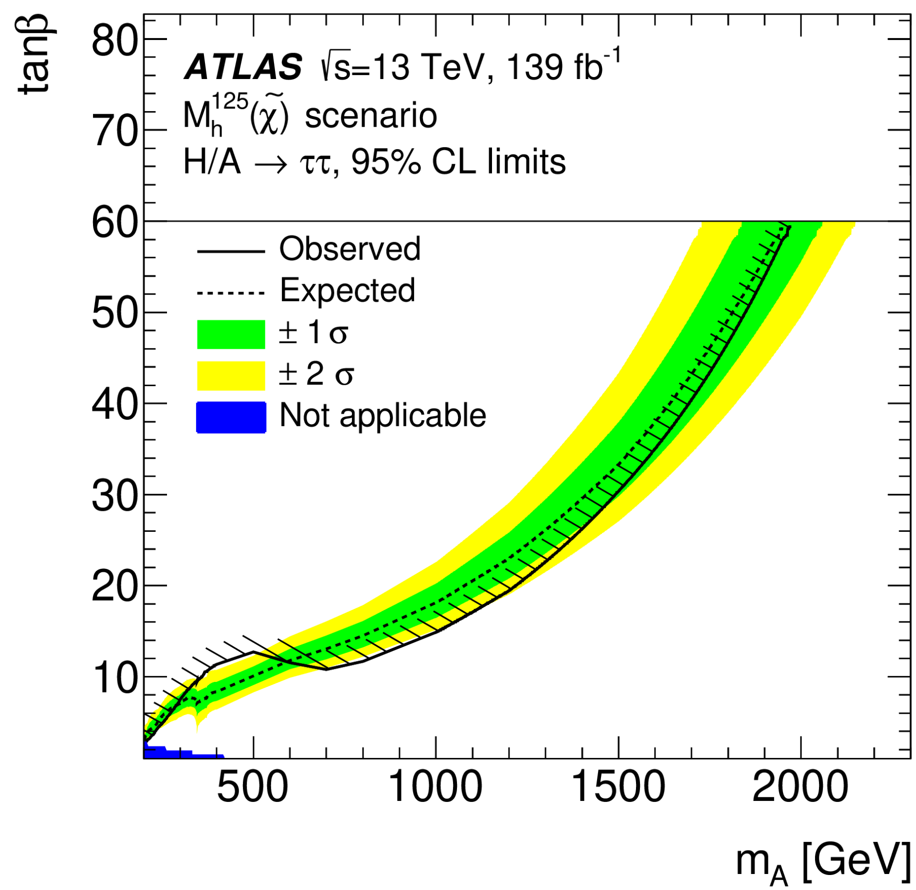
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

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.





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,

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

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

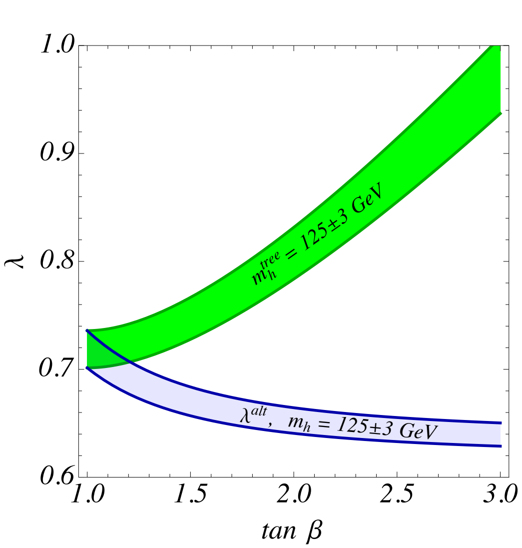
- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to $\Delta\lambda_4 = \lambda^2$)

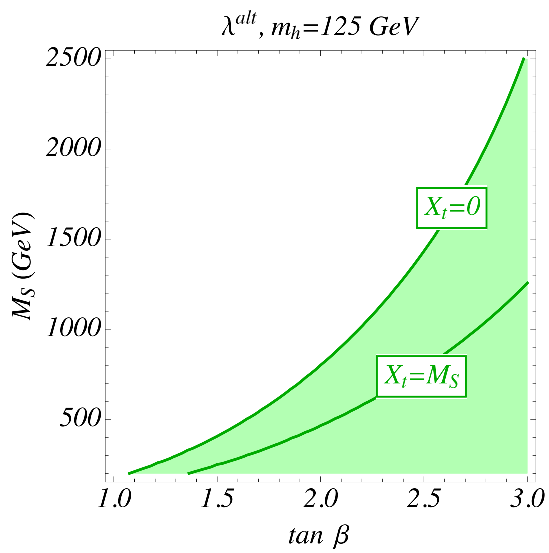
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}} \right)$$

- 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

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

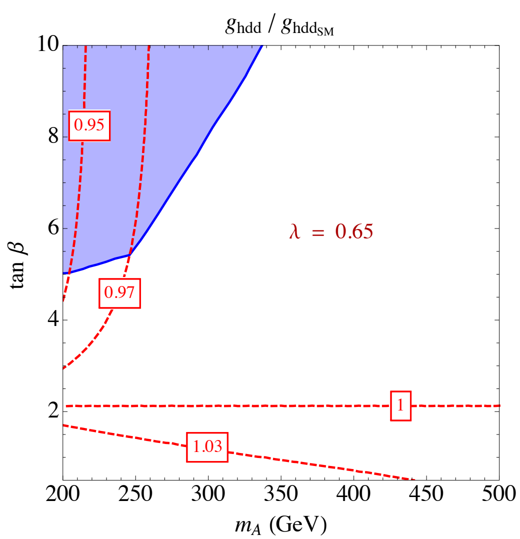
Alignment in the NMSSM (heavy or Aligned singlets)

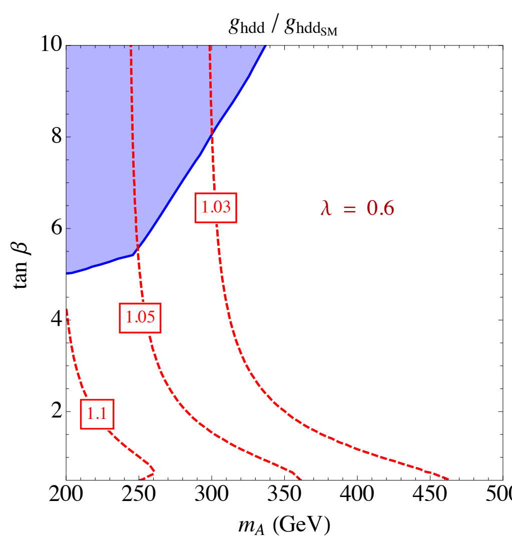




Carena, Low, Shah, C.W.'13
Carena,Haber,Low,Shah,C.W.'15

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



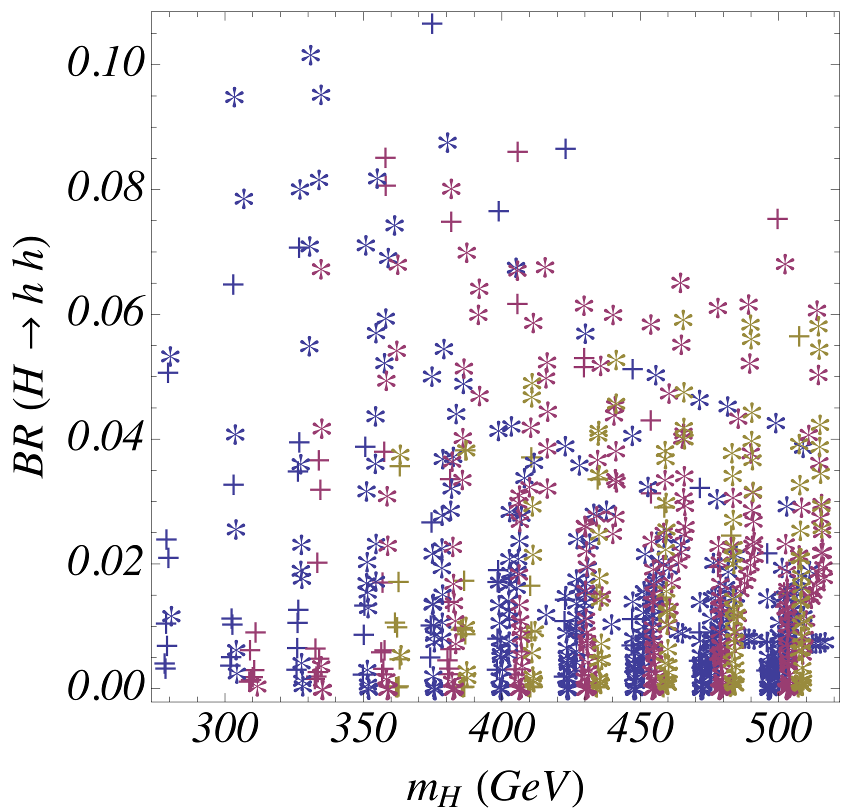


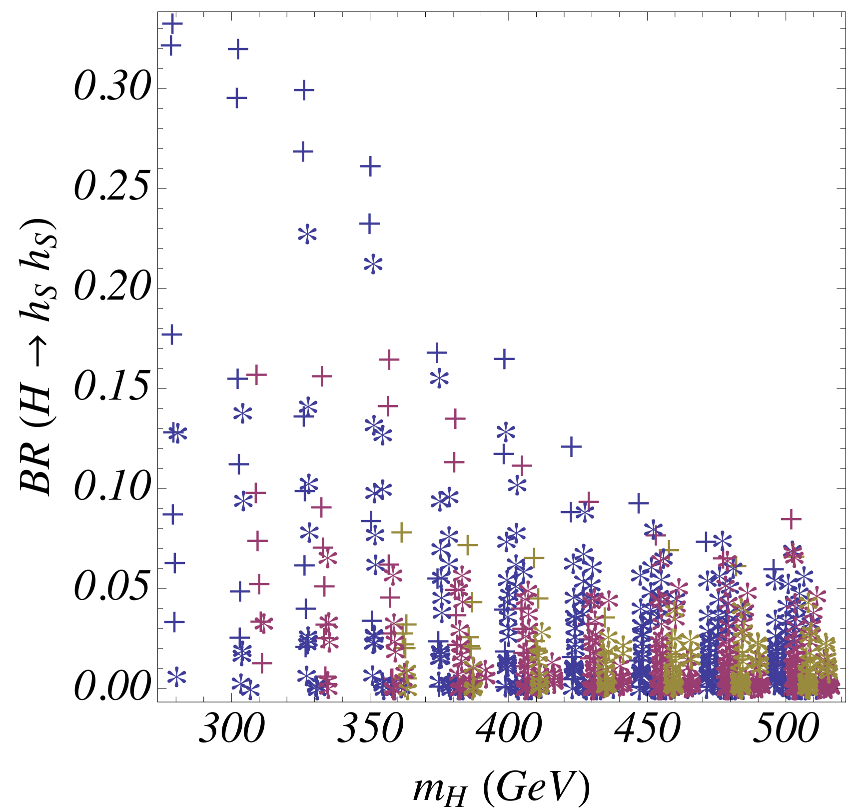
Decays into pairs of SM-like Higgs bosons suppressed by alignment

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: $\tan\beta = 3$





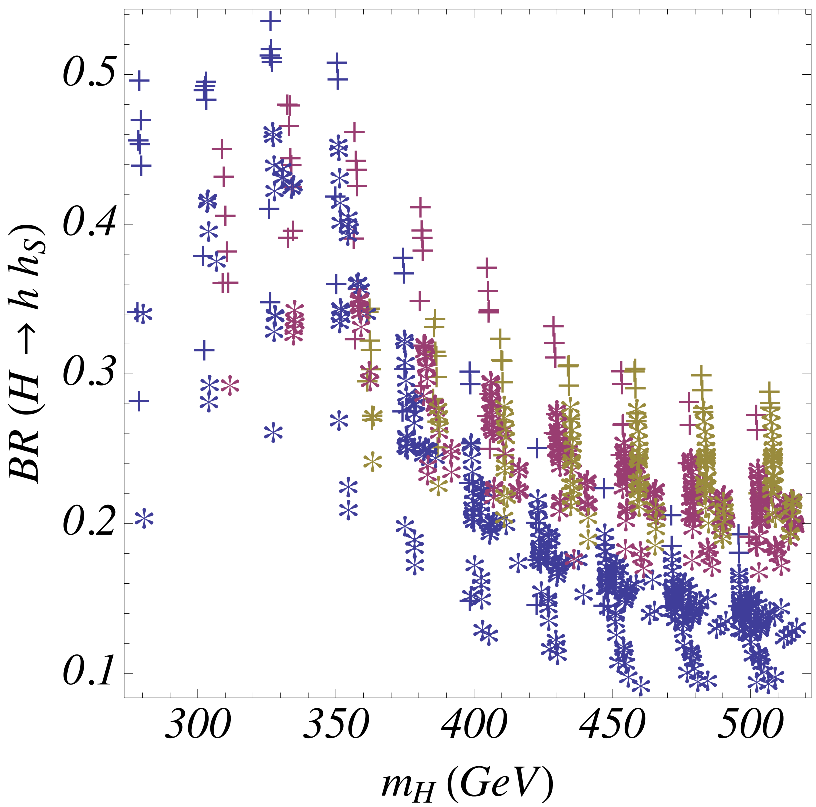
Significant decays of heavier Higgs Bosons into lighter ones and Z's

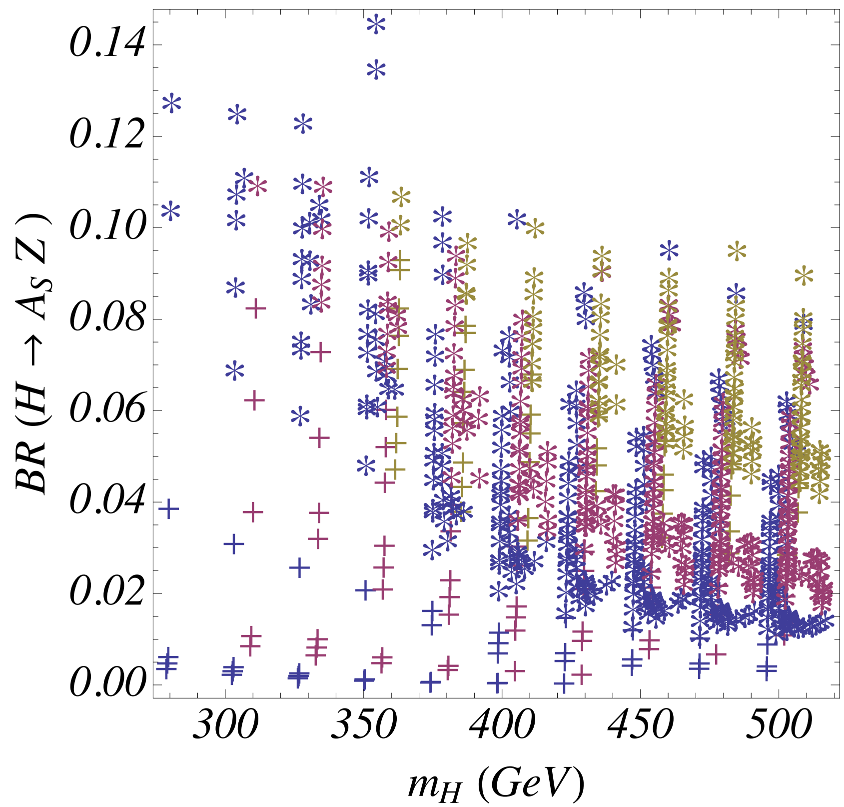
Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

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

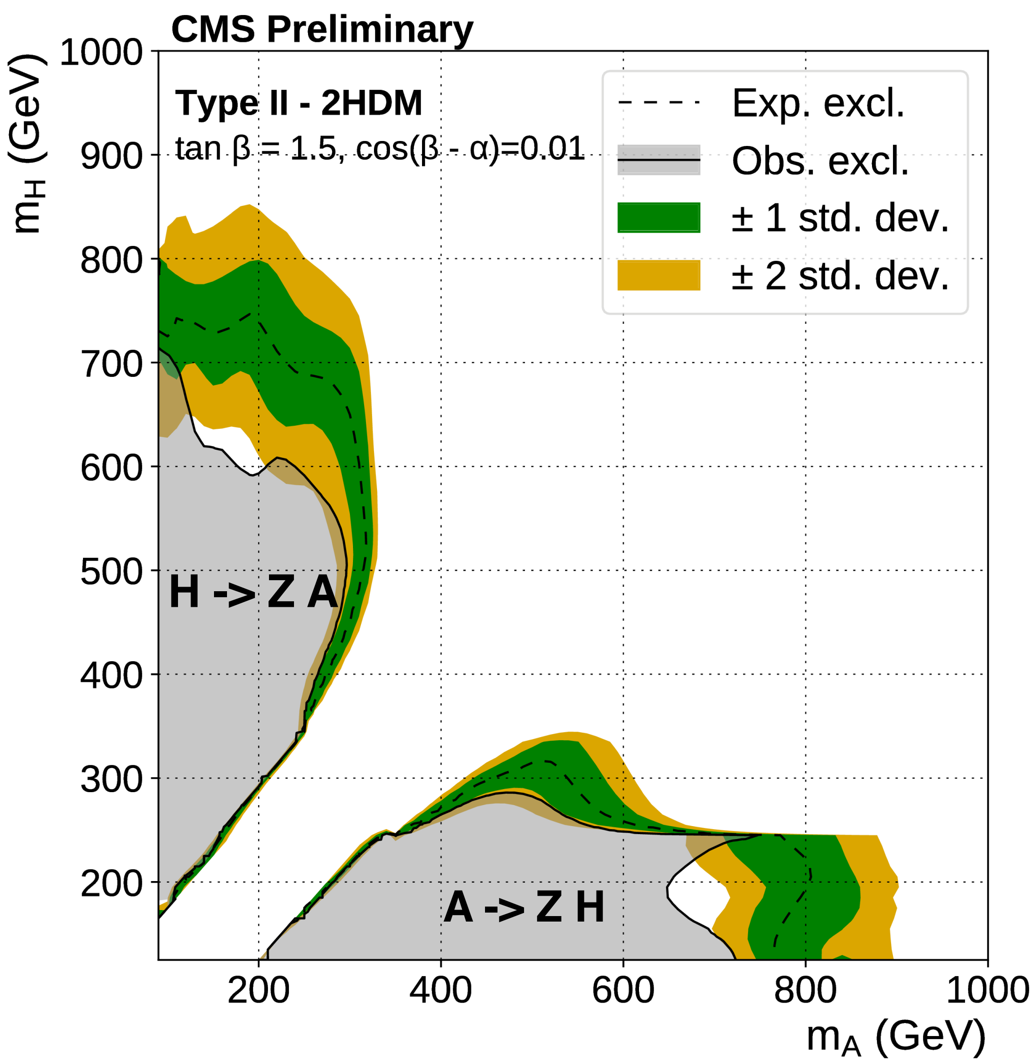
Carena, Haber, Low, Shah, C.W.'15





Search for (psudo-)scalars decaying into lighter ones

CMS-PAS-HIG-18-012

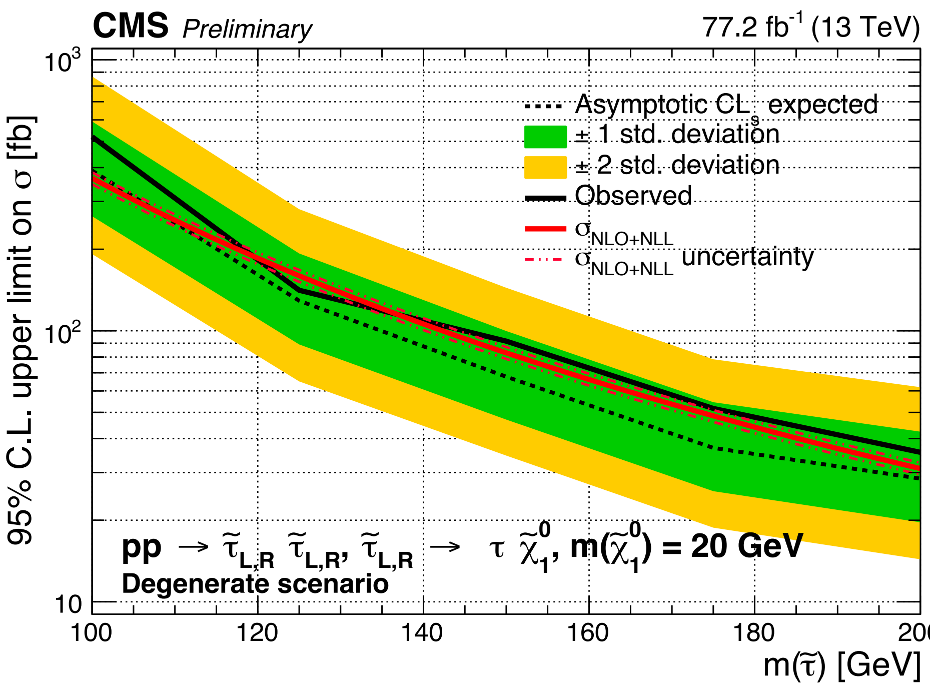


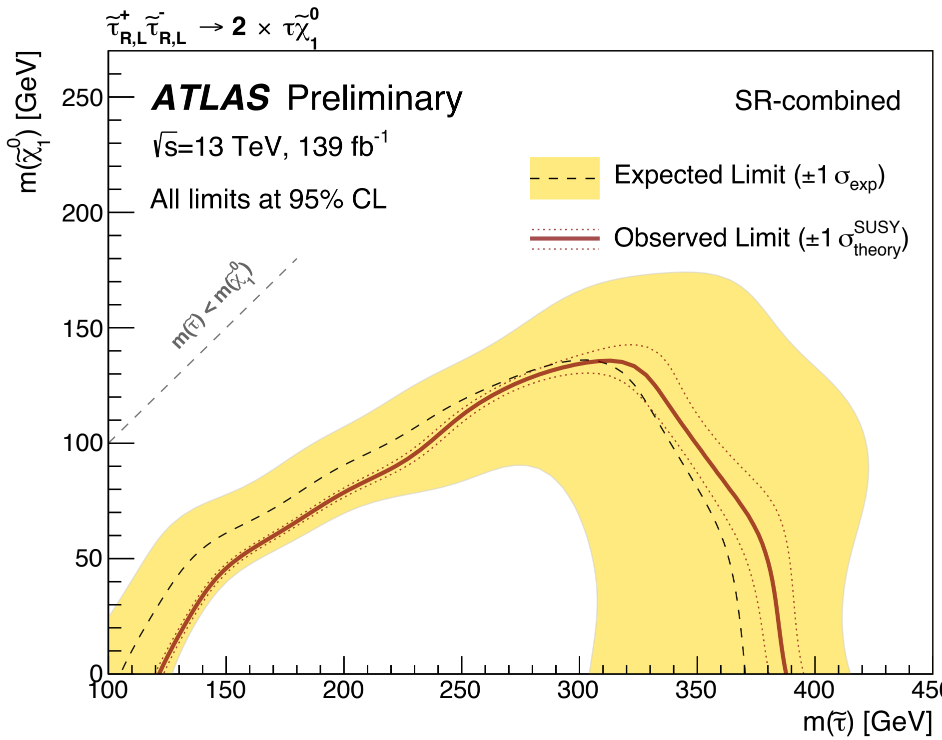
It is relevant to perform similar analyses replacing the Z by a SM Higgs (and changing the CP property of the Higgs)

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.

Stau Searches : Bounds depend on stau mixing.





Weak limit at this point, start to explore region beyond the LEP ones.
Observe that this assumes both staus are degenerate

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 $\quad +M_1$

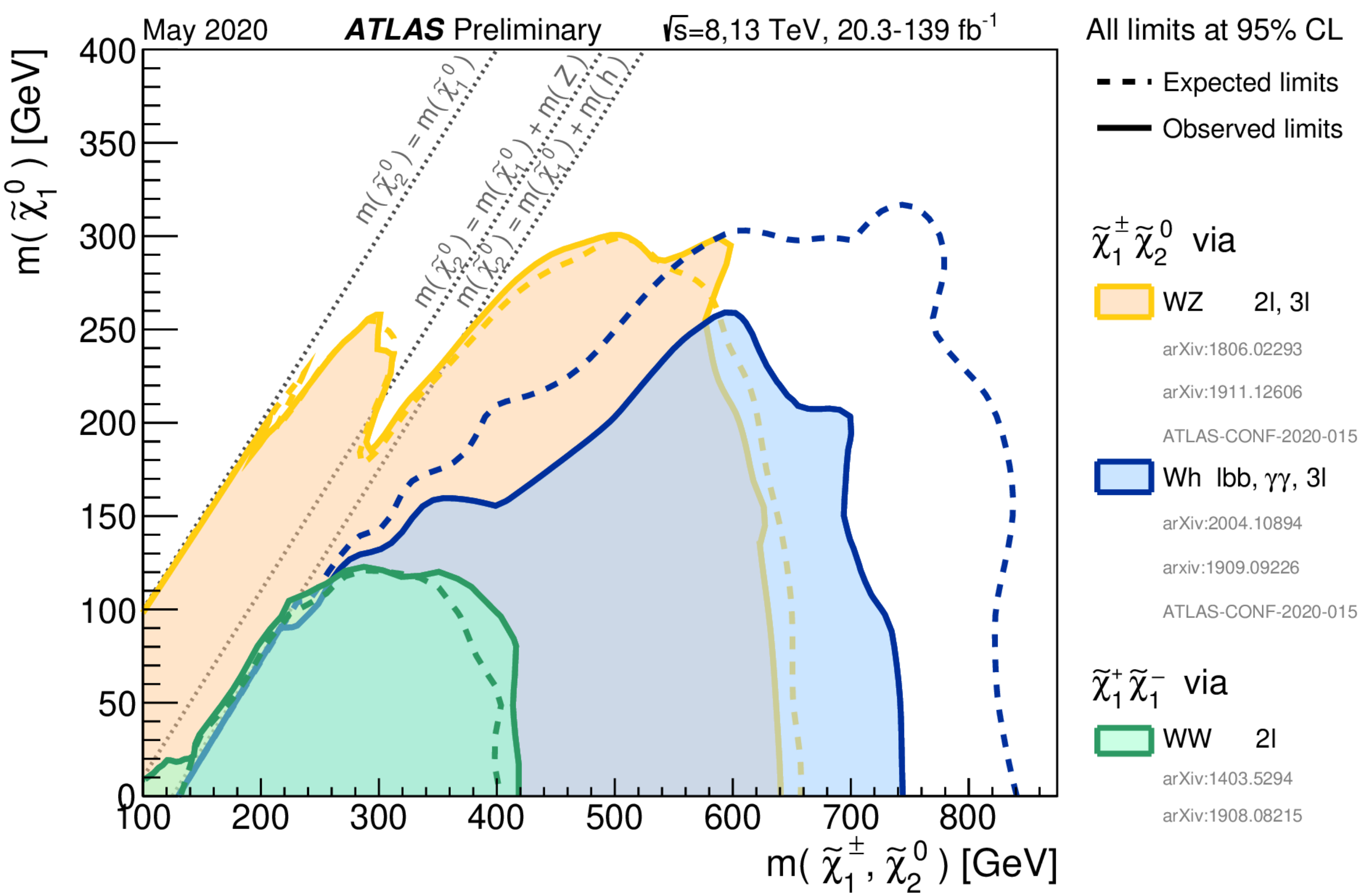
Expected to be among the lightest sparticles

Φ_μ, Φ_1

CP phases

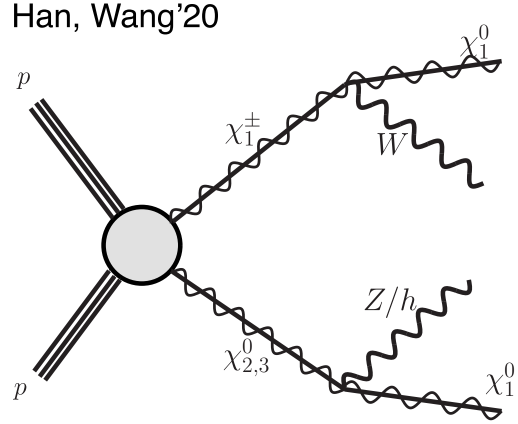
A good starting point towards SUSY parameter determination

Current Electroweakino Mass Bounds
Wino NLSP BR = 1

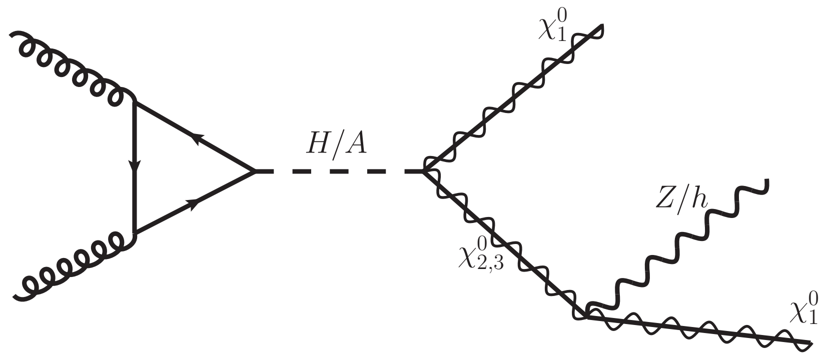


Relevant Electroweakino Production and Decay at the LHC (Bino LSP)

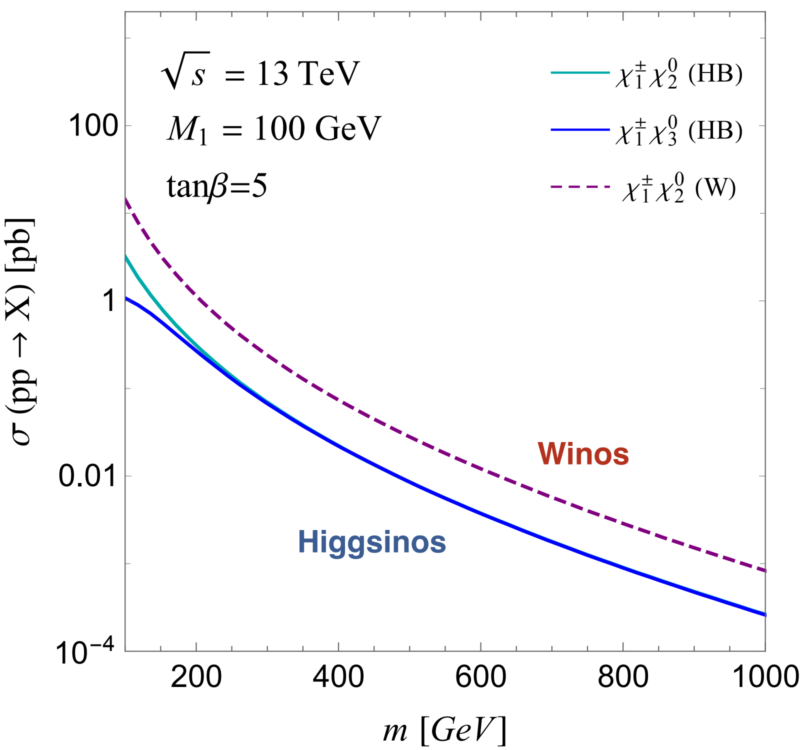
Canepa, Han, Wang'20



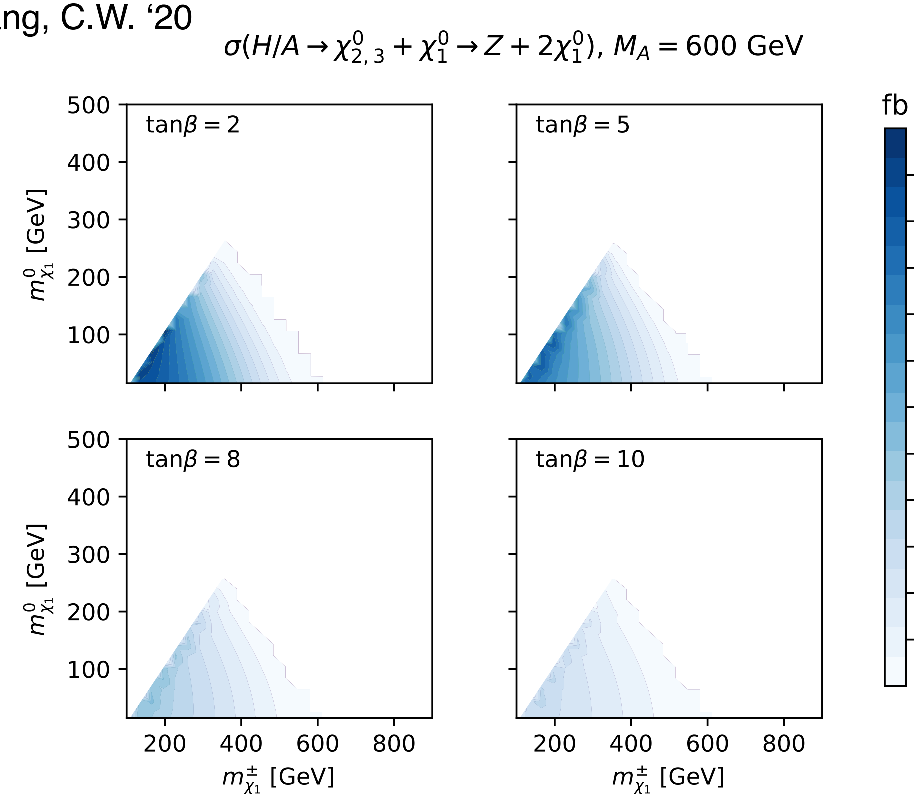
Baum, Freese, Shah, Shakya'17,
Gori, Liu, Shakya'18, Bahl, Liebler, Stefaniak'19,
Adhikary, Bhattacherjee, Godbole, Kahan, Kulkarni'20



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



Higgsinos

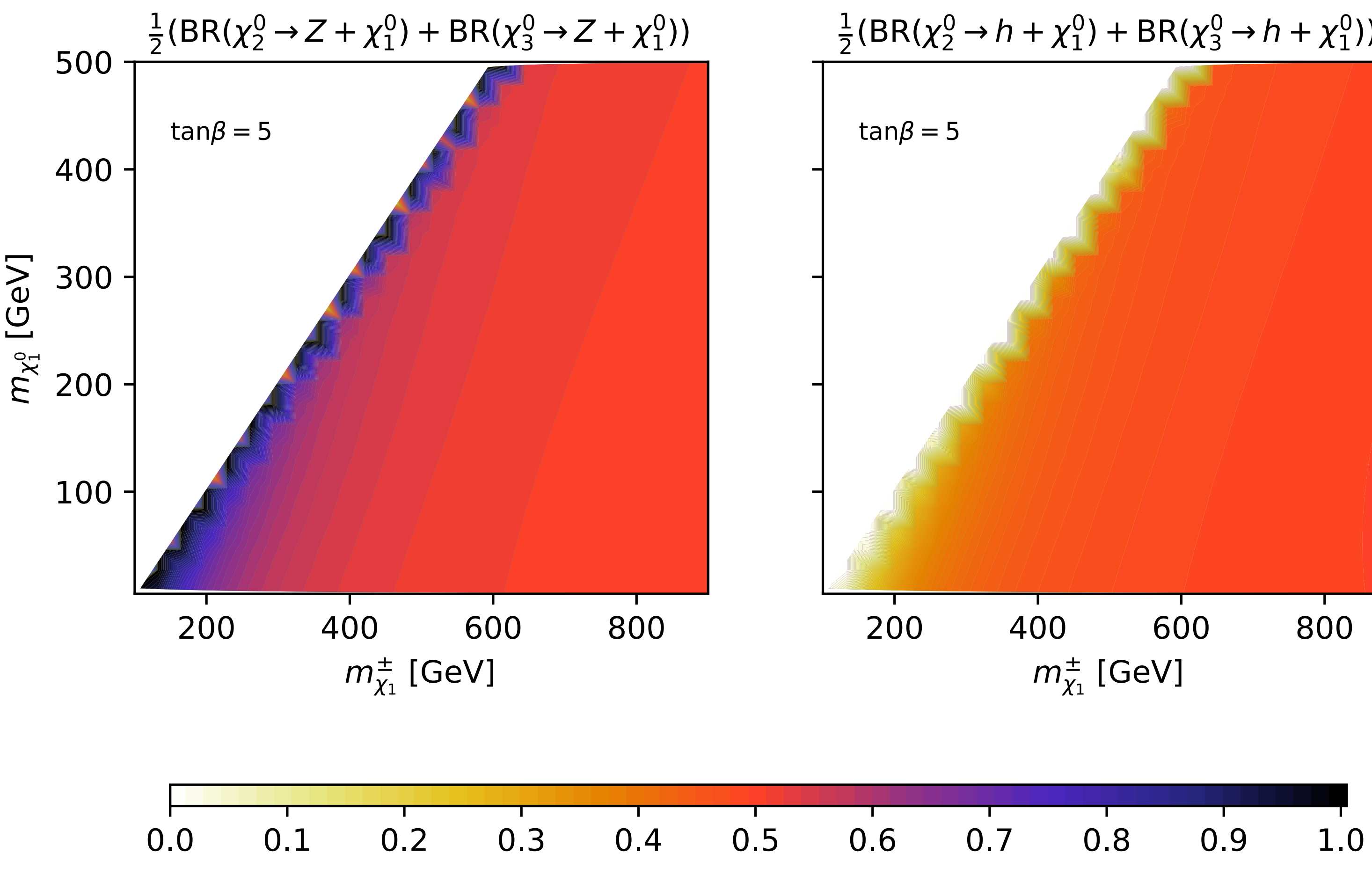


Neutral Higgsino Decays

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.

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

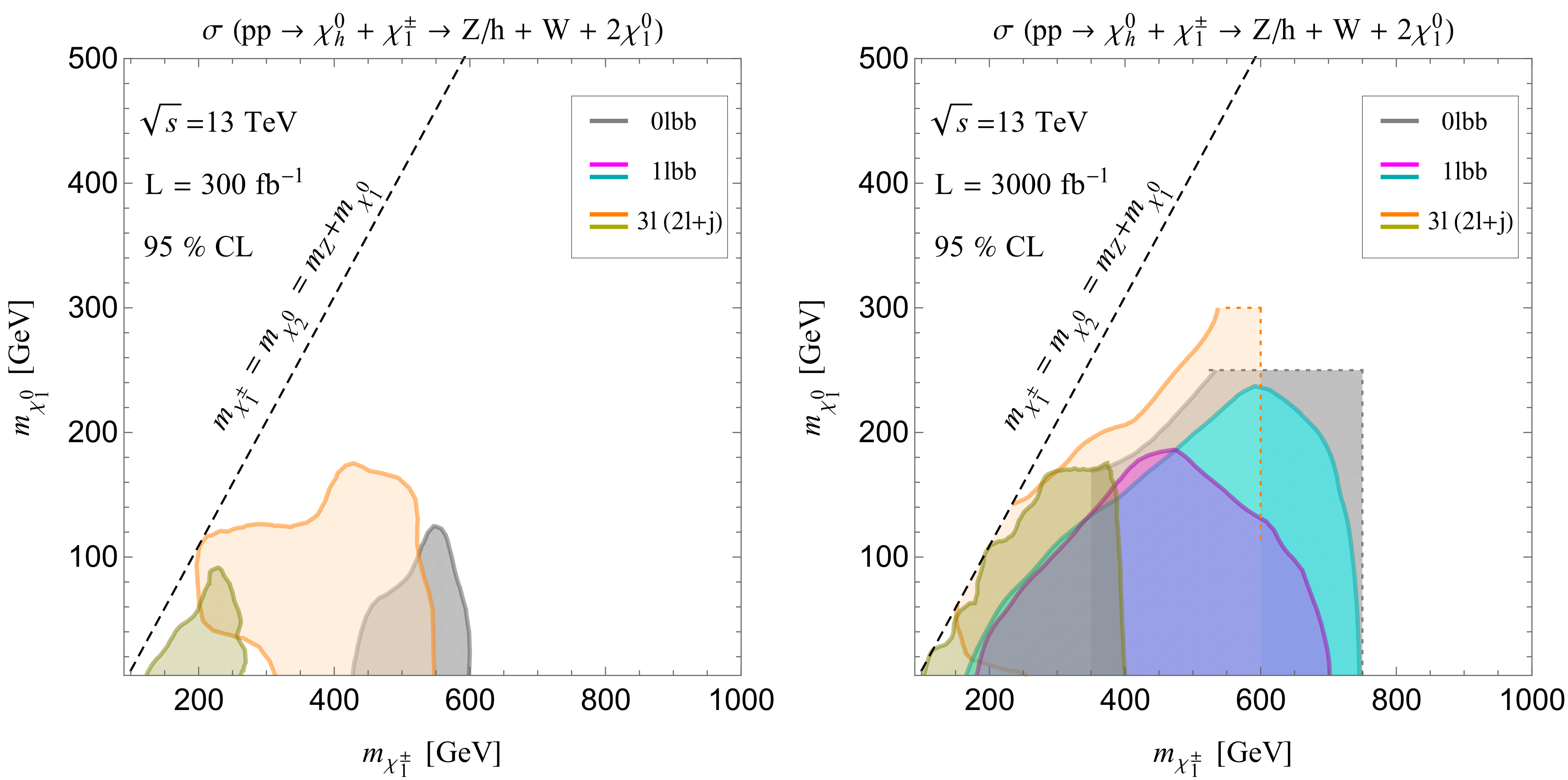


Heavy Winos : Higgsino-Bino LHC Probes

Results from a recast of current CMS and ATLAS bounds.

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

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



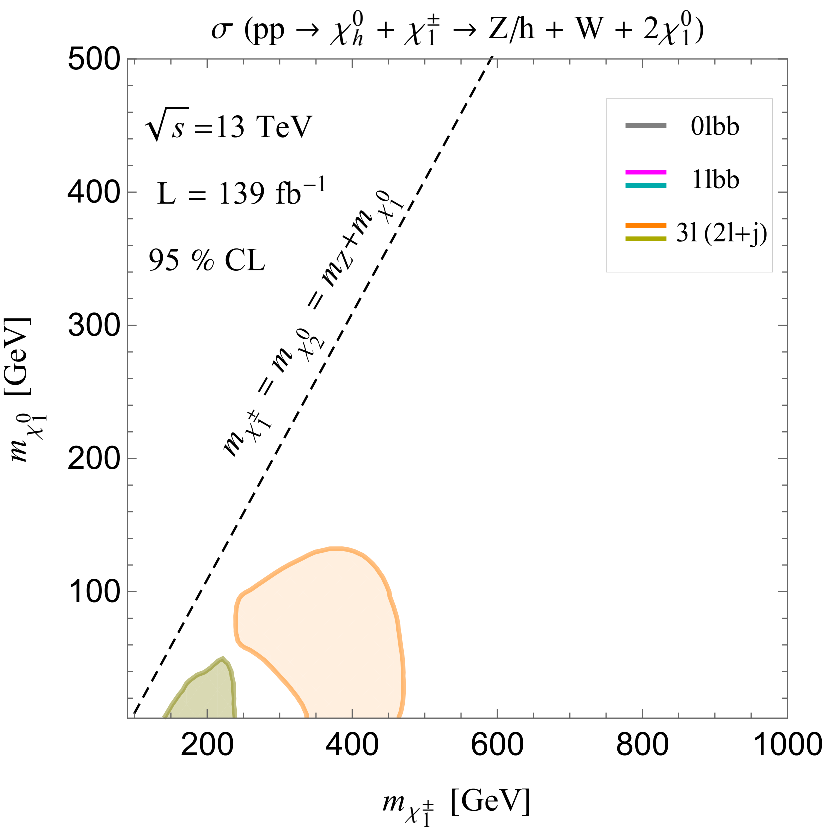
Compressed Region hard to Probe in direct production

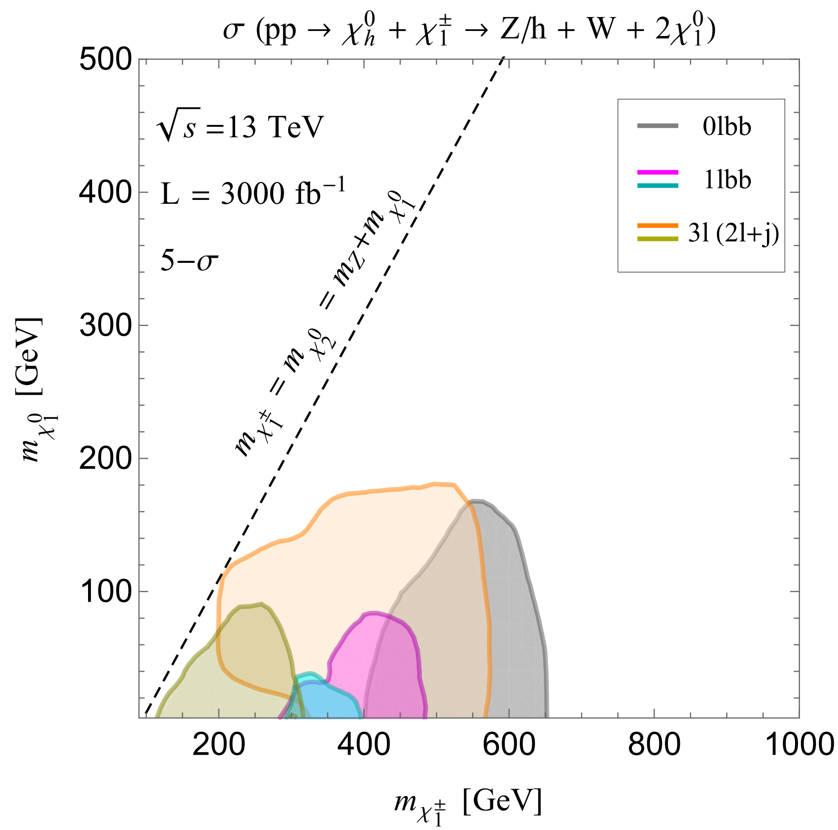
Heavy Winos : Higgsino-Bino
Current Exclusion and Discovery Reach

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.

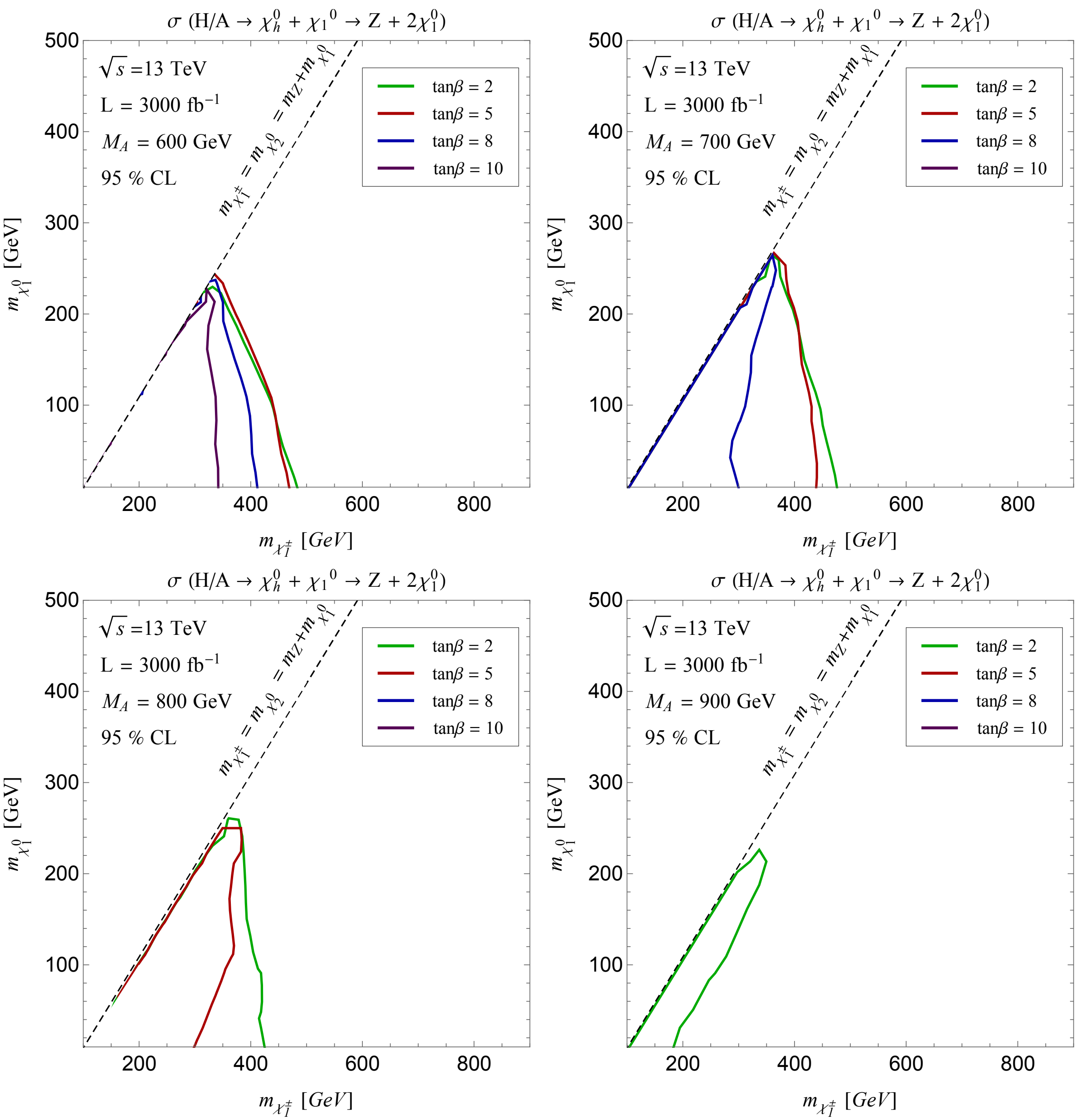
J. Liu, N. McGinnis, X. Wang, C.W. '20





Reach from heavy Higgs Production

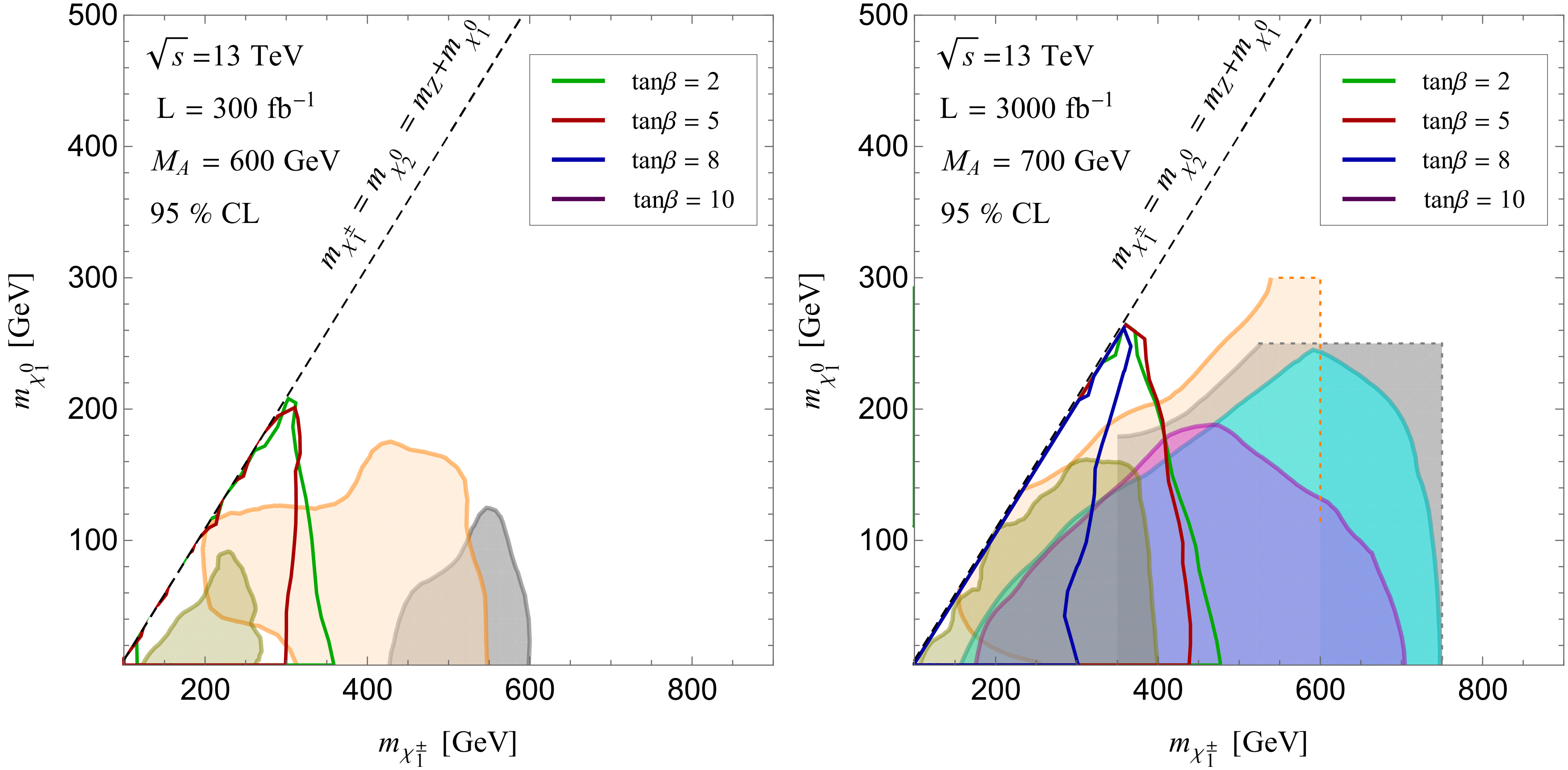
J. Liu, N. McGinnis, X. Wang, C.W. ‘20



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

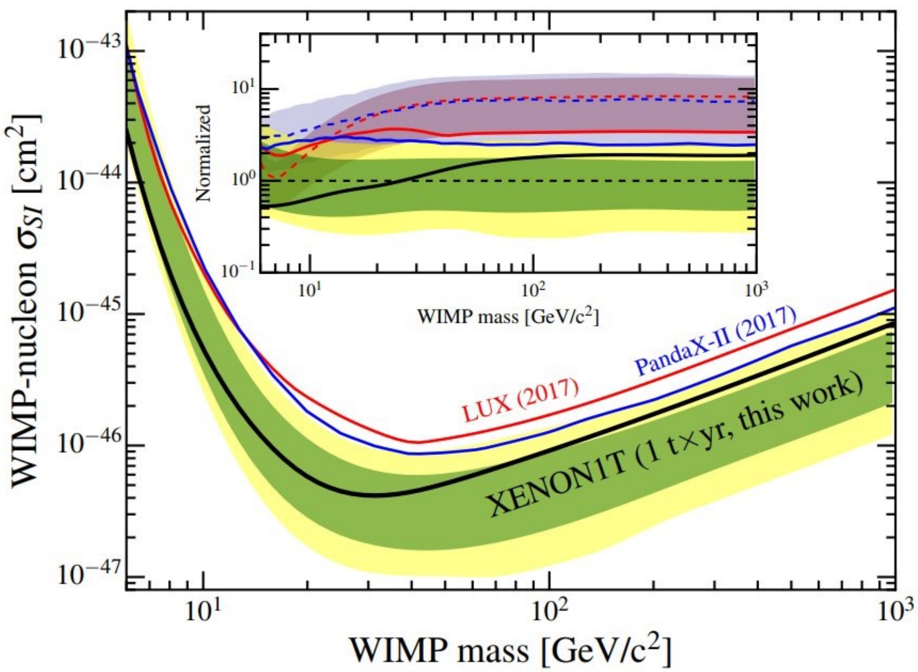
Complementarity of Direct and Higgs Decay Production

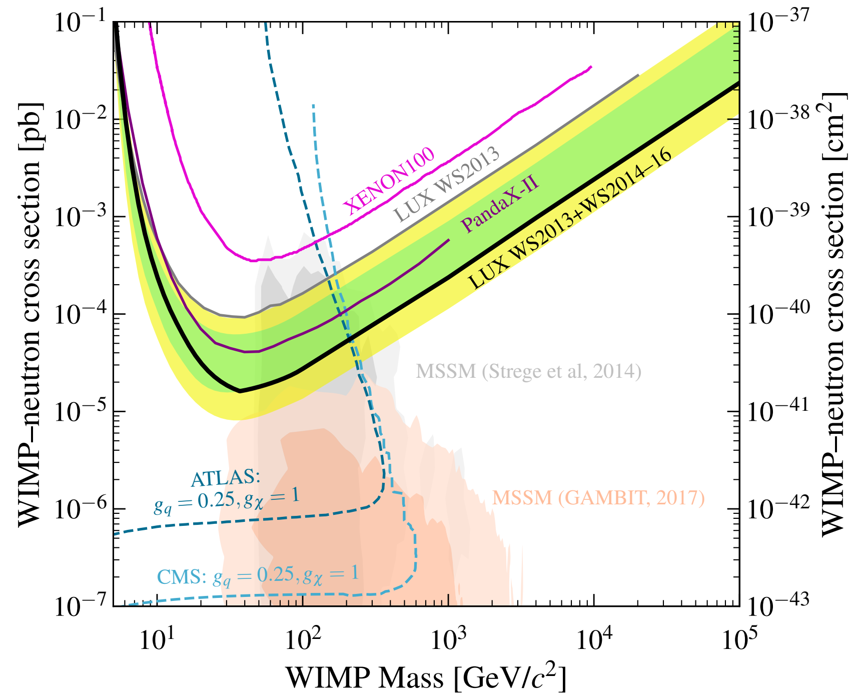
J. Liu, N. McGinnis, X. Wang, C.W. '20



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

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

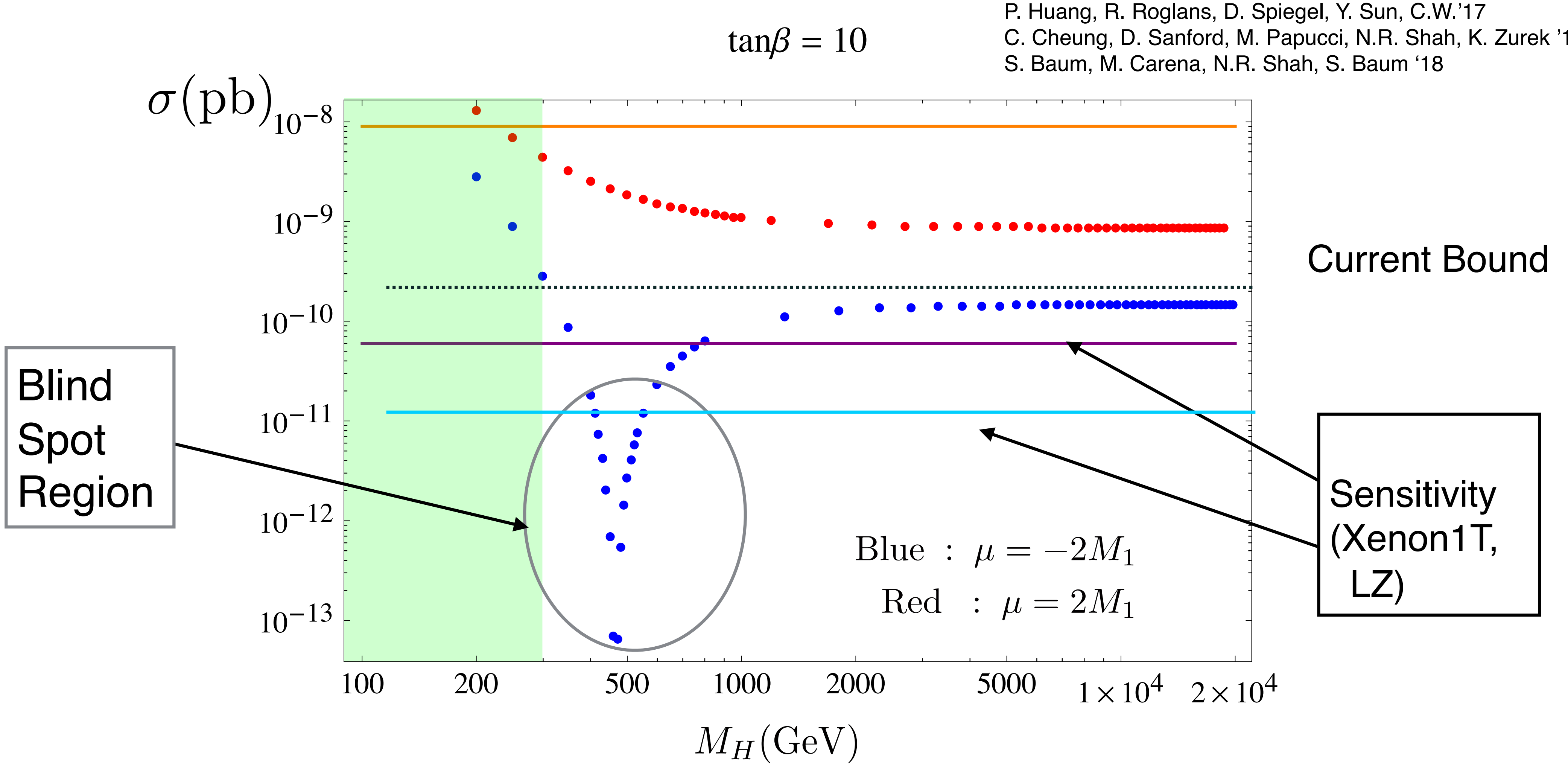
$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

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



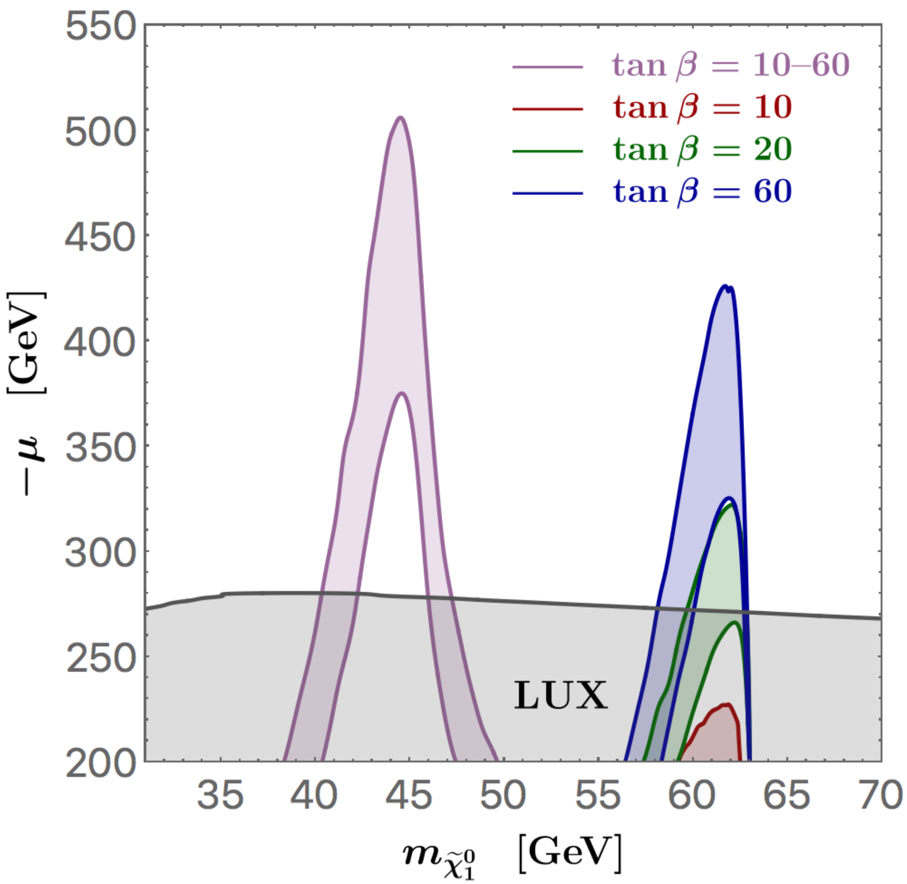
$$m_{\chi^\pm}=|\mu|,\quad m_\chi^0=M_1,\qquad M_1=200\ \text{GeV}$$

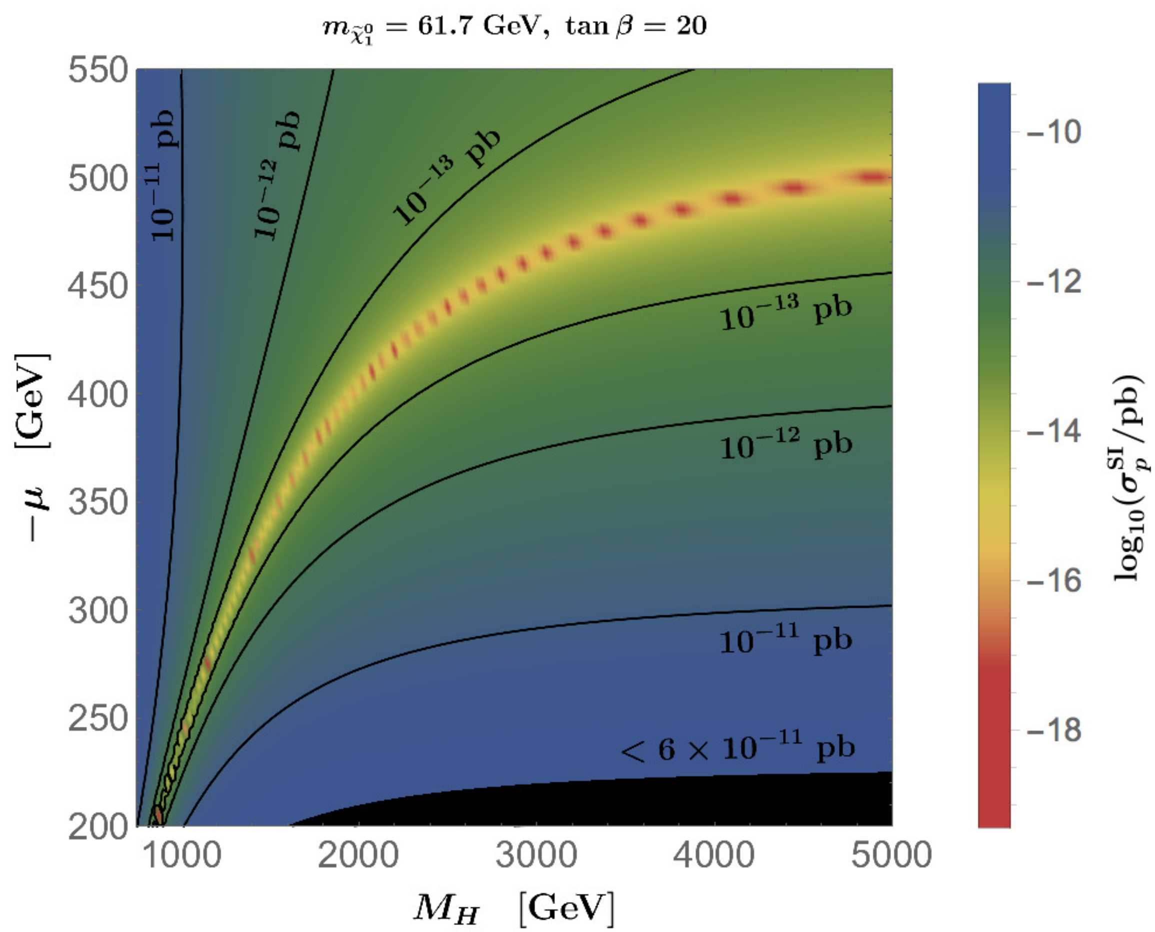
Carena, Osborne, Shah, C.W. ’18'19

Dark Matter Phenomenology

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

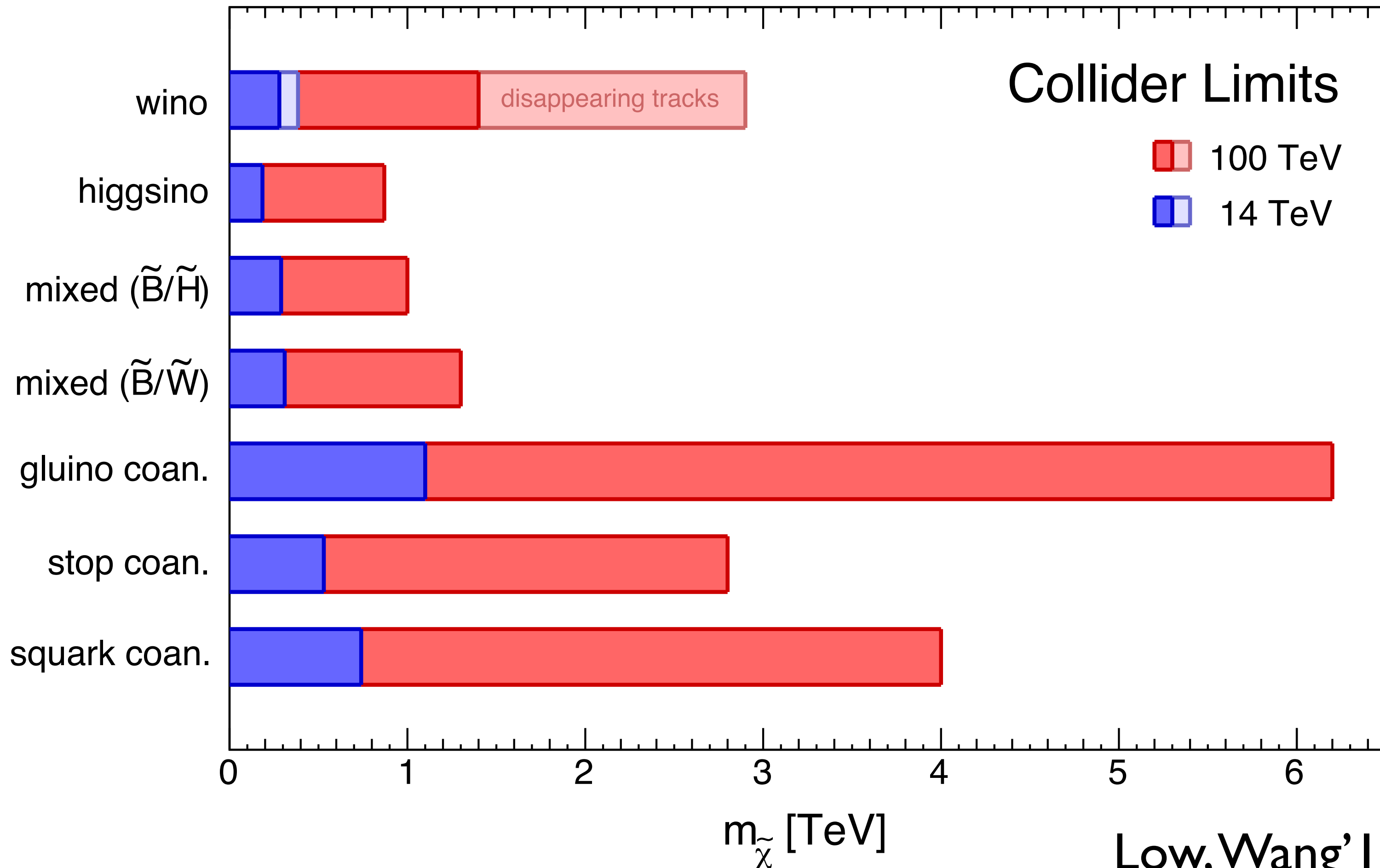
Existence of Blind Spot Regions Suppresses the SI cross section below the current limits in most of the parameter space.





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

Future Colliders : Direct Production Limits



Low, Wang'14

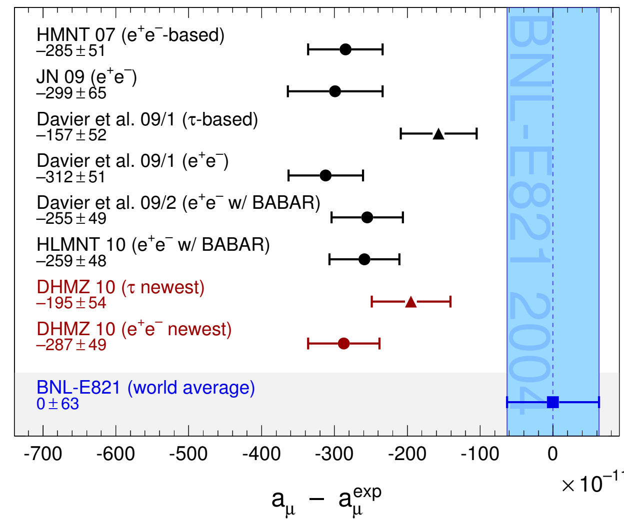
100 TeV collider will probe most promising regions

Muon Anomalous Magnetic Moment

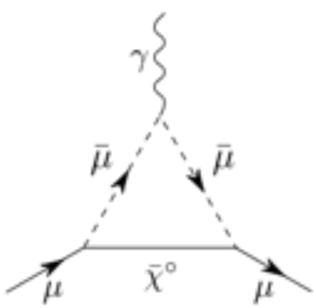
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

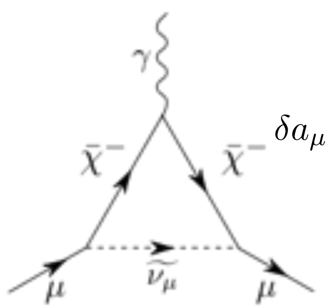
$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm theory} = 268(63)(43) \times 10^{-11}$$

3.6σ Discrepancy



New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry





$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2} \frac{m_\mu^2}{\widetilde{m}^2} {\rm Sgn}(\mu M_2) \tan\beta \simeq 130 \times 10^{-11} \left(\frac{100 \ {\rm GeV}}{\widetilde{m}} \right)^2 {\rm Sgn}(\mu M_2) \tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

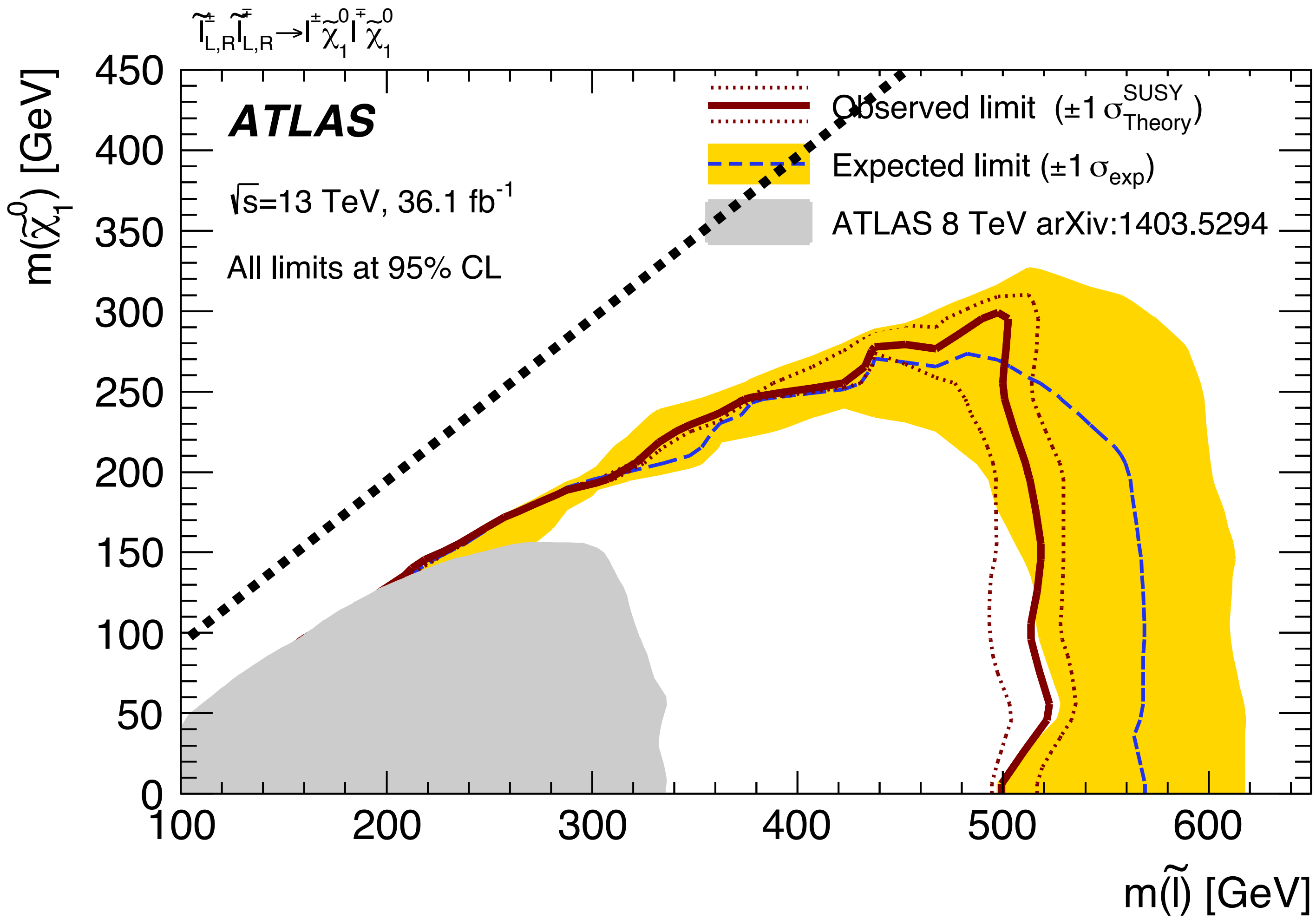
If Winos are heavy, one would need larger values of tanβ to explain the current anomaly.

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 ?
- There is still clear room for discovery at the LHC.
- Moreover, if electroweakinos are at the weak scale, they could lead to a solution of the DM problem. Tensions will current direct detection data could be highly ameliorated for negative values of μ.

Backup

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