Higgs and Dark Matter Physics in Low Energy Supersymmetry

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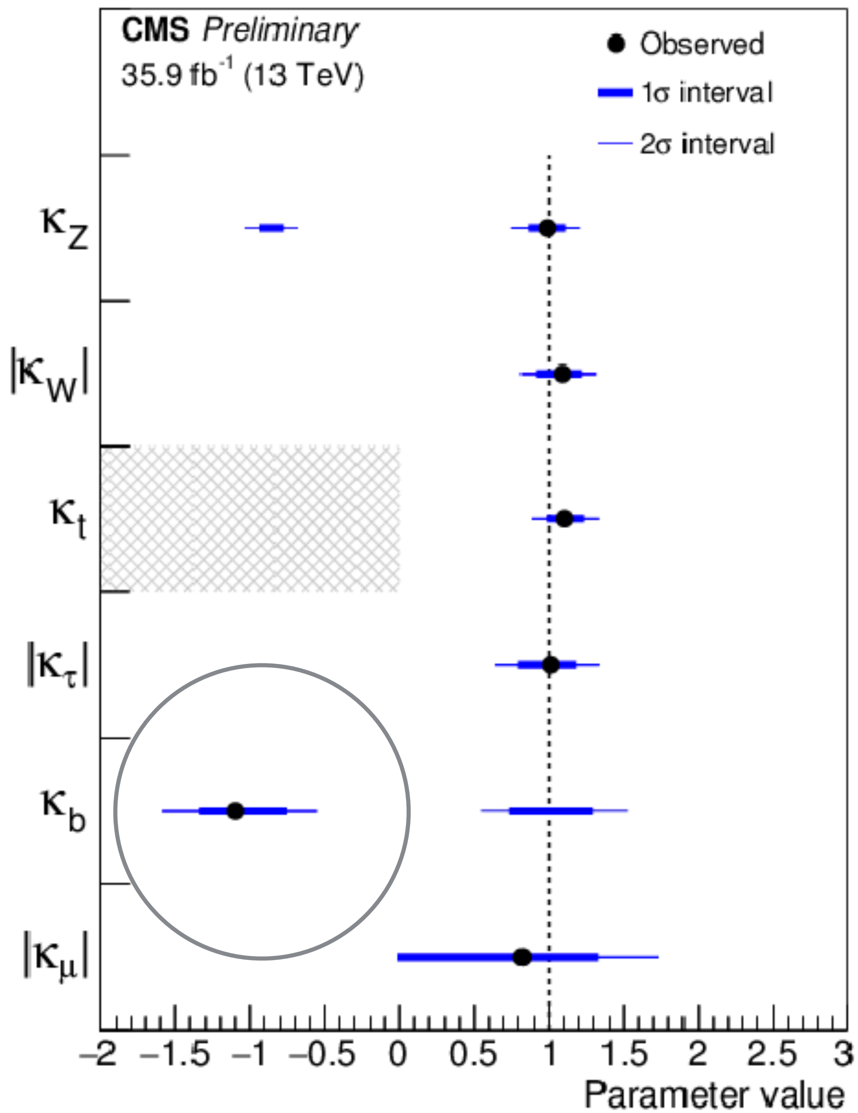
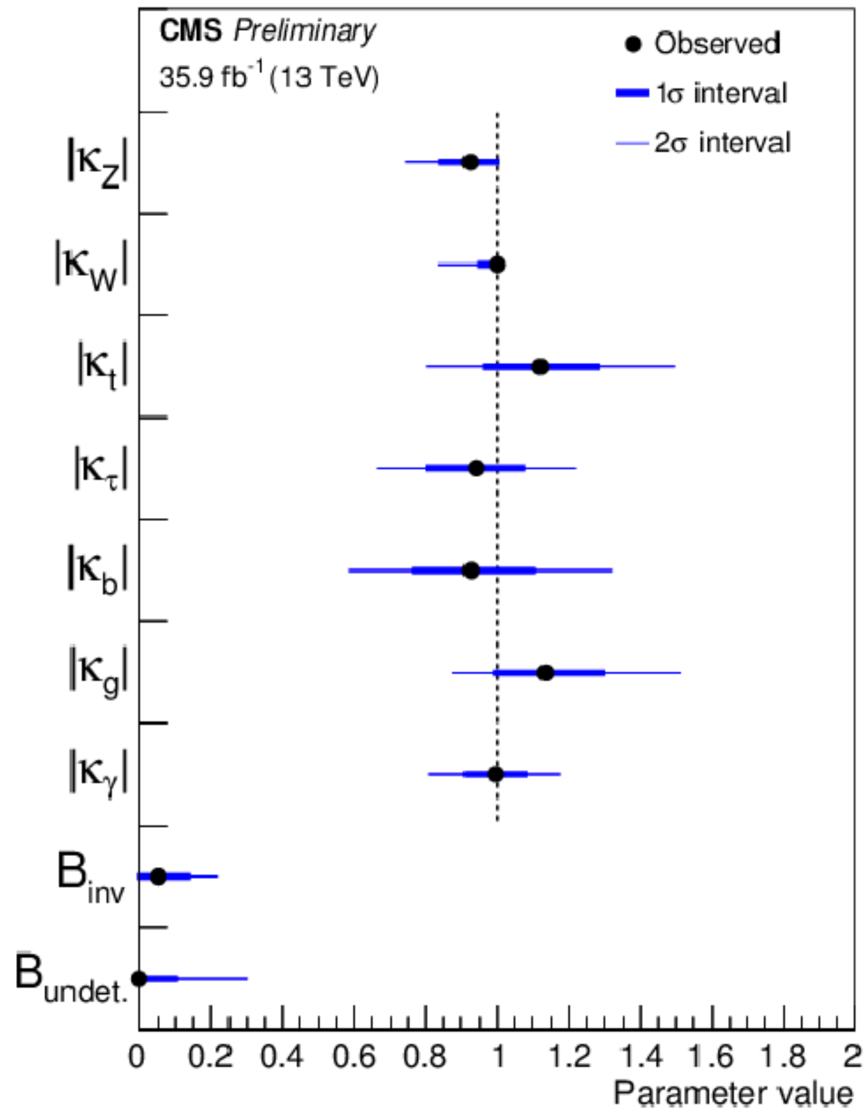
Based on the following works :

- M. Carena, I. Low, N. Shah, C.W., arXiv:1310.2248, JHEP 1404 (2014)
- M. Carena, H. Haber, I. Low, N. Shah, C.W., arXiv:1410.4969, PRD91 (2015); arXiv:1510.09137, PRD93 (2016)
- N. Coyle, C.W., to appear
- P. Huang, C.W., arXiv:1404.0392, PRD90 (2014)
- P. Huang, D. Spiegel, R. Roglans, Y. Sun, C.W., arXiv:1707.02737, PRD95 (2017)
- S. Baum, M. Carena, N.R. Shah, C.W., arXiv:1712.09873, JHEP 1804 (2018)
- M. Carena, J. Osborne, N.R. Shah, C.W., arXiv:1809.11082, PRD95 (2018)
- M. Carena, J. Osborne, N.R. Shah, C.W., arXiv:1905.06738, PRD100 (2019)

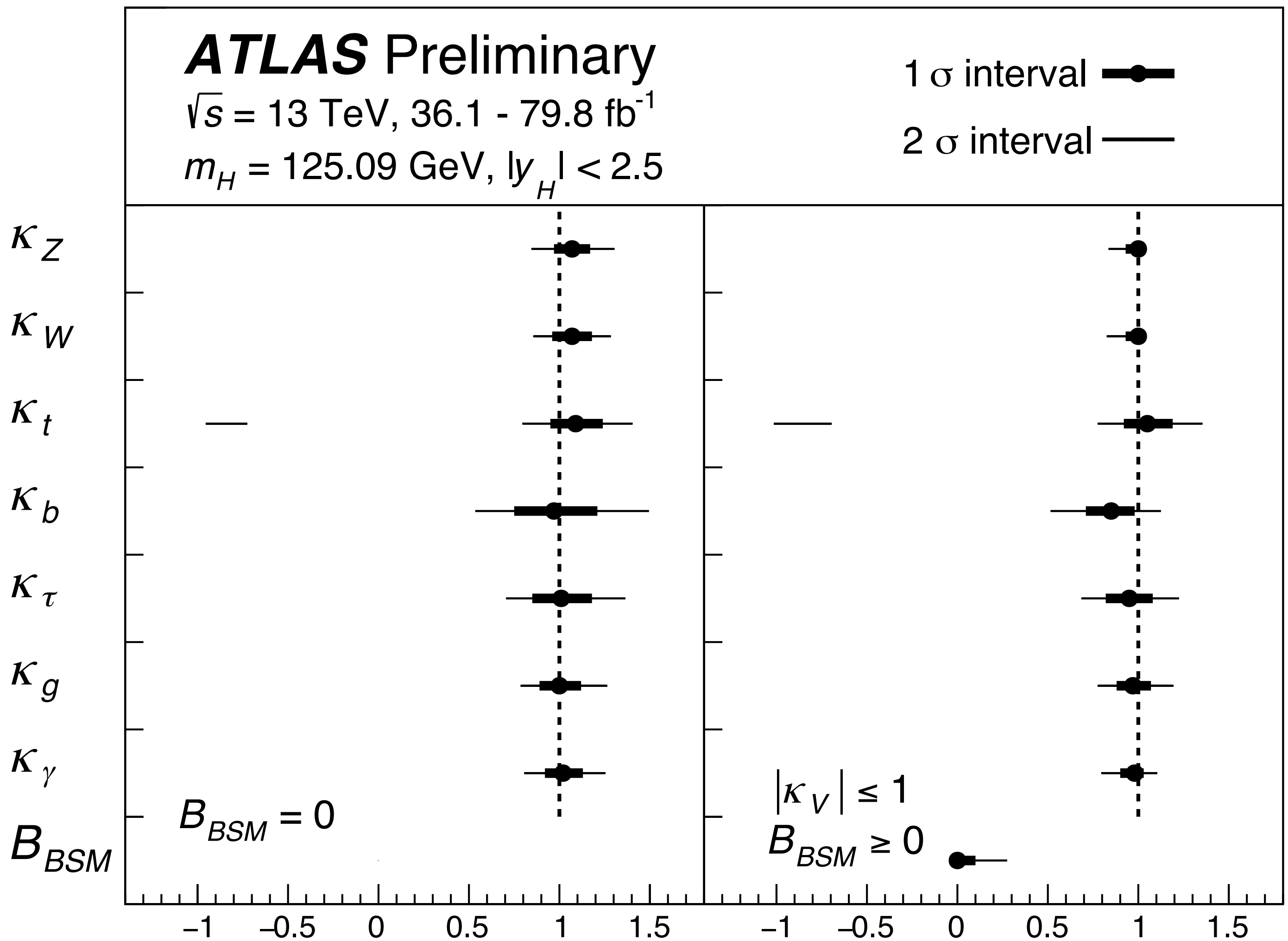
CMS Fit to Higgs Couplings
Remarkable agreement with SM values





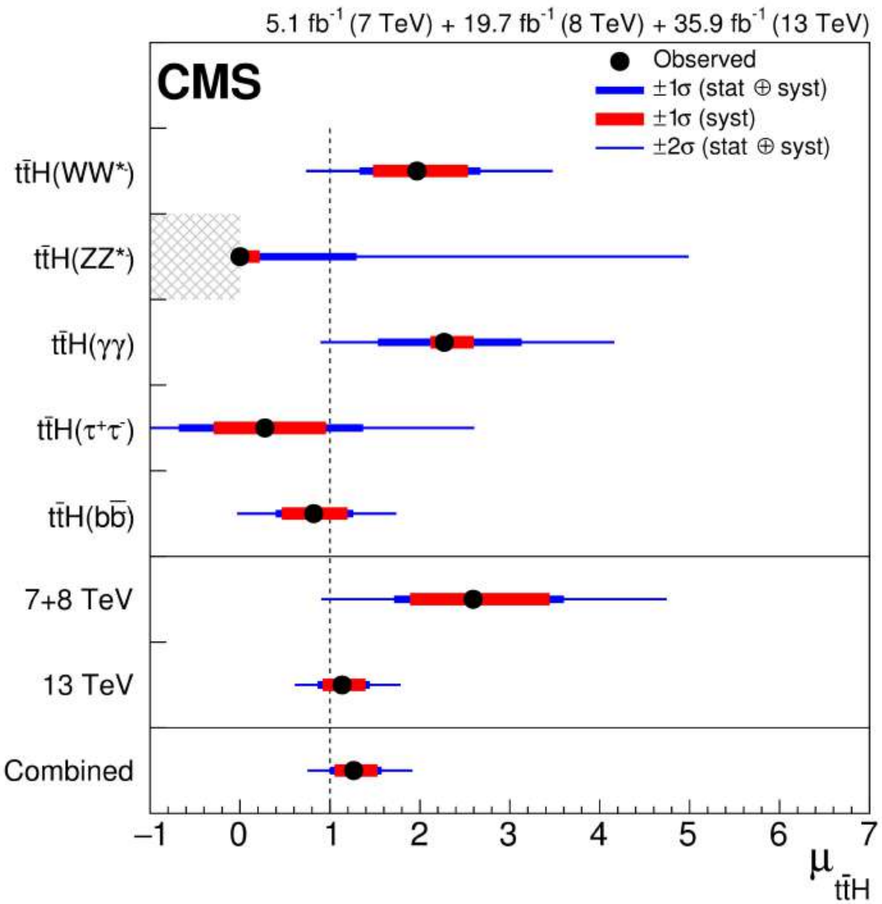
ATLAS Fit to Higgs Couplings

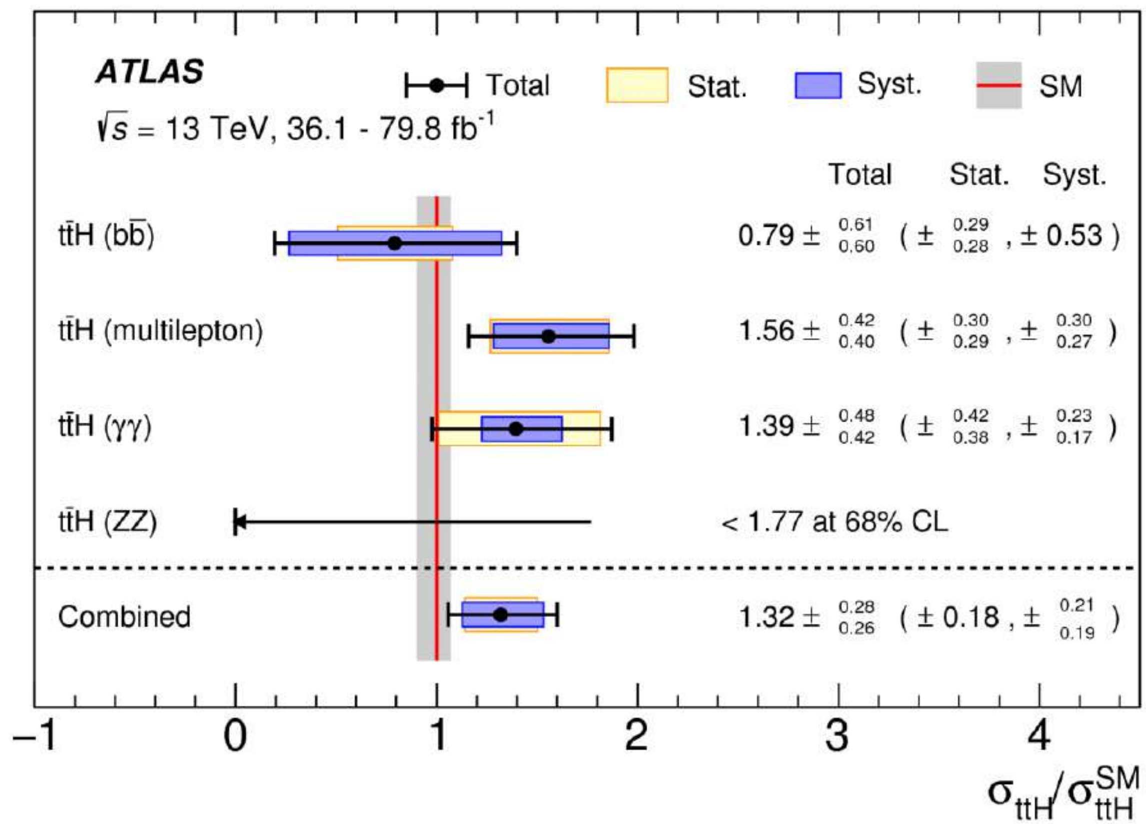
Departure from SM predictions of the order of at most a few tens of percent allowed at this point



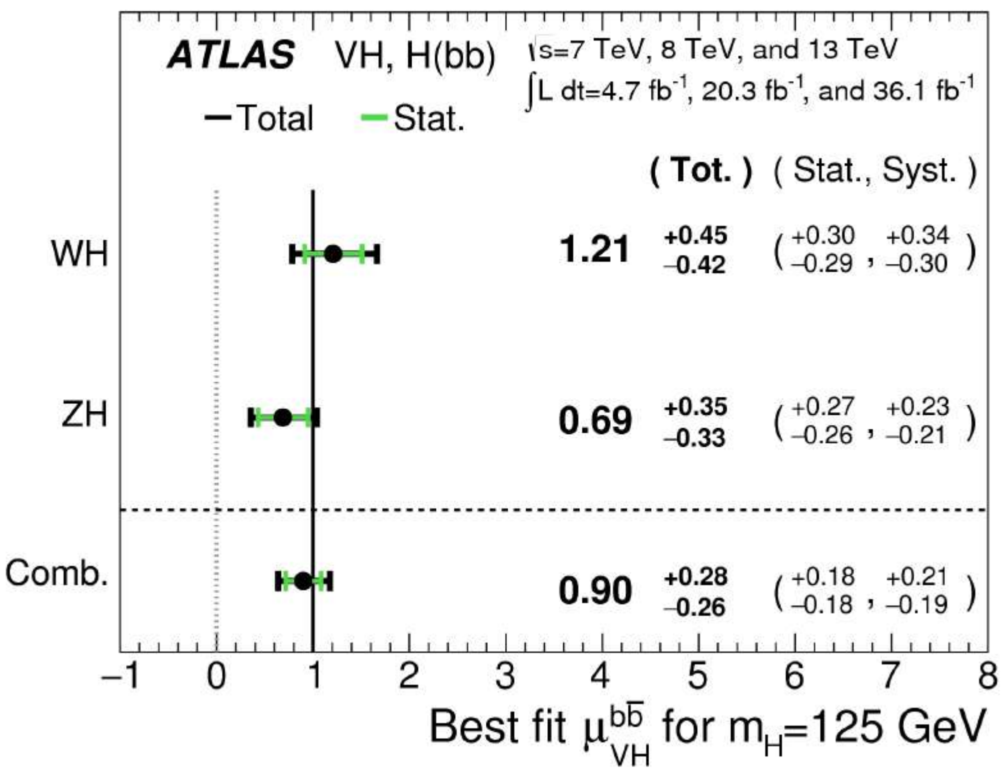
tth results

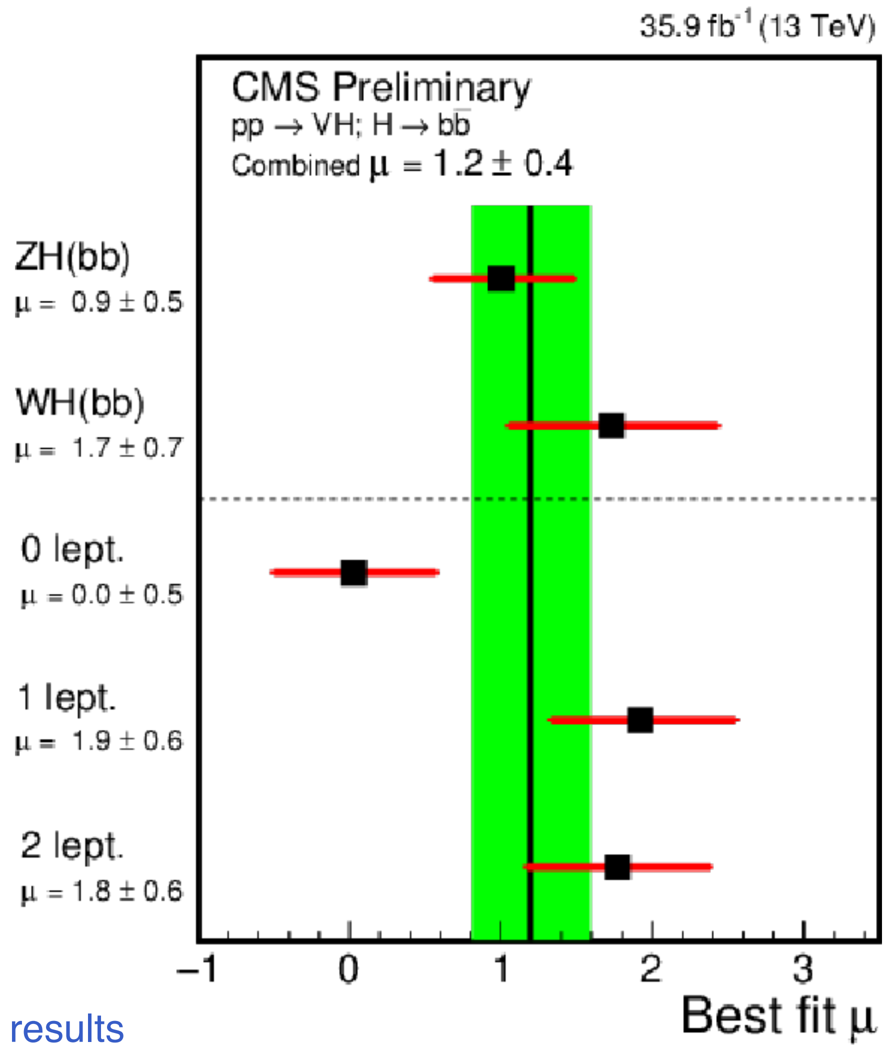
Values overall consistent with the SM, but a few interesting small discrepancies are present at both experiments.





There is today evidence of a Higgs decaying to bottom quarks





Consistency with SM results

Errors are still large an admit deviations of a few tens of percent from the SM results

Modifying the top and bottom couplings in two Higgs Doublet Models

- Measurement of the couplings still subject to relatively large errors.
- The hint of enhancement on the top coupling is much weaker in the 13 TeV data.
- Modifying the top-quark coupling is simple in type II for small values of tanβ, but the bottom coupling is modified as well in an opposite direction

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

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

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

Haber and Gunion'03

Alignment Condition : $\cos(\beta-\alpha) = 0$

SM-like Higgs tree level couplings equal to SM couplings

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

Alignment Conditions

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

- If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- For $\lambda_6 = \lambda_7 = 0$ the conditions simplify, but can only be fulfilled if

$$\lambda_1 \ \geq \ \lambda_{\rm SM} \ \geq \ \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \ \geq \ \lambda_{\rm SM} \ \geq \ \tilde{\lambda}_3 \ ,$$

or

$$\lambda_1 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3 \quad \text{and} \quad \lambda_2 \ \leq \ \lambda_{\rm SM} \ \leq \ \tilde{\lambda}_3$$

- Conditions not fulfilled in the MSSM, where both $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$

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

Deviations from Alignment

$$c_{\beta-\alpha} = t_\beta^{-1}\eta \;, \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

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

The couplings of down fermions are not only the ones that dominate the Higgs width but also tend to be the ones which differ at most from the SM ones

$$g_{hVV} \approx \left(1 - \frac{1}{2}t_\beta^{-2}\eta^2\right) g_V \;, \qquad g_{HVV} \approx t_\beta^{-1}\eta\, g_V \;,$$

$$g_{hdd} \approx (1-\eta)\, g_f \;, \qquad g_{Hdd} \approx t_\beta(1 + t_\beta^{-2}\eta) g_f$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \;, \qquad g_{Huu} \approx -t_\beta^{-1}(1-\eta) g_f$$

For small departures from alignment, the parameter η can be determined as a function of the quartic couplings and the Higgs masses

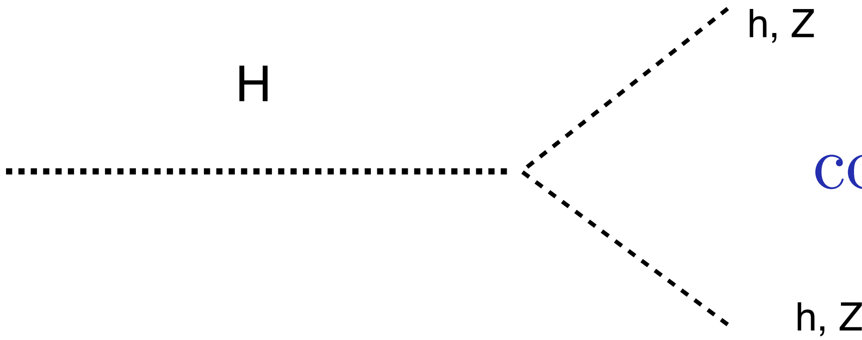
$$\eta = s_\beta^2\left(1 - \frac{\mathcal{A}}{\mathcal{B}}\right) = s_\beta^2 \frac{\mathcal{B}-\mathcal{A}}{\mathcal{B}}, \qquad \mathcal{B} - \mathcal{A} = \frac{1}{s_\beta}\left(-m_h^2 + \tilde{\lambda}_3 v^2 s_\beta^2 + \lambda_7 v^2 s_\beta^2 t_\beta + 3\lambda_6 v^2 s_\beta c_\beta + \lambda_1 v^2 c_\beta^2\right)$$

$$\tilde{\lambda}_3 = \lambda_3 + \lambda_4 + \lambda_5$$

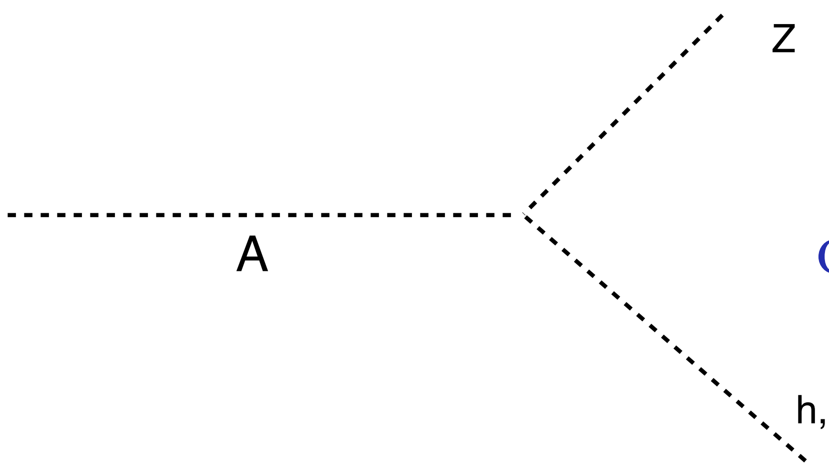
$$\mathcal{B} = \frac{\mathcal{M}_{11}^2 - m_h^2}{s_\beta} = \left(m_A^2 + \lambda_5 v^2\right) s_\beta + \lambda_1 v^2 \frac{c_\beta}{t_\beta} + 2\lambda_6 v^2 c_\beta - \frac{m_h^2}{s_\beta}$$

H and A Decay to Boson Pairs

Suppressed at Alignment



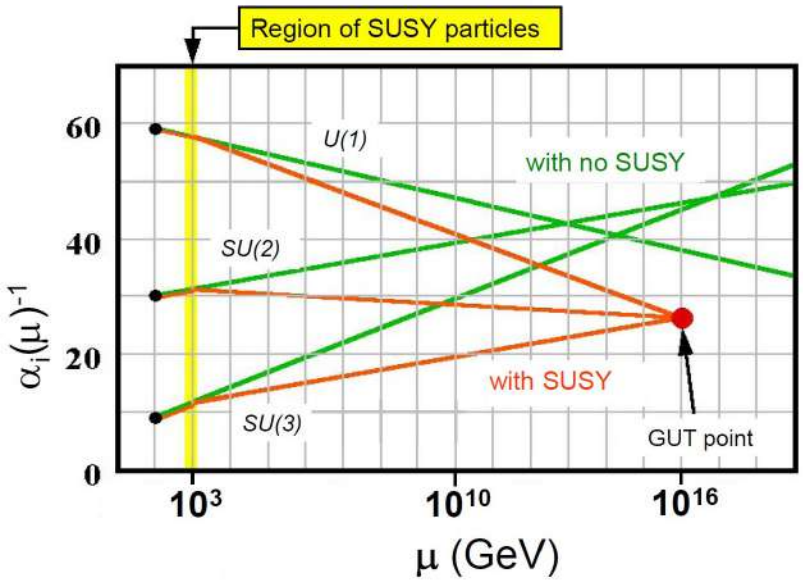
$$\cos(\beta - \alpha)$$



$$\cos(\beta - \alpha)$$

Consequences of SUSY

Unification



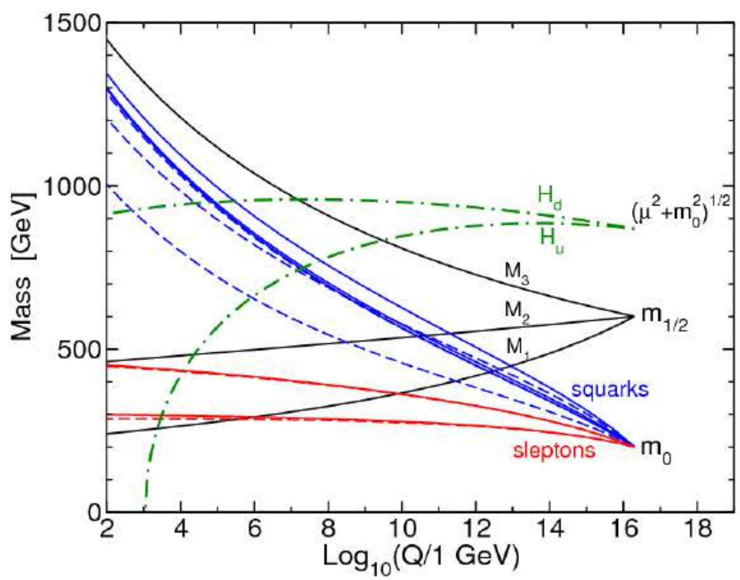
SUSY Algebra

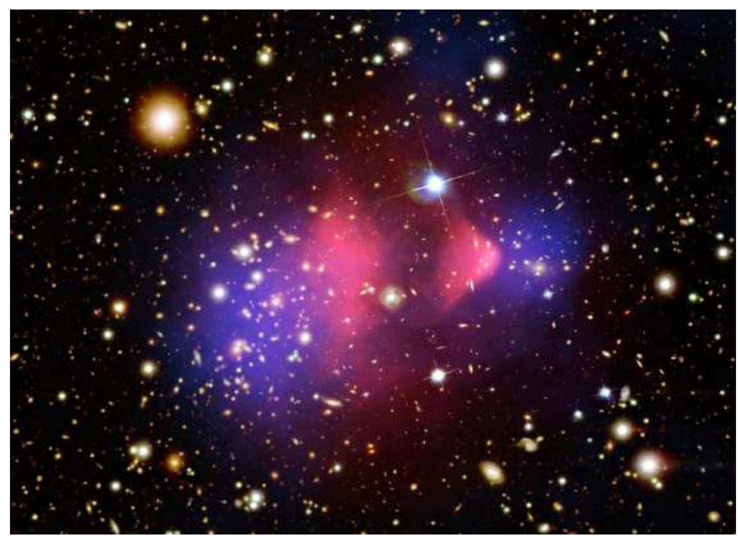
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

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

Quantum Gravity ?

Electroweak Symmetry Breaking





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

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

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

$$t = \log(M^2_{SUSY}/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M^2_{SUSY}}\left(1 - \frac{X_t^2}{12 M^2_{SUSY}}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

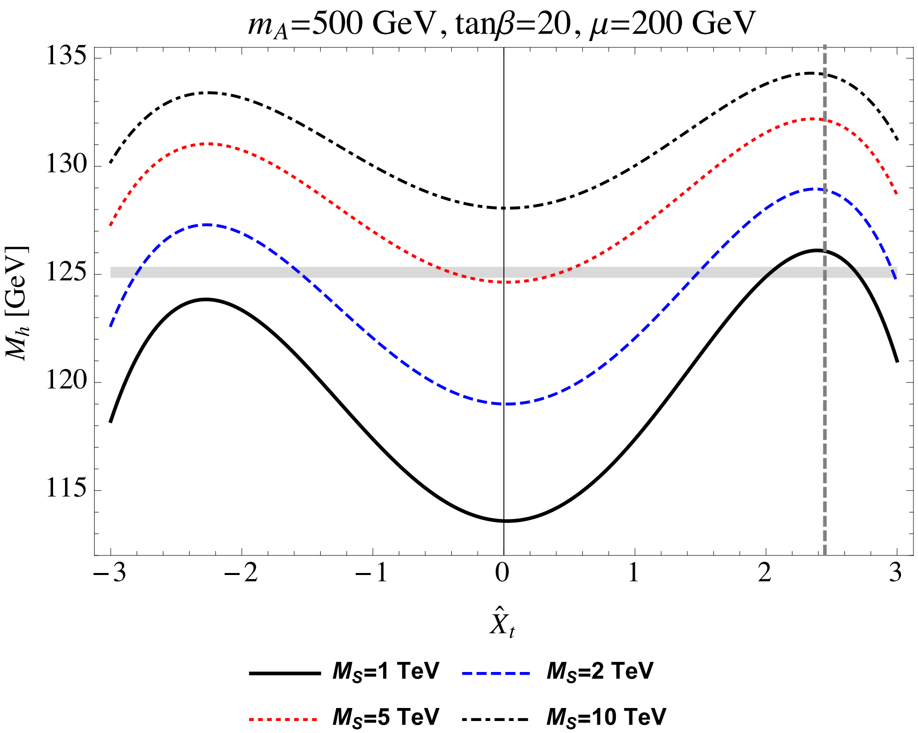
Carena, Espinosa, Quiros, C.W.'95,96

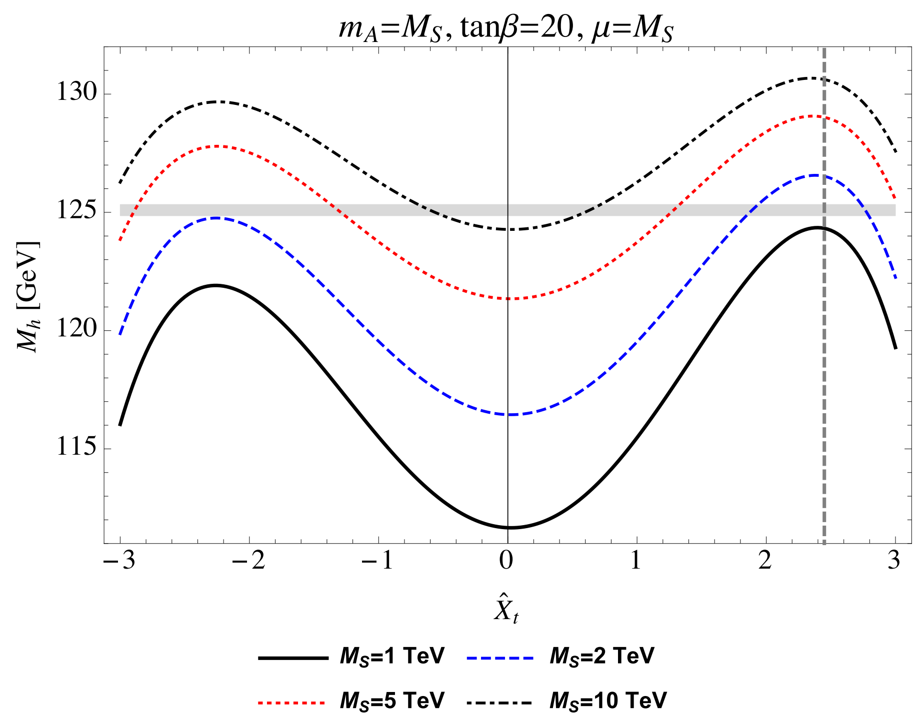
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

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

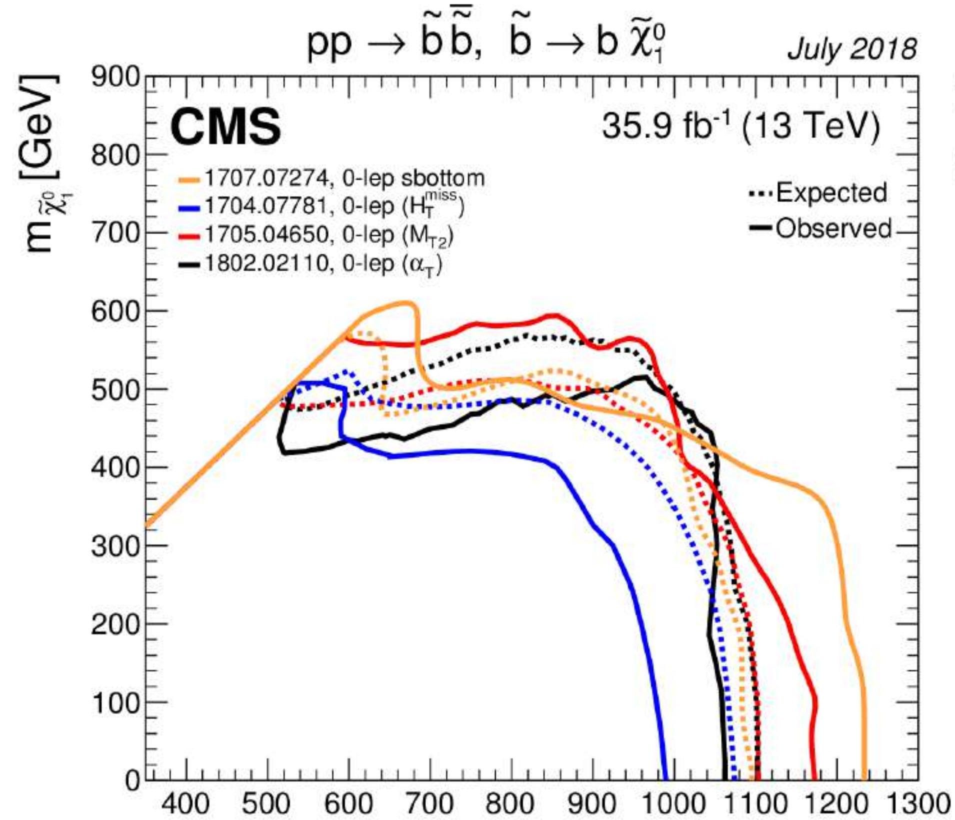


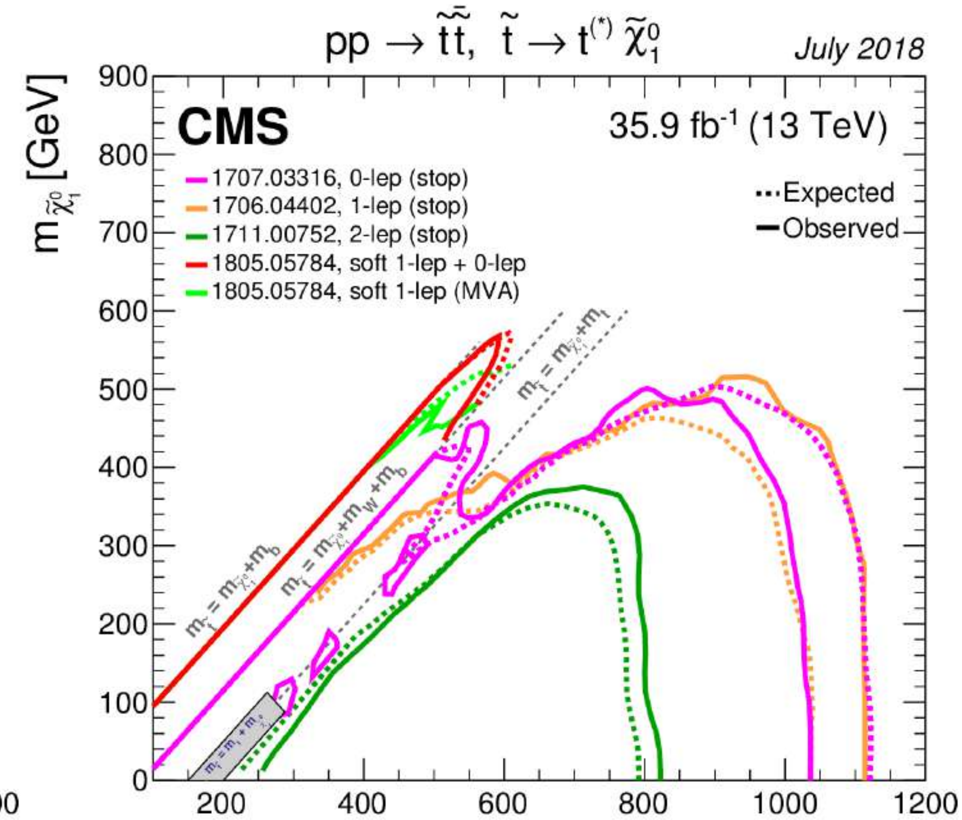


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

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

Stop-sbottom Searches





Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for bottoms and 550 GeV for stops. Islands in one search are apparently covered by other searches.

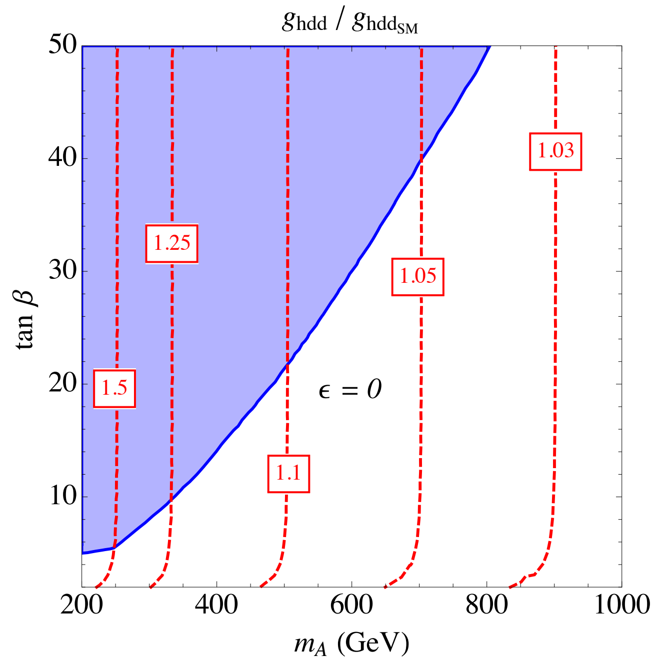
We are just starting to explore the mass region suggested by the Higgs mass determination !

Down Couplings in the MSSM for low values of μ

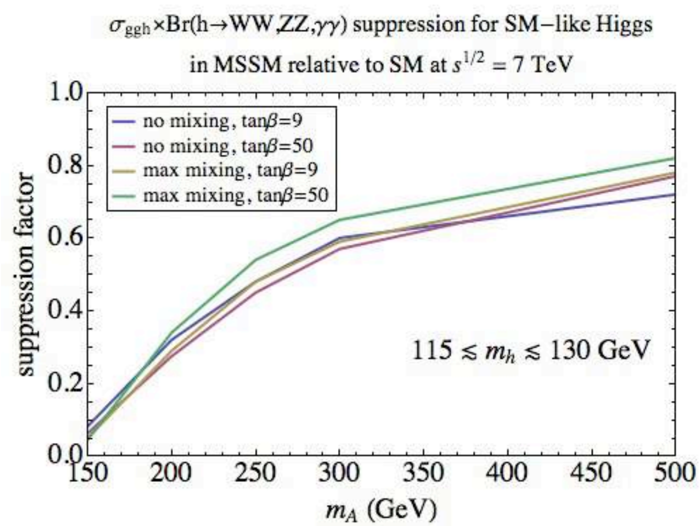
- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26 \qquad \lambda_7 \propto \frac{A_t \mu}{M_S^2}\left(1 - \frac{A_t^2}{6M_S^2}\right)$$

$$\lambda_2 \simeq \frac{M_Z^2}{v^2} + \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{A_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{A_t^2}{12 M_{\rm SUSY}^2}\right)\right]$$



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



All vector boson branching ratios suppressed by enhancement of the bottom decay width

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

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

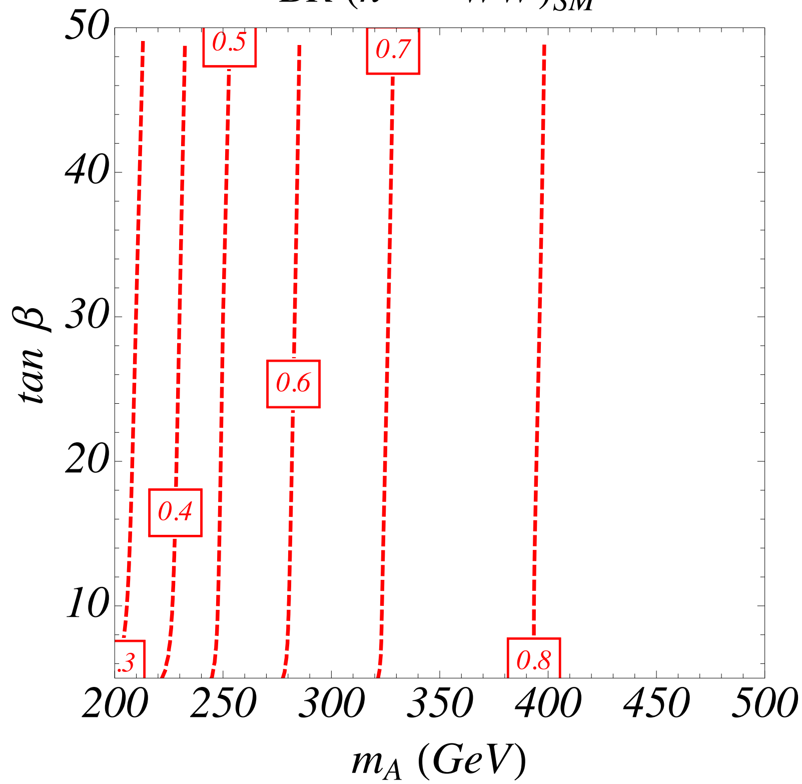
M. Carena, I. Low, N. Shah, C.W.' 13

Higgs Decay into Gauge Bosons

Mostly determined by the change of width

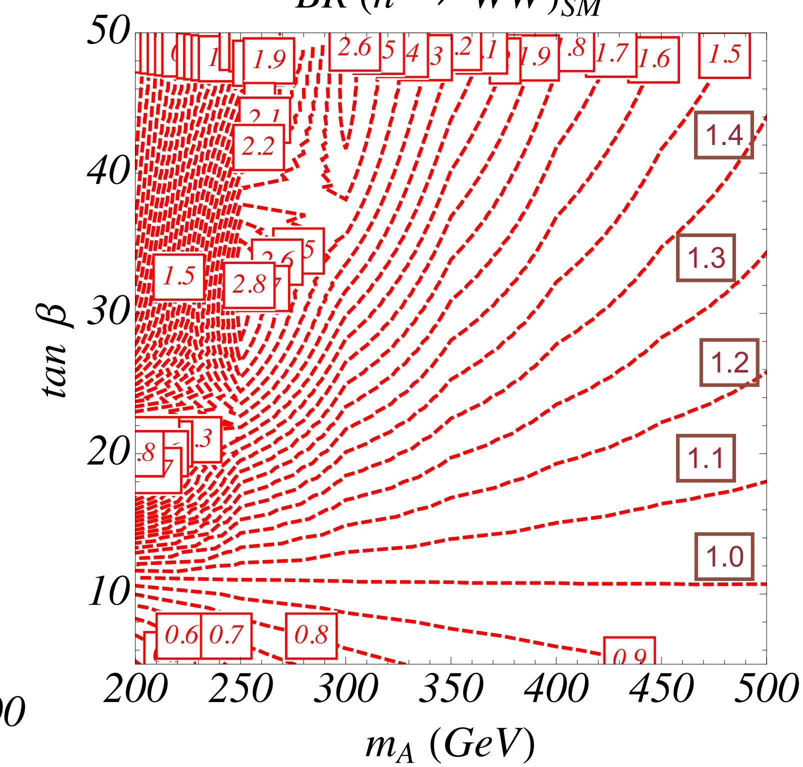
Small μ

$$\frac{BR(h \to WW)}{BR(h \to WW)_{SM}}$$



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

$$\frac{BR(h \to WW)}{BR(h \to WW)_{SM}}$$



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

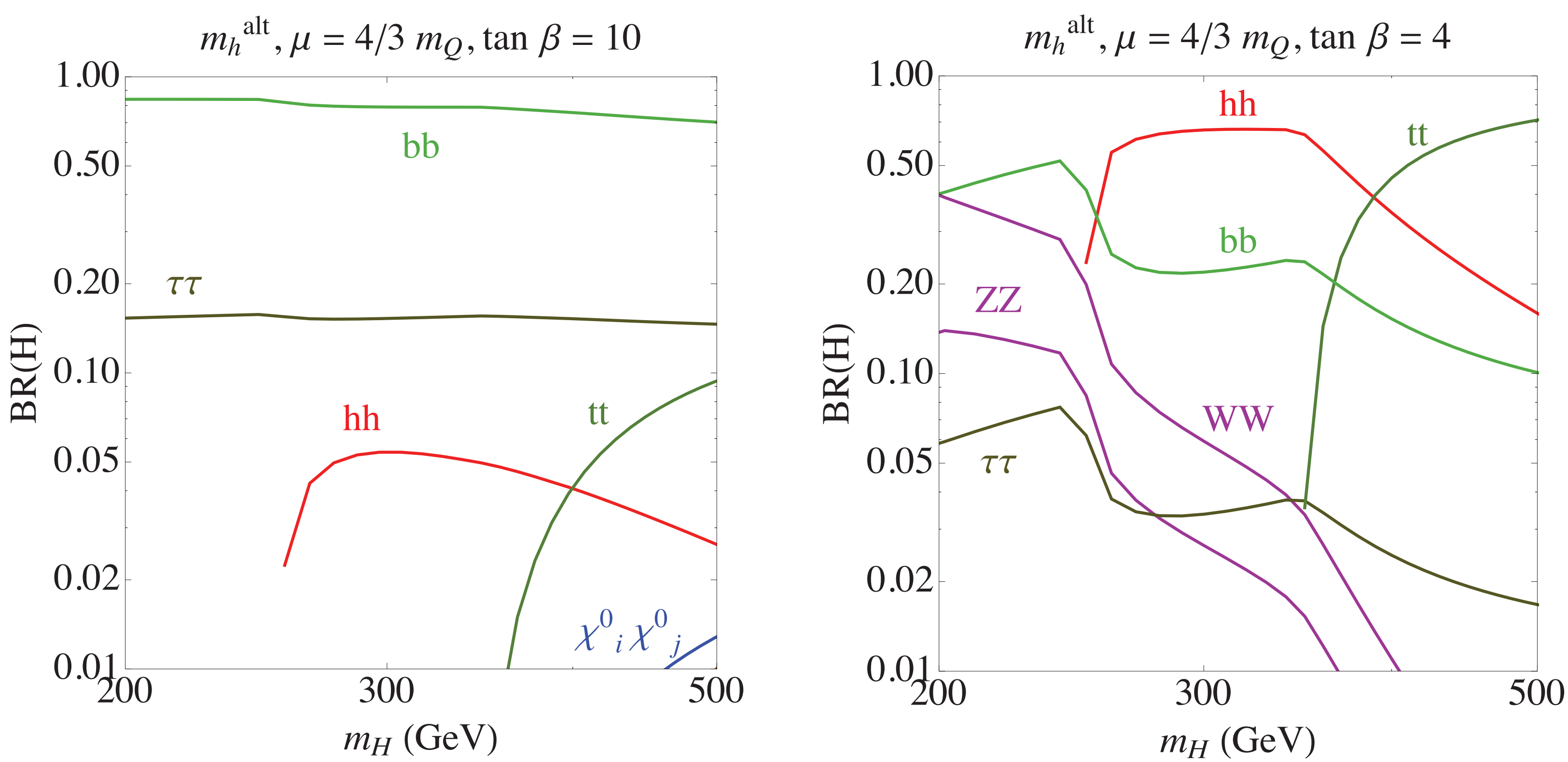
Heavy Supersymmetric Particles

Heavy Higgs Bosons : A variety of decay Branching Ratios

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

$m_h^{\rm alt}$: Large μ. Alignment at values of $\tan\beta \simeq 12$

Depending on the values of μ and tanβ different search strategies must be applied.

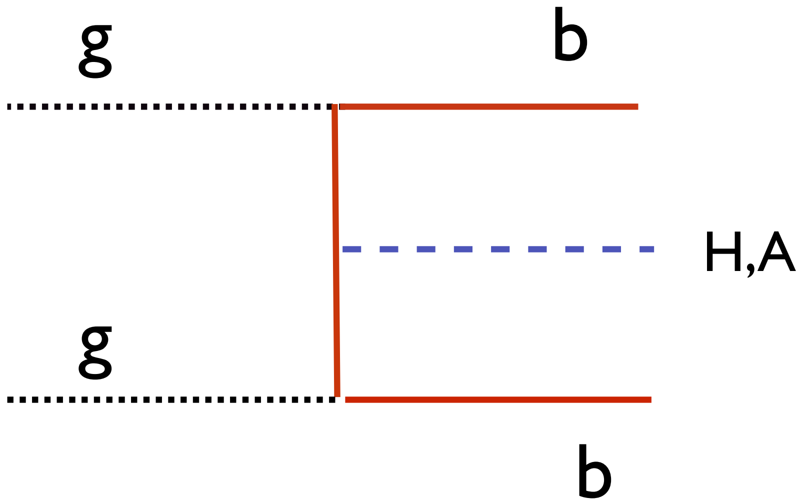


At large tanβ, bottom and tau decay modes dominant.

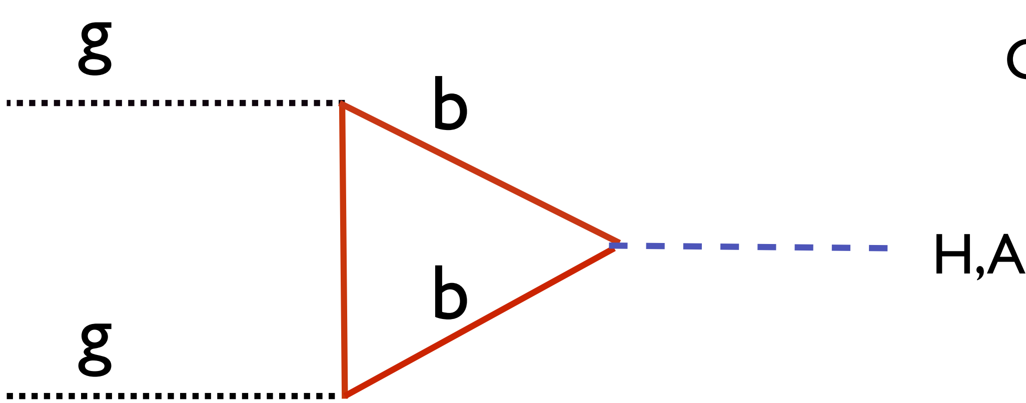
As tanβ decreases decays into SM-like Higgs and wek bosons become relevant

Non-Standard Higgs Production

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



Associated Production



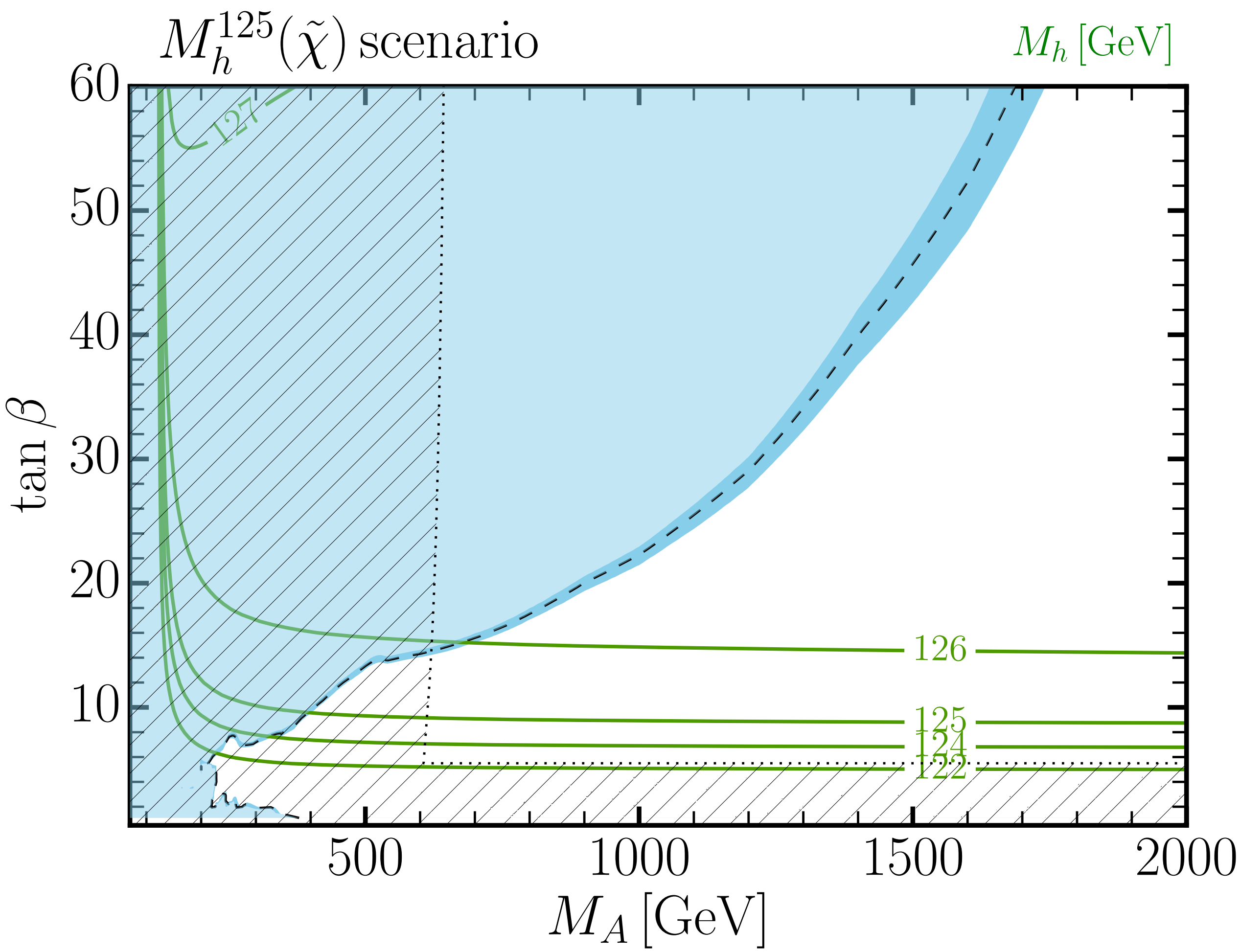
Gluon Fusion

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

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 NMSSM

see also Kang, Li, Li,Liu, Shu'13, Agashe,Cui,Franceschini'13, Delgado, Nardini, Quiros'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 λ_4)

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

$$\delta\tilde{\lambda}_3 = \lambda^2 \qquad \cos(\beta - \alpha) \simeq -M_S^2(1,2)/(m_H^2 - m_h^2)$$

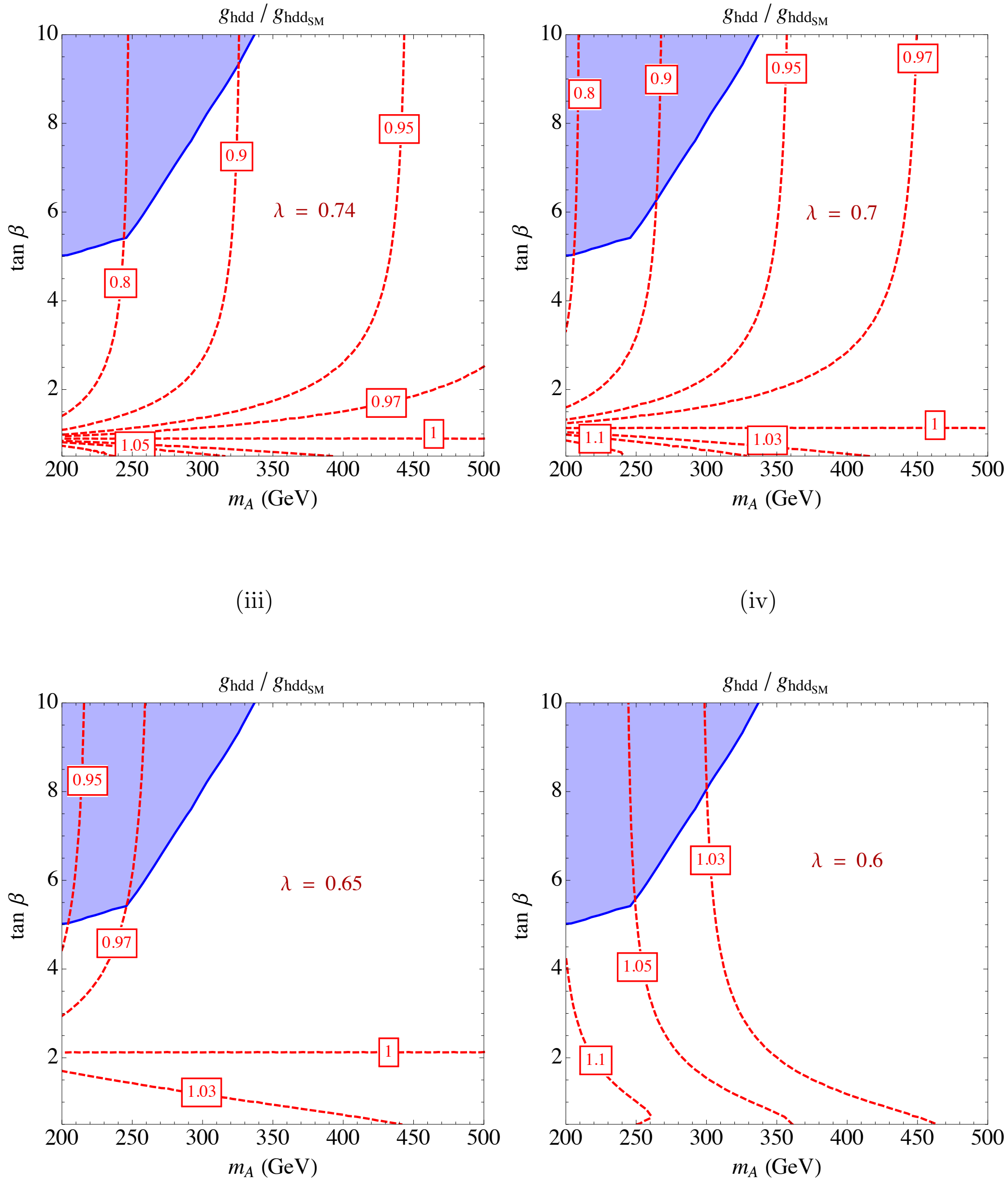
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- The values of λ 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



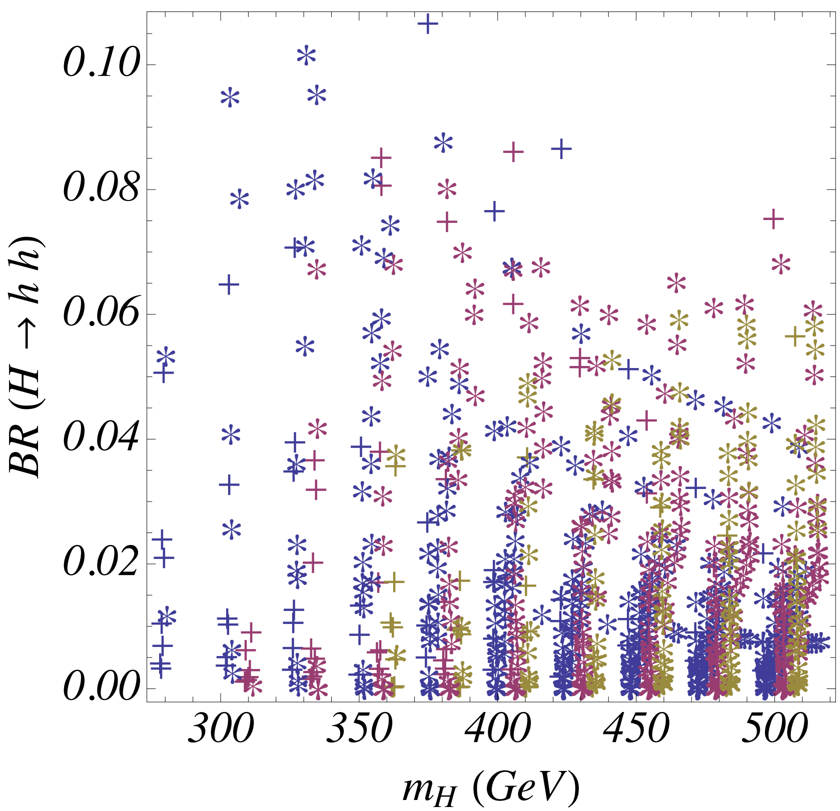
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided λ is about 0.65

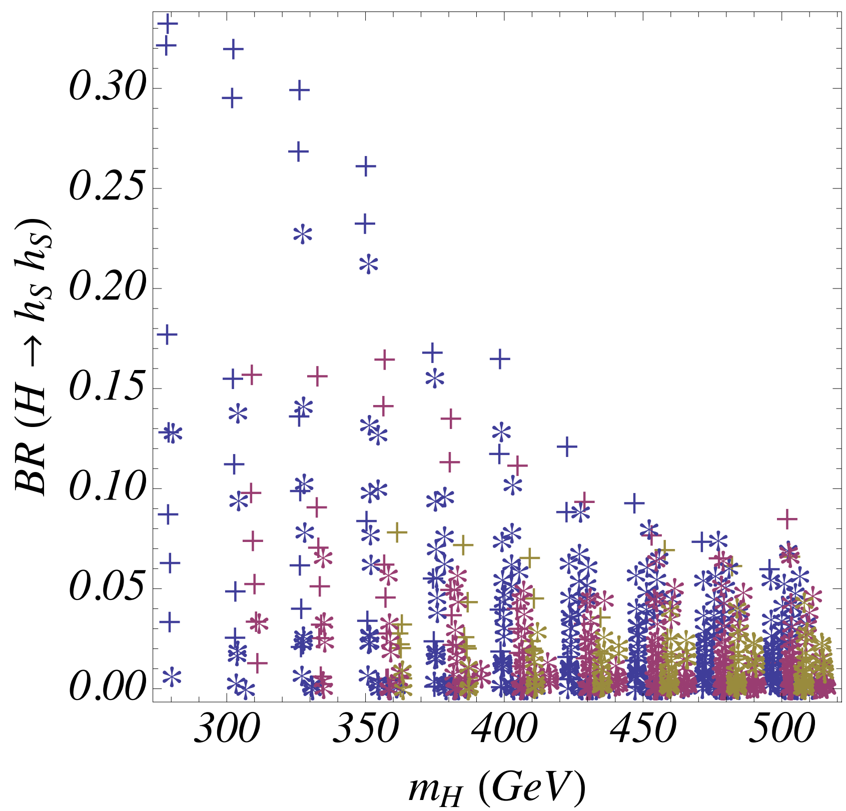
Decays into pairs of SM-like Higgs bosons suppressed by alignment

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: $\tan\beta = 3$





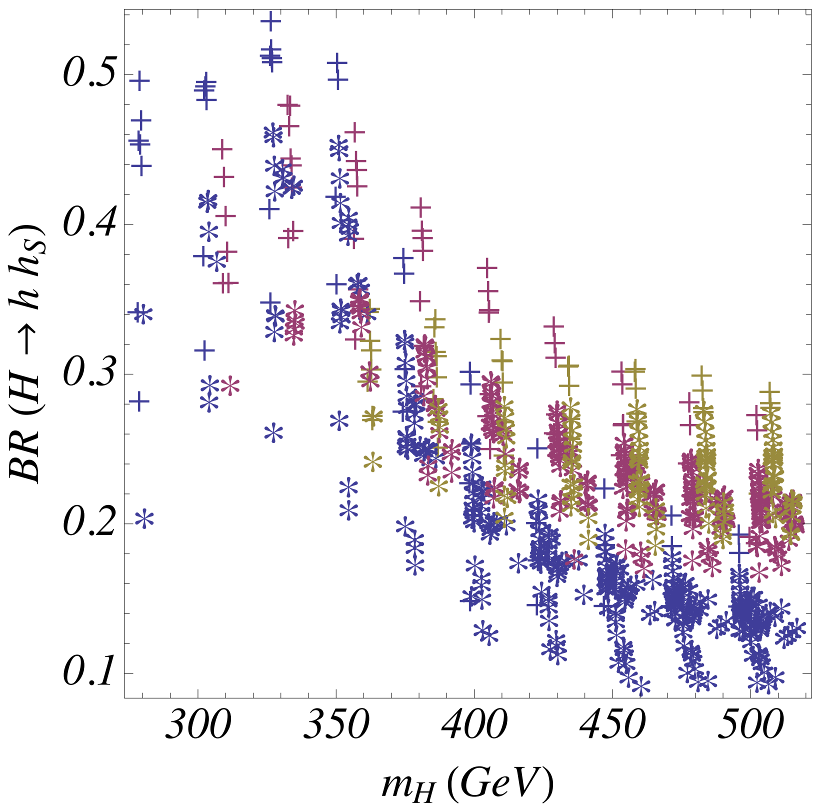
Significant decays of heavier Higgs Bosons into lighter ones and Z's

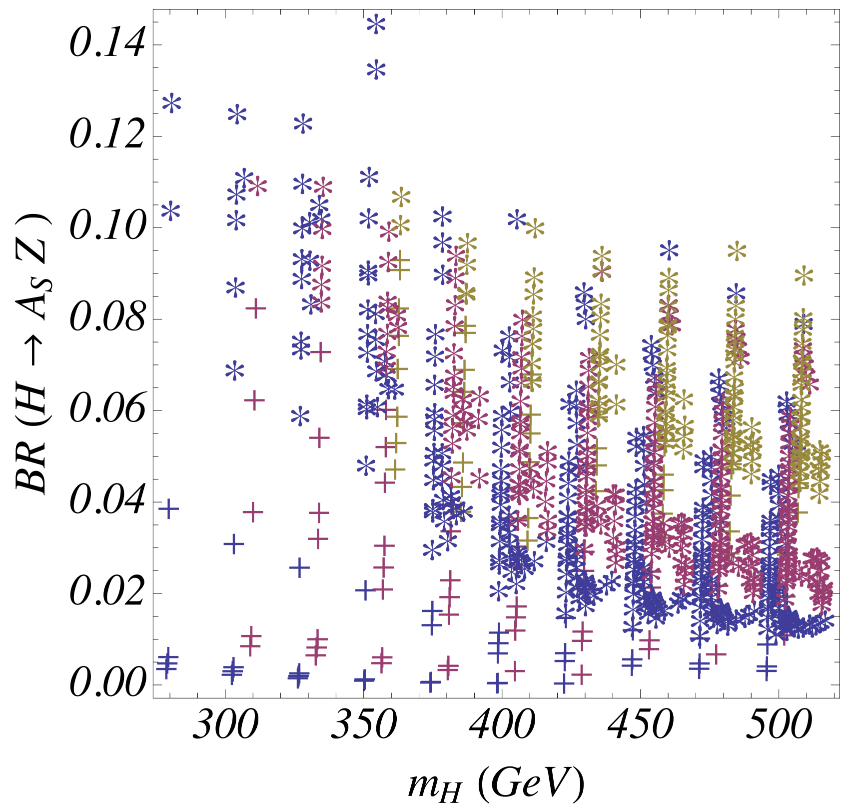
Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

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

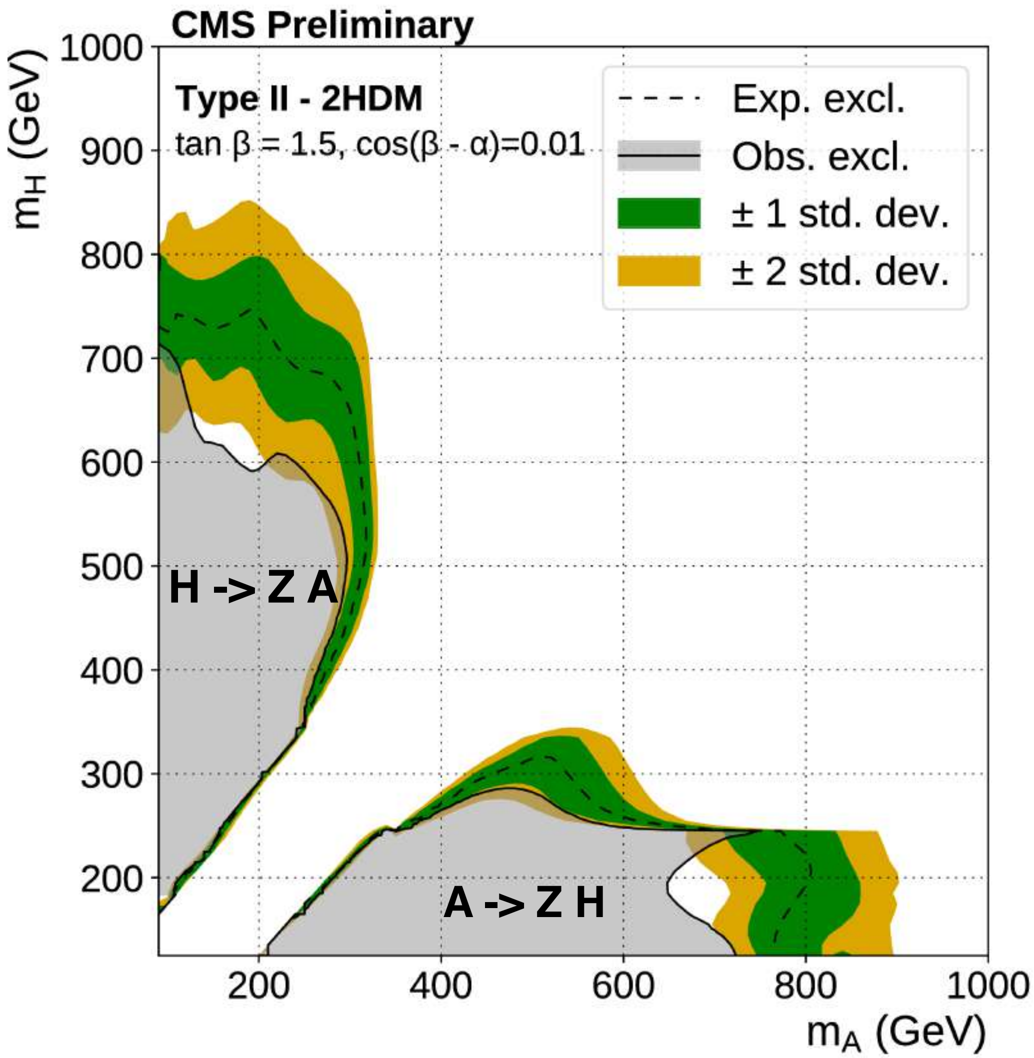
Carena, Haber, Low, Shah, C.W.'15





Search for (psudo-)scalars decaying into lighter ones

CMS-PAS-HIG-18-012

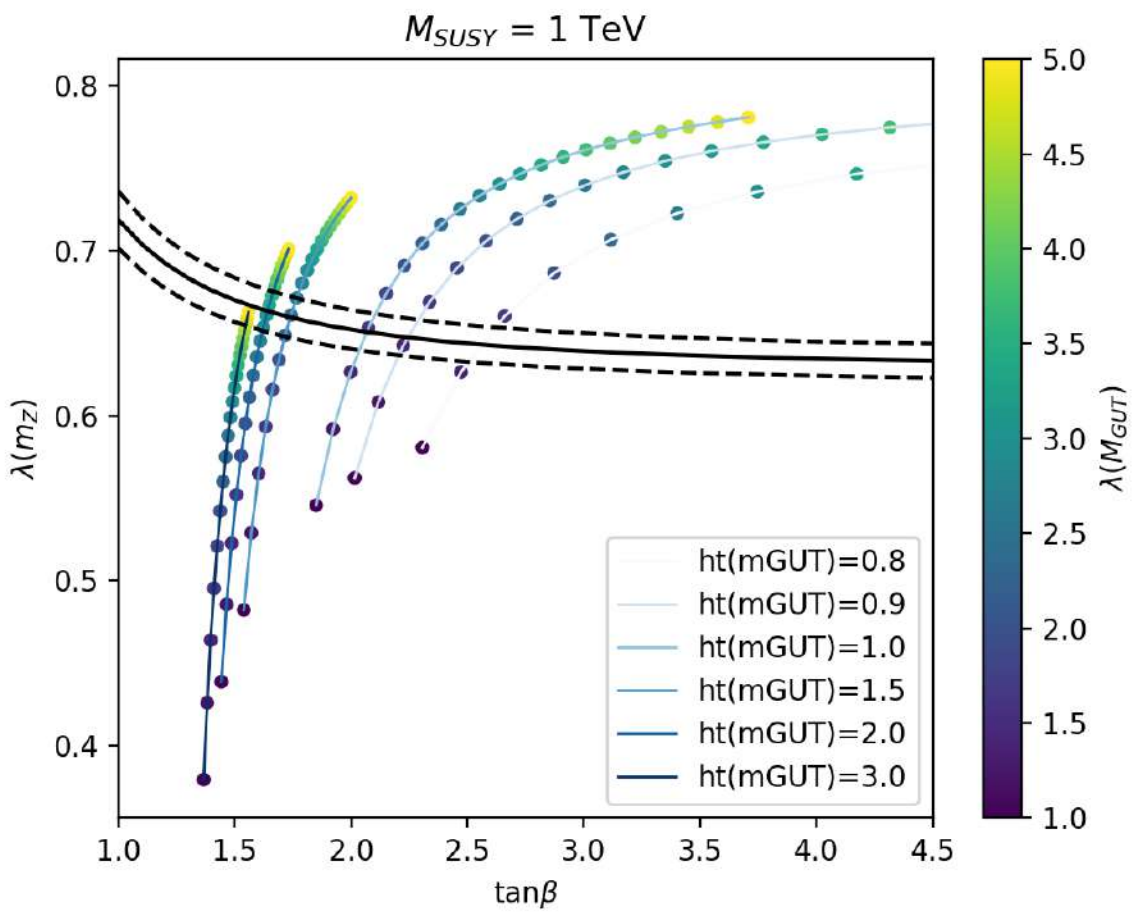


It is relevant to perform similar analyses replacing the Z by a SM Higgs (and changing the CP property of the Higgs)

Dynamical Alignment in the NMSSM

N. Coyle and C.W., to appear

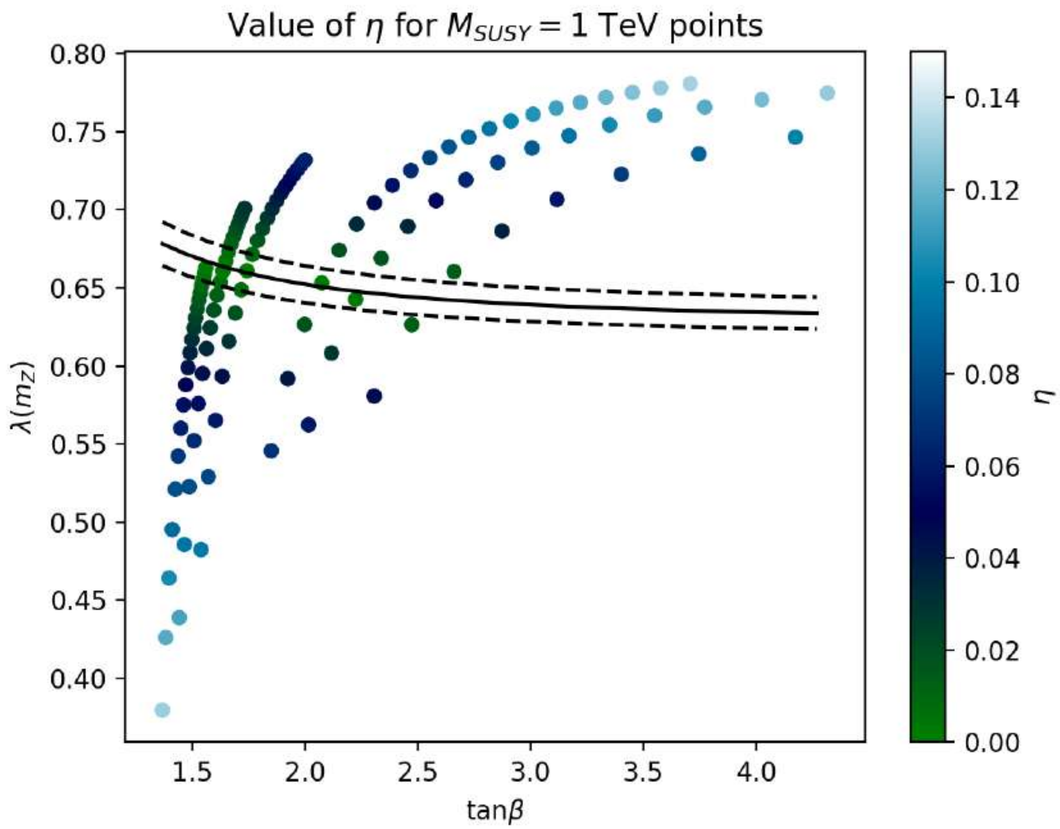
Alignment suggests large values of λ at the GUT scale



N. Coyle and C.W., to appear

Modification of the bottom Higgs coupling (Heavy Singlets)

Value of $m_A = 300$ GeV was assumed.
Values of $\eta \propto 1/m_A^2$.



Deviations from alignment pretty mild in the whole parameter space

N. Coyle, C.W. , to appear

Composite (Fat Higgs) Model

- Large values of λ suggest that the singlet is a composite, with a compositeness scale close to the GUT scale.

- One can construct a dynamical model, following Harnik et al,

$$W = ySST^1T^3 + y'S'T^3T^4 - mT^5T^6$$

- Assuming that the fields T are doublets of a strongly interacting SU(2) theory, one obtains

$$T^5T^6 = \frac{S\Lambda}{4\pi}, \qquad W = \lambda S H_u H_d + t_F S$$

$$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \propto \begin{pmatrix} T^1T^3 \\ T^2T^3 \end{pmatrix}, \qquad \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \propto \begin{pmatrix} T^1T^4 \\ T^2T^4 \end{pmatrix}$$

- A scalar tadpole is also obtained after supersymmetry breaking, making the singlet naturally heavier than the weak scale.

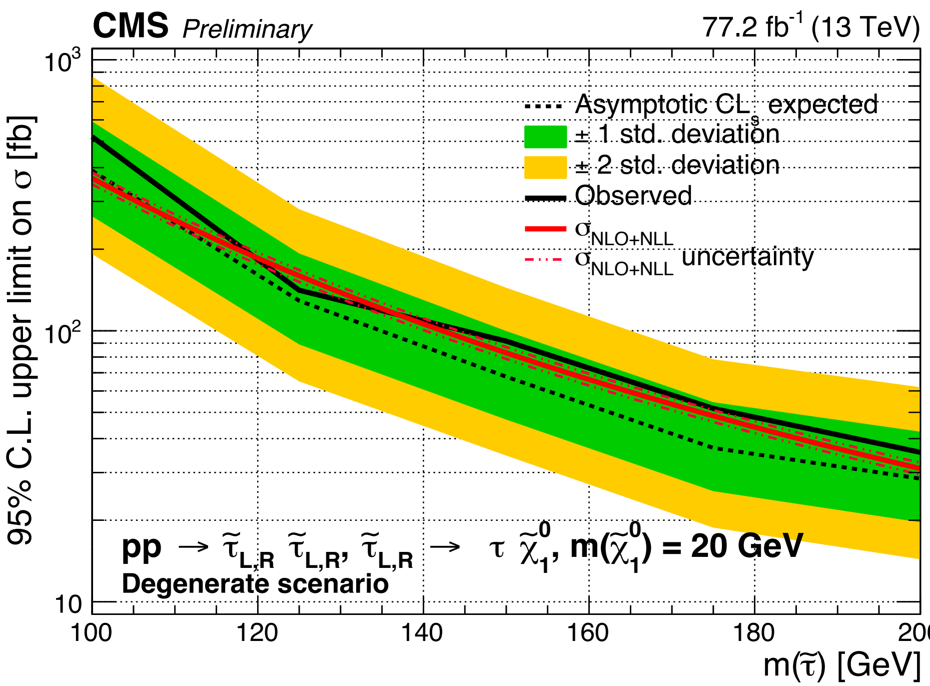
- The conditions of alignment may be then obtained dynamically from a composite model at scales of the order of the GUT scale.

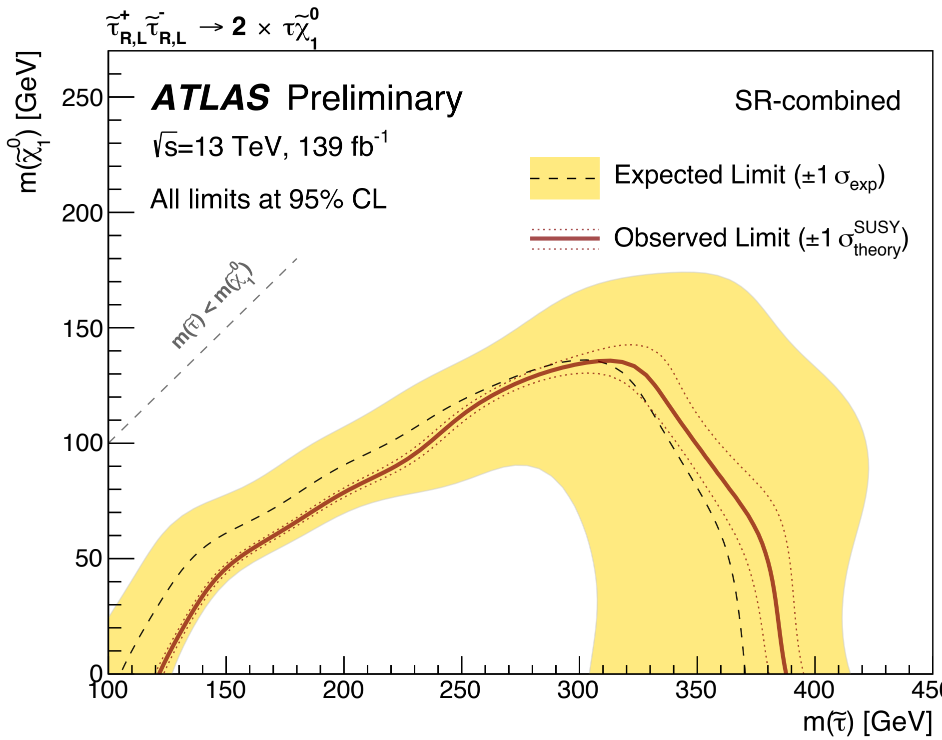
Dark Matter and
the SUSY Electroweak Sector

Searches for Electroweak Interacting Sparticles

- 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 $\quad + M_1$

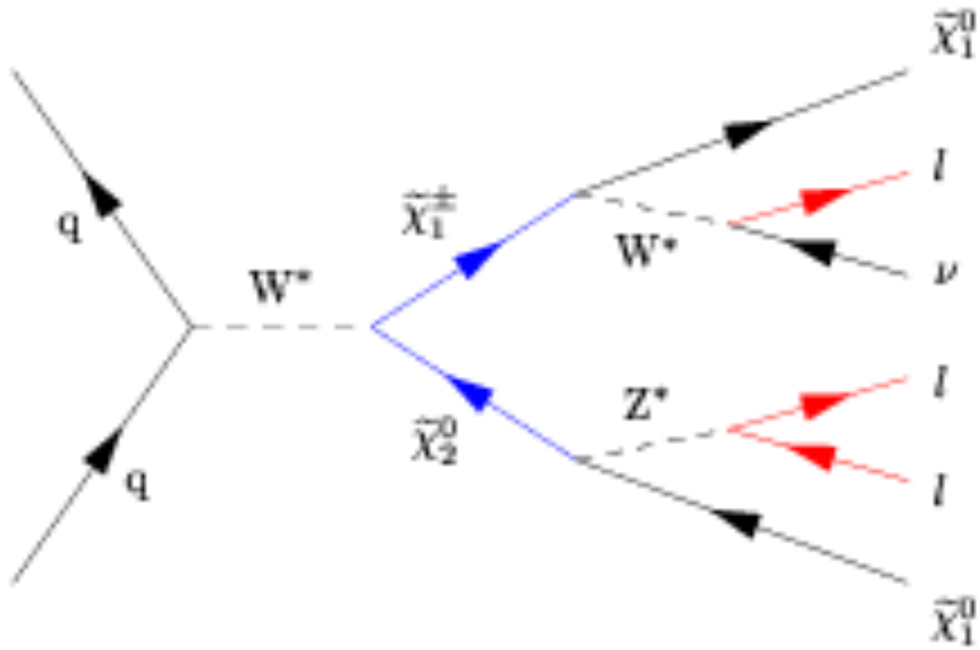
Φ_μ, Φ_1

CP phases

Expected to be among the lightest sparticles

⇨ A good starting point towards SUSY parameter determination

Chargino-Neutralino Production



- Winos, in the adjoint representation of SU(2), are produced at a stronger rate than Higgsinos.
- The cross section for Wino production is about a factor 4 larger than the one for Higgsino production.
- Mixing increases for smaller mass differences, leading to a reduction of the wino cross section.

Excess in Trilepton channel ?

Signal region	SR2ℓ_High	SR2ℓ_Med	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	0	1	19	11
Total background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$

Signal region	SR3ℓ_High	SR3ℓ_Med	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0

Low Effective Masses.
Low Masses/Mass Splittings
Compressed region/ISR jets

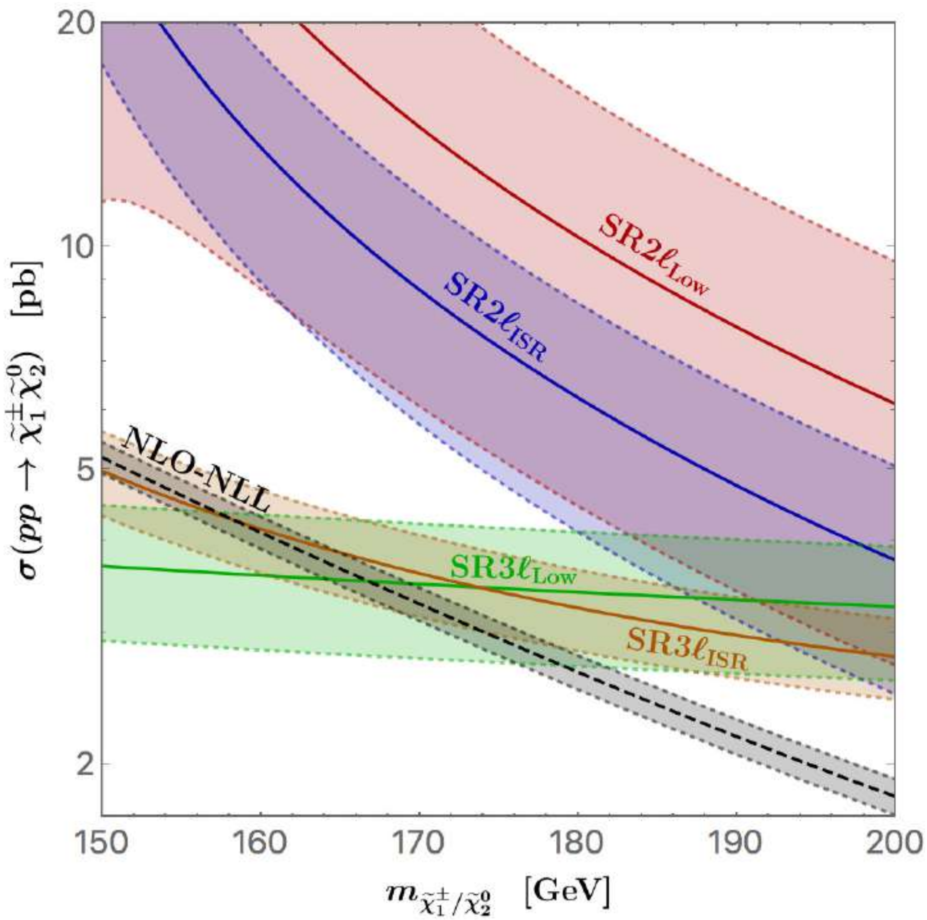
Cross Sections Consistent with Observed Excesses

Carena, Osborne, Shah, C.W. ‘18

Concentrated on the region consistent with 3-leptons plus missing energy that is the most sensitive one.

Masses of about 165 GeV and cross section of about 3pb.

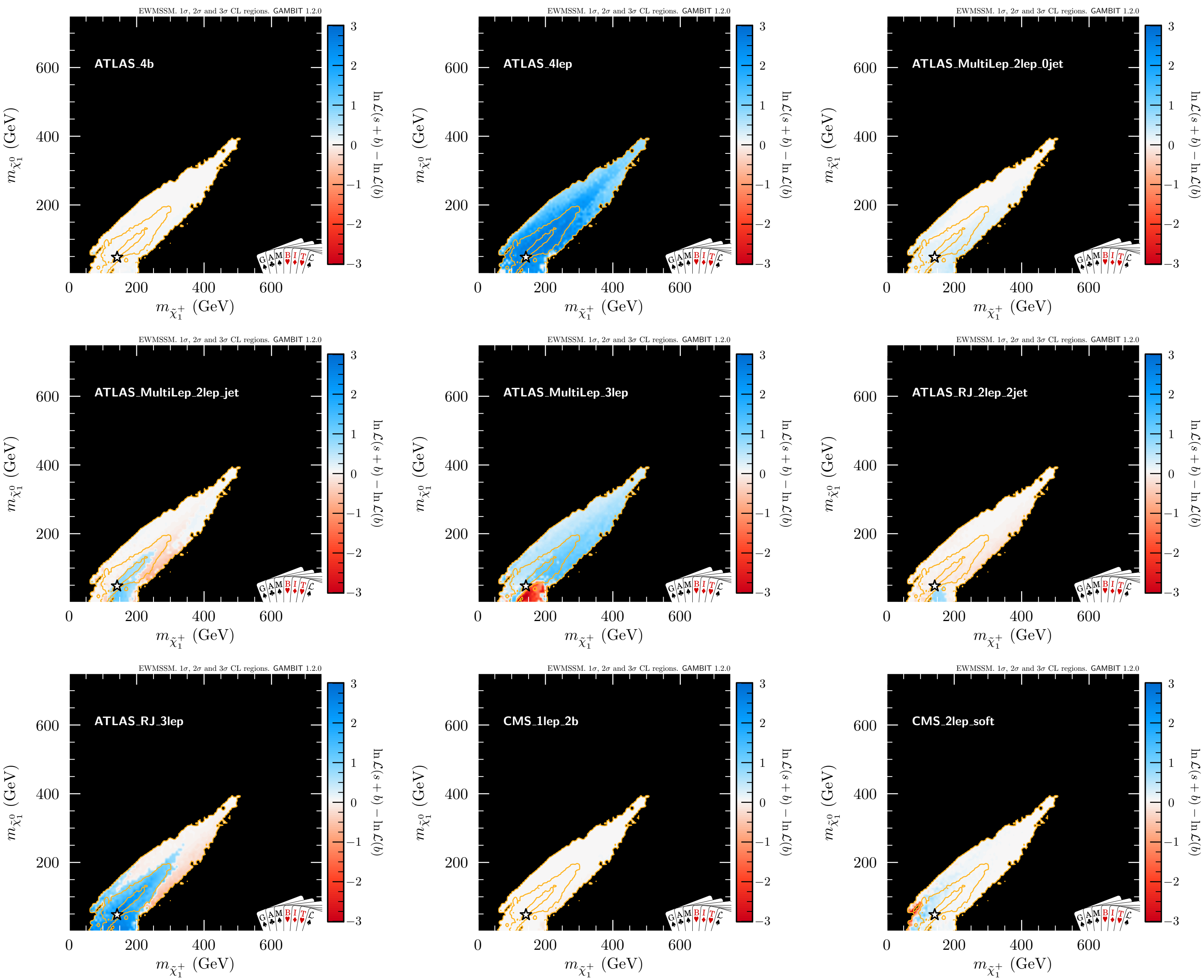
Additional region with masses of 200 GeV interesting, too.



Fit to the Data

RJR Optimized for region where
$m_{\tilde{\chi}_2} - m_{\tilde{\chi}_1} \simeq 100$ GeV

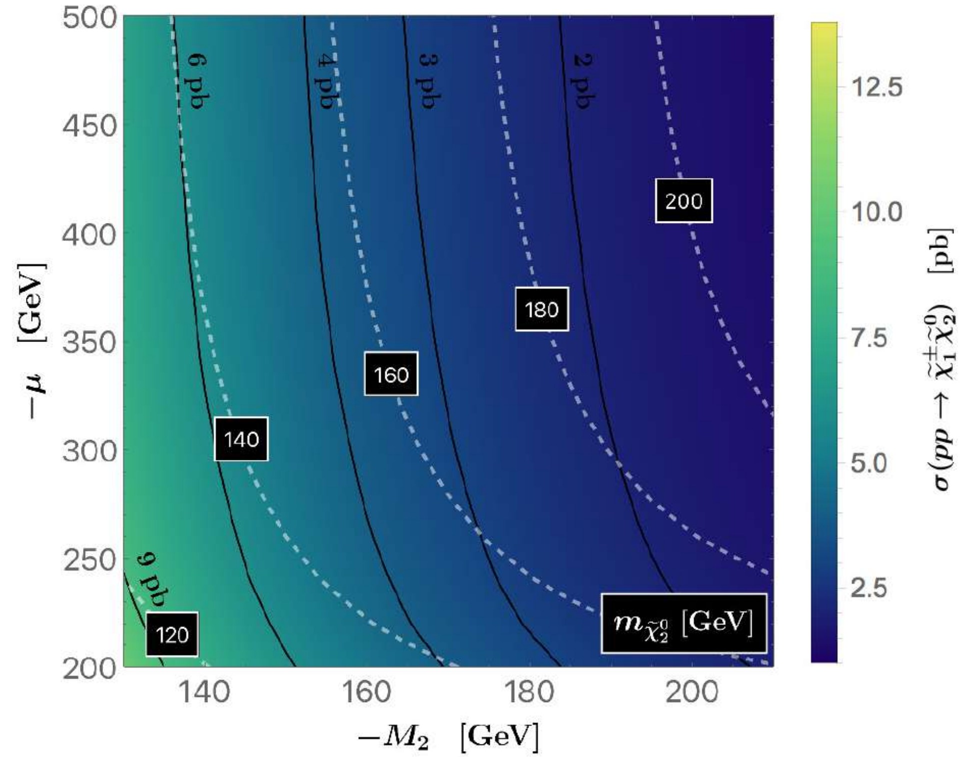
GAMBIT Collaboration,
arXiv:1807.03208, 1809.02097



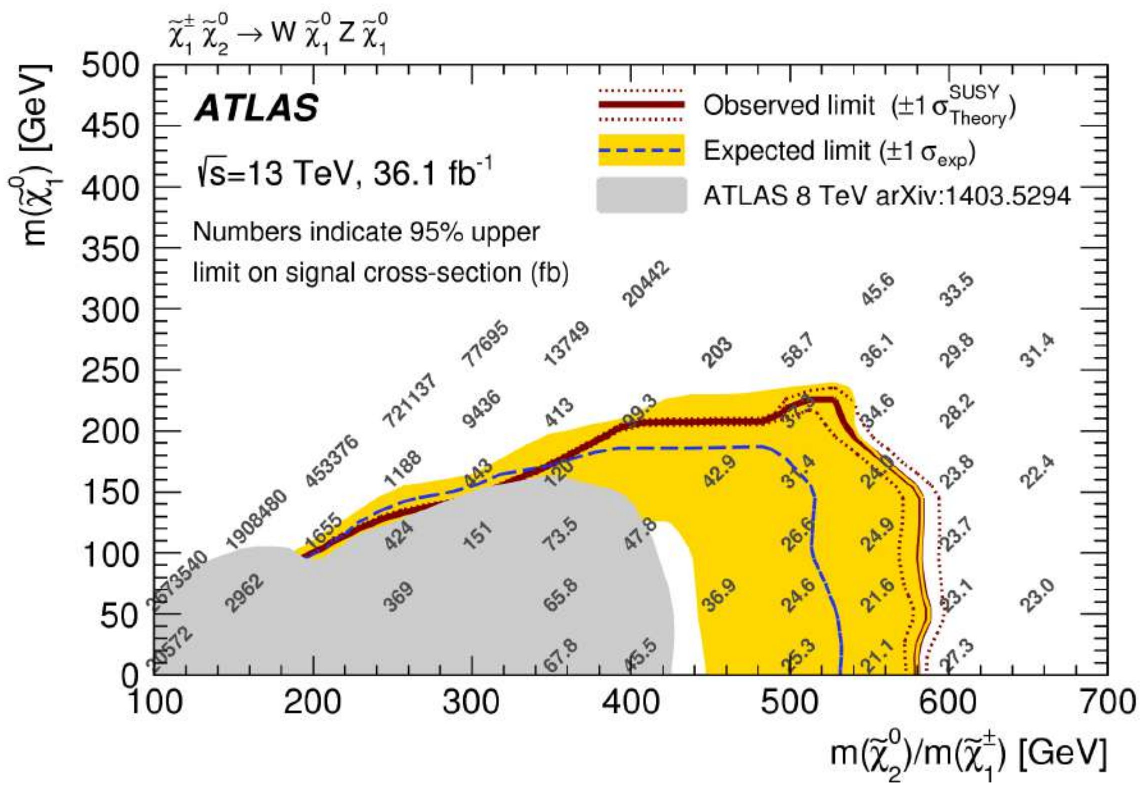
Claim that bounds from conventional searches become weaker once realistic spectrum is taken into account.

Carena, Osborne, Shah, C.W. ‘18

Comparison with Limits from Conventional Searches

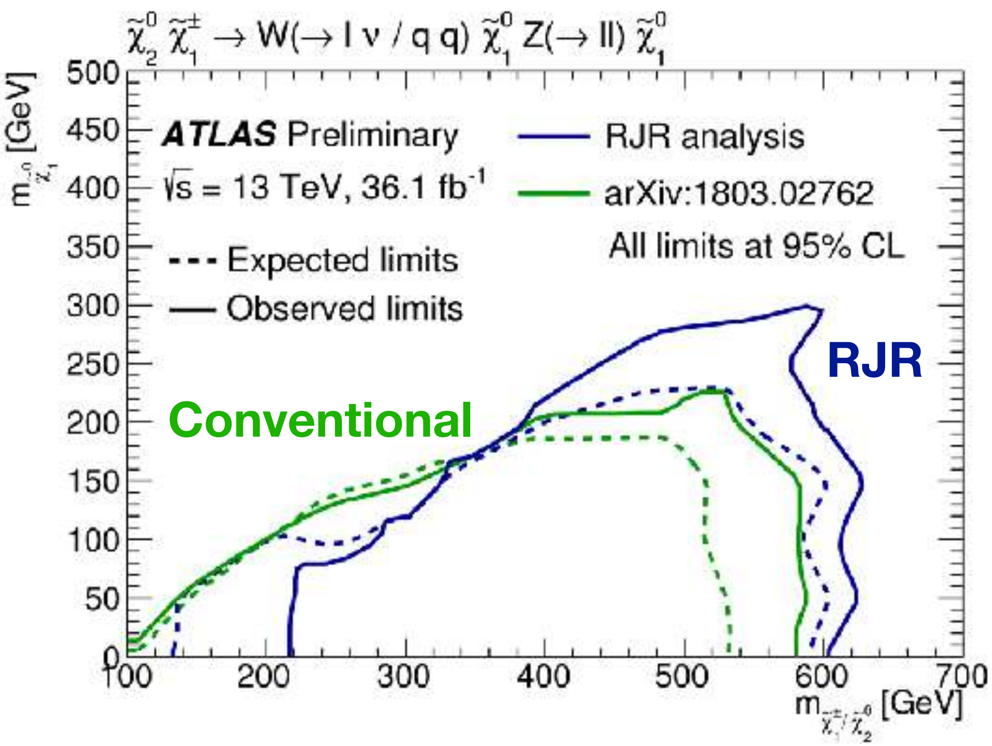


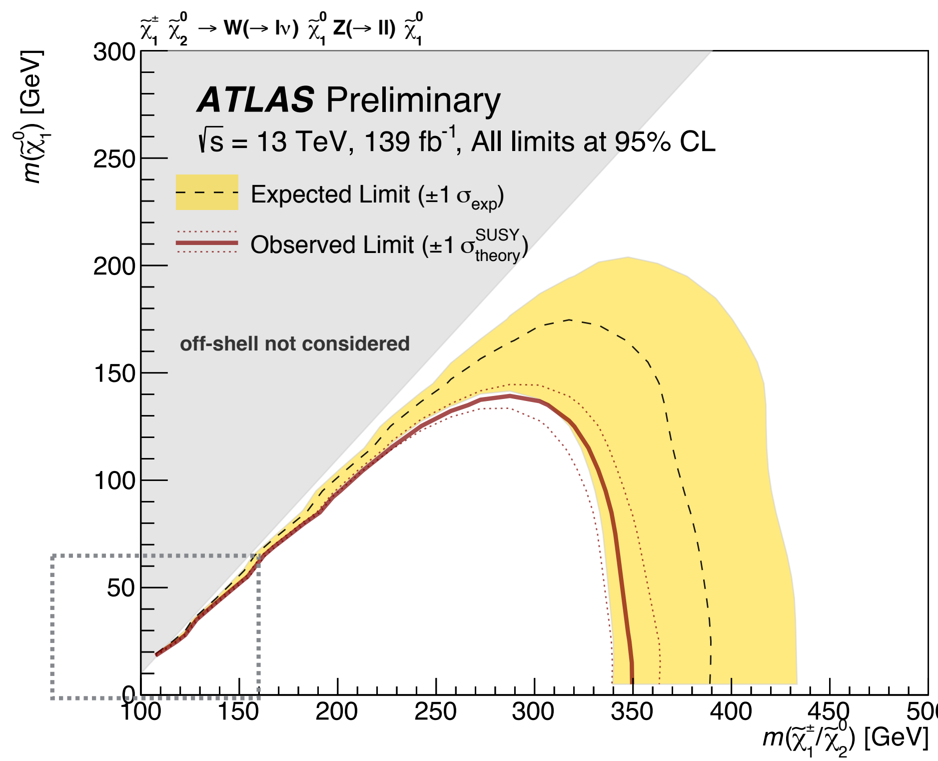
Chargino Masses of about 165 GeV and Neutralino Masses of about 65 GeV, with cross sections of about 3 pb are in marginal tension with conventional searches and lead to an explanation of the RJR excess within 1 standard deviation.



ATLAS-CONF-2019-020	SR-low	SR-ISR
Observed events	51	30
Fitted SM events	46 ± 5	23.0 ± 2.2

- **Emulated Recursive Jigsaw Reconstruction (eRJR)** confirmed the 3σ excess with 36 fb^{-1}, but **sees a reduction in excess significance with full 139 fb^{-1}**
- Low mass sensitivity now observes 1σ **excess of events** in signal regions designed for 3ℓ+ISR processes

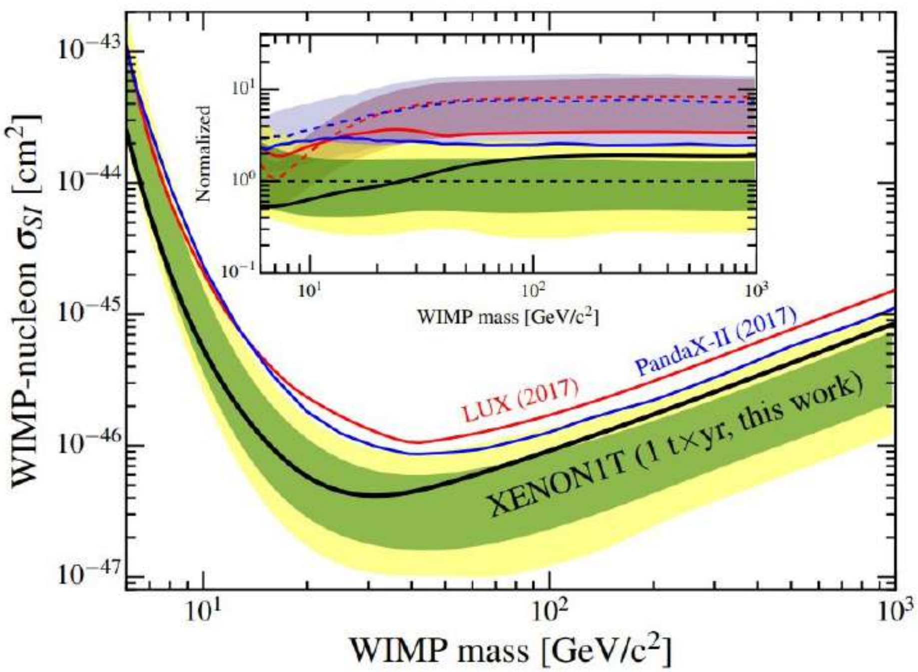


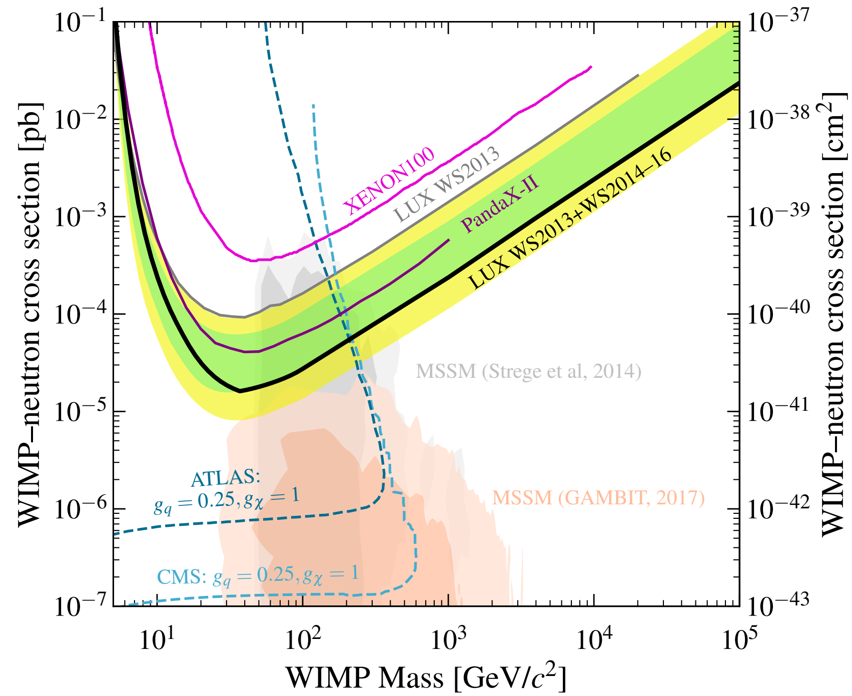


Region with mass difference of about 100 GeV not excluded, particularly due to Higgsino mixing. But if the RJR confirms these new limits…

Chargino/Neutralino Bounds/Signals disappear for large values of the Wino Mass

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 :

$$2\left(m_{\tilde\chi_1^0} + 2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2} + \frac{1}{2m_{\tilde Q}^2}\right)$$

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

$$m_{\tilde\chi^0} \simeq M_1$$

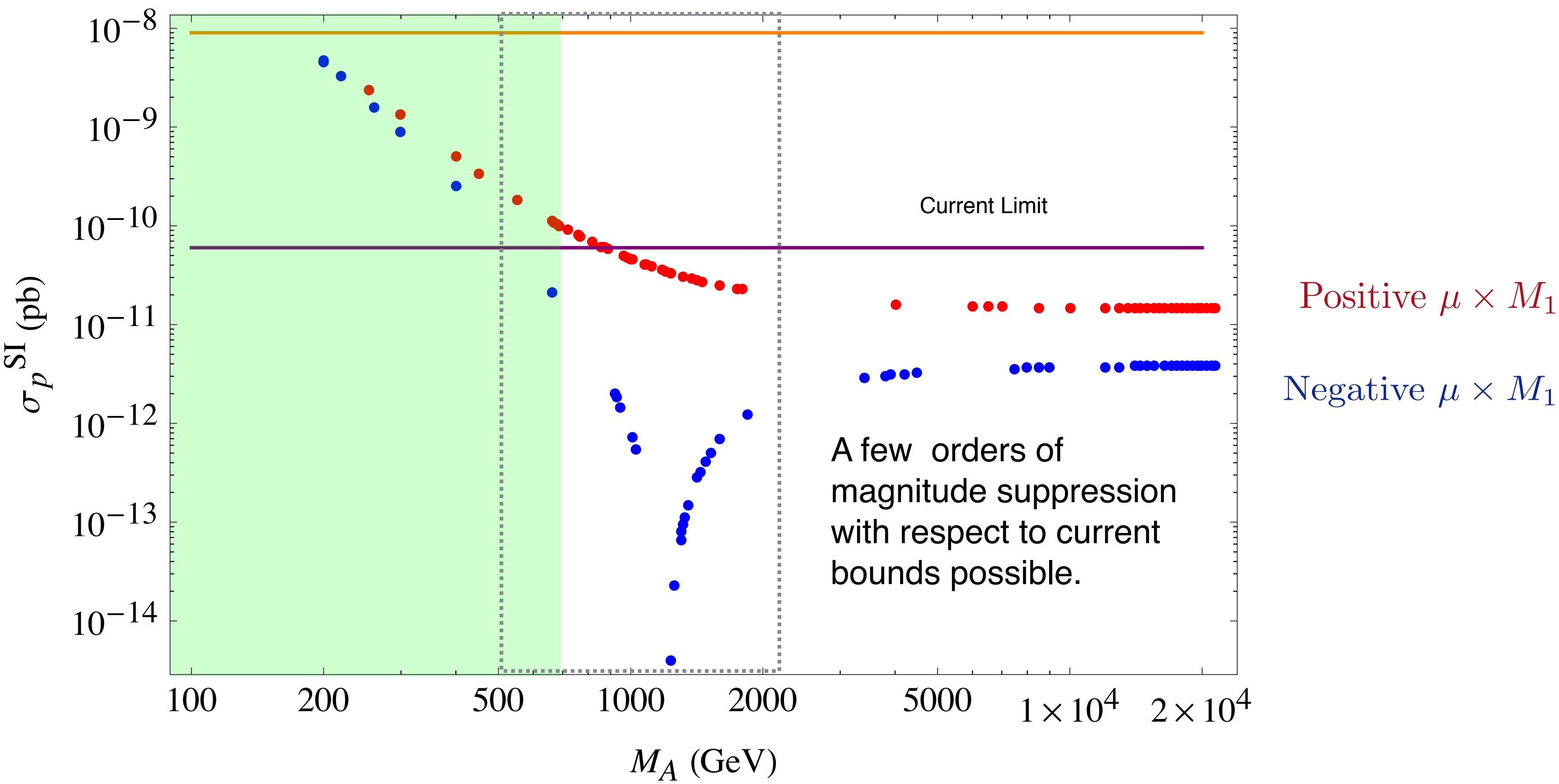
Cheung, Hall, Pinner, Ruderman'12, Huang, C.W.'14, Cheung, Papucci, Shah, Stanford,Zurek'14, Han,Liu,Mukhopadhyay,Wang'18

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

Blind Spots in the Spin-Independent Cross Section

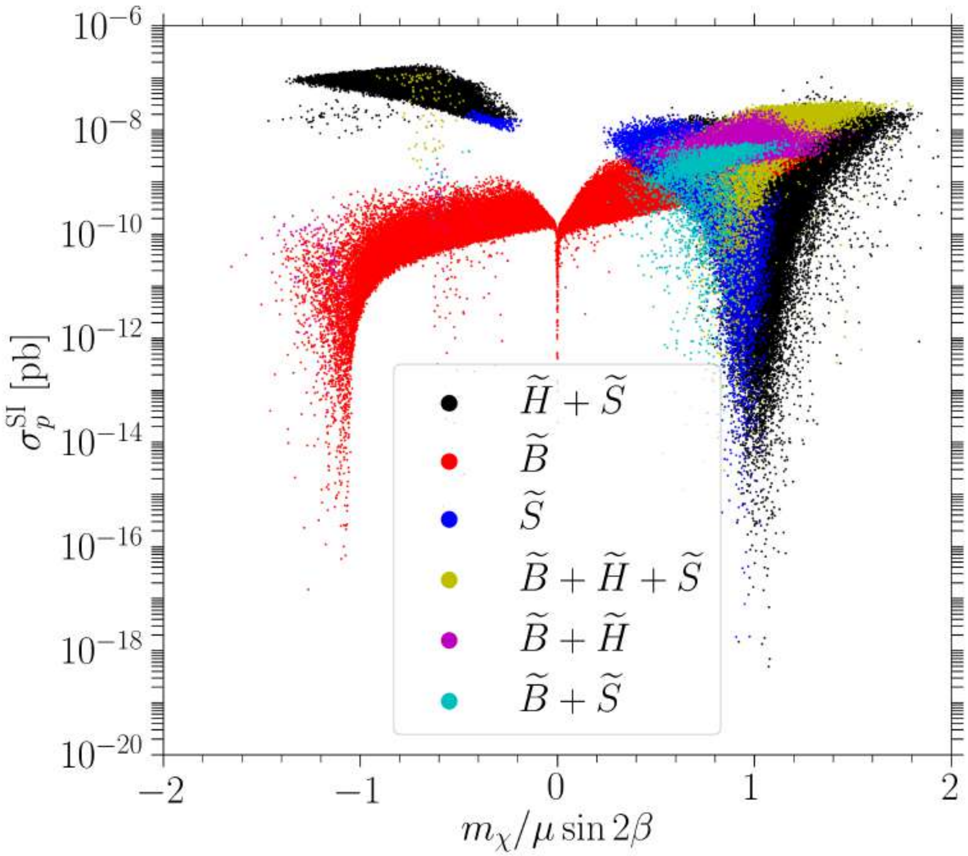
C. Cheung, L. Hall, D. Pinner, J. Ruderman'12
P. Huang, C.W.'14
P. Huang, R. Roglans, D. Spiegel, Y. Sun, C.W.'17
C. Cheung, D. Sanford, M. Papucci, N.R. Shah, K. Zurek '14
S. Baum, M. Carena, N.R. Shah, S. Baum '18

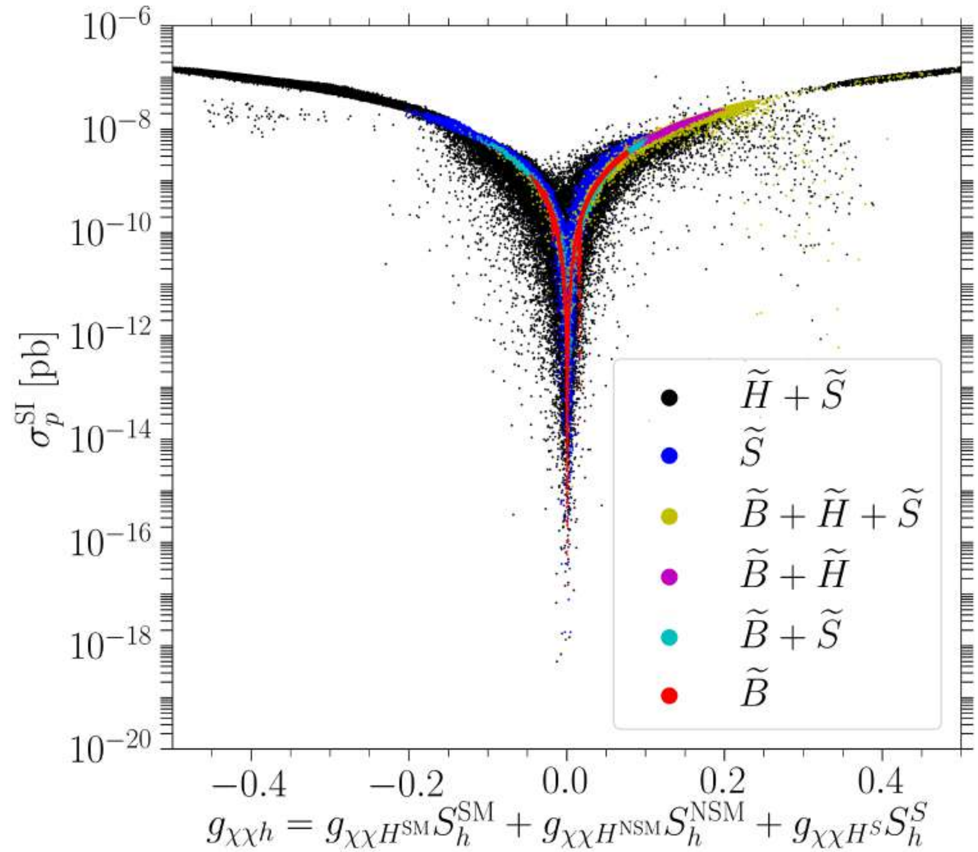
$\tan\beta = 30, \quad \mu = \pm M_1, \quad M_1 \simeq 60\ GeV$



S. Baum, M. Carena, N. Shah, C.W.'18

NMSSM
Lower values of tanβ



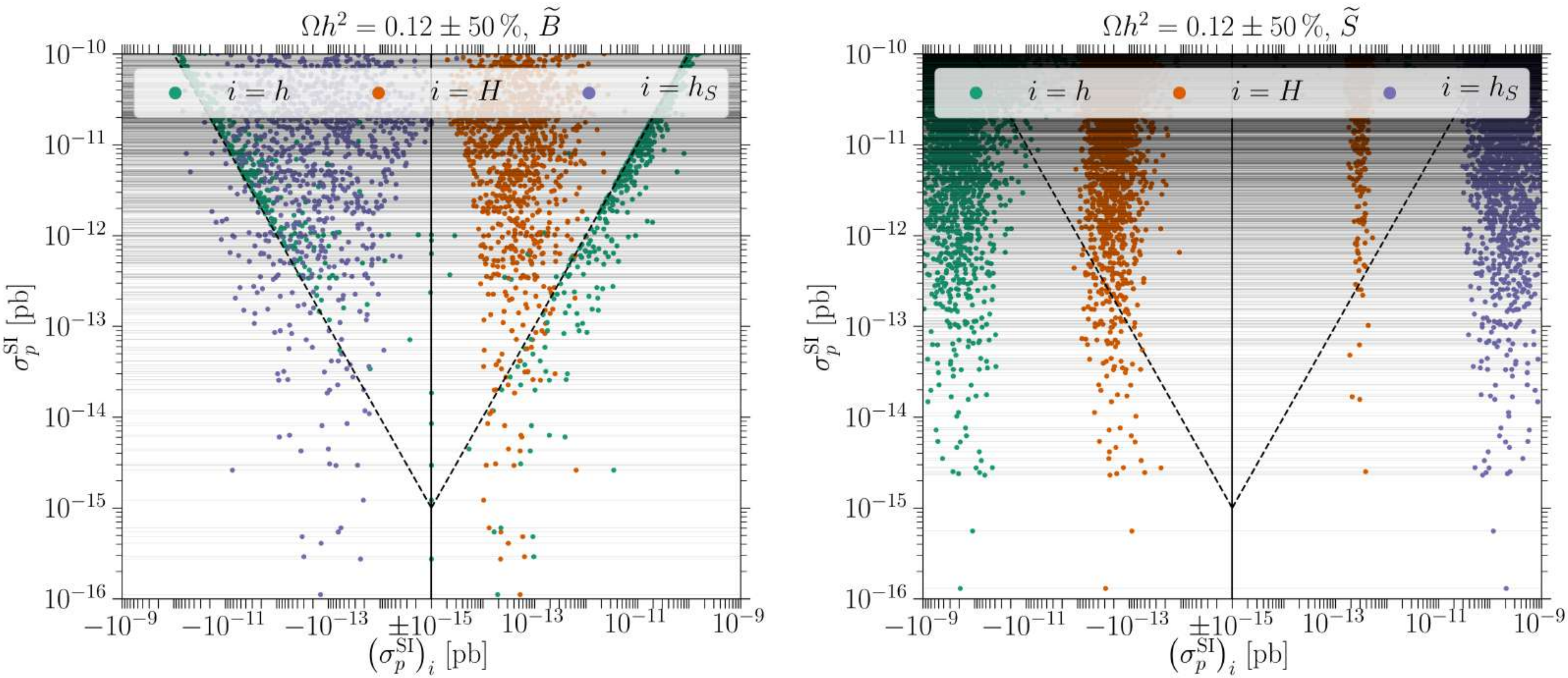


Cancellation of the coupling of DM to the SM-Higgs bosons

$$m_\chi = \pm\mu \sin 2\beta$$

S. Baum, M. Carena, N. Shah, C.W.'18

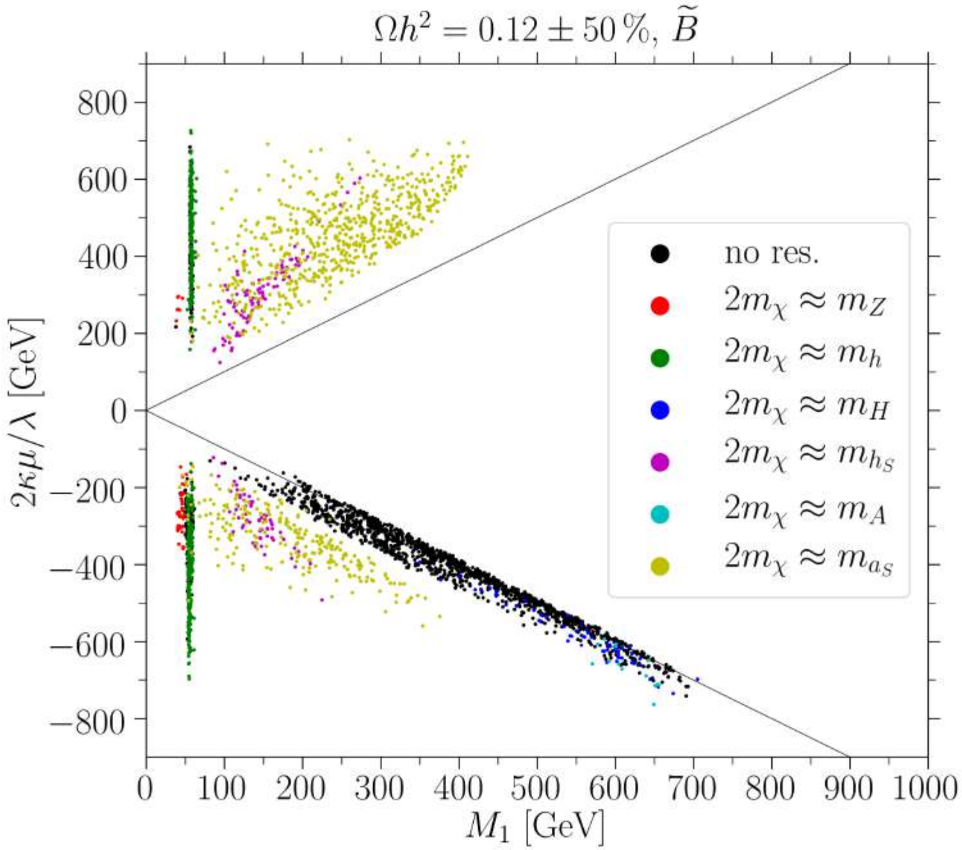
Contribution of each scalar to the SI Cross Section (with amplitude sign)

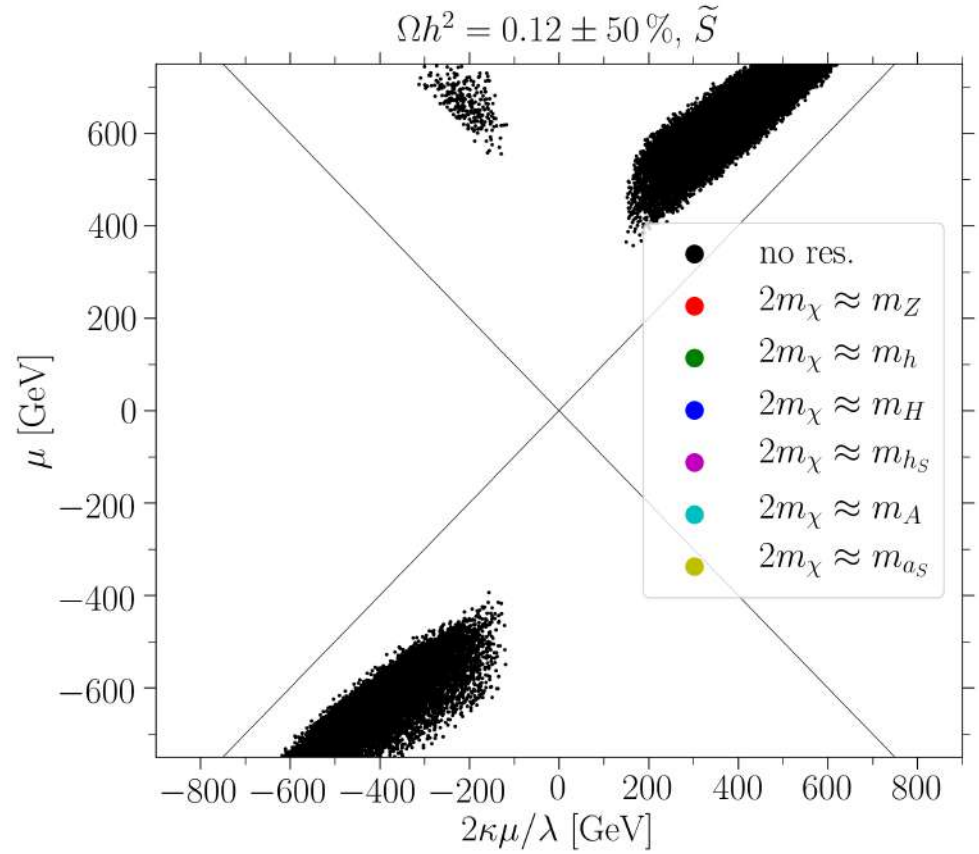


Interference quite significant in the Singlino case. Less so in the Bino case.

S. Baum, M. Carena, N. Shah, C.W.'18

Relic Density





Proper relic density obtain, in the Bino case, by either resonant annihilation or by co-annihilation with the singlino.

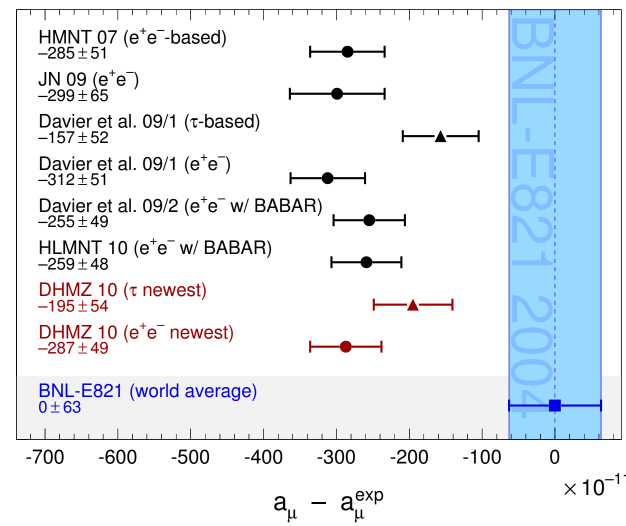
New Well-tempered Bino-Singlino scenario.

Muon Anomalous Magnetic Moment

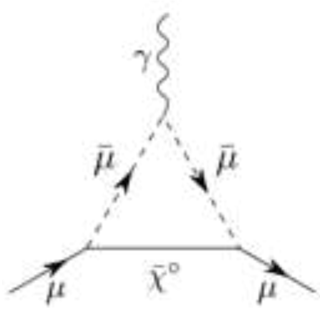
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

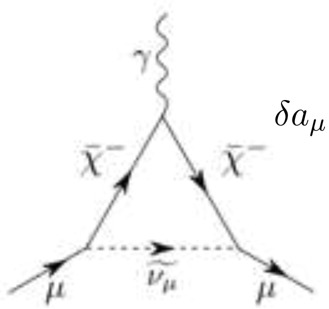
$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm theory} = 268(63)(43) \times 10^{-11}$$

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.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

Benchmark Point

Carena, Osborne, Shah, C.W. '18

$$\text{Blind Spots}: \mu \times M_1 < 0$$
$$(g-2)_\mu : \mu \times M_2 > 0$$

$\tan\beta = 20$

Param.	[GeV]	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
μ	-300	M_2	-172	$M_{\tilde{L}}$	400	M_H	1500
M_1	63.5	M_3	2000	$M_{\tilde{Q}}$	2000	A_t	3000

Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	125.84	$\tilde{\chi}_1^\pm$	165.0	$\tilde{\nu}_e$	395.0	$\tilde{u}_R$	2069.8
H	1500.03	$\tilde{\chi}_2^\pm$	333.6	$\tilde{\nu}_\mu$	395.0	$\tilde{u}_L$	2069.5
H_3	1500.00	$\tilde{\tau}_1$	389.5	$\tilde{\nu}_\tau$	395.0	$\tilde{d}_R$	2070.3
$H^\pm$	1502.38	$\tilde{\tau}_2$	415.0	$\tilde{g}$	2129.2	$\tilde{d}_L$	2071.0
$\tilde{\chi}_1^0$	61.7	$\tilde{e}_R$	402.4	$\tilde{t}_1$	1927.7	$\tilde{s}_R$	2070.3
$\tilde{\chi}_2^0$	164.8	$\tilde{e}_L$	402.6	$\tilde{t}_2$	2131.6	$\tilde{s}_L$	2071.0
$\tilde{\chi}_3^0$	314.2	$\tilde{\mu}_R$	402.4	$\tilde{b}_1$	2067.1	$\tilde{c}_R$	2069.8
$\tilde{\chi}_4^0$	331.2	$\tilde{\mu}_L$	402.6	$\tilde{b}_2$	2074.1	$\tilde{c}_L$	2069.5

$\sigma(pp \to \chi_1^\pm \chi_2^0) = 2.92 \text{ pb}$

$\Omega_{\rm CDM} h^2 = 0.121$

$a_\mu^{\rm MSSM} = 248 \times 10^{-11}\,.$

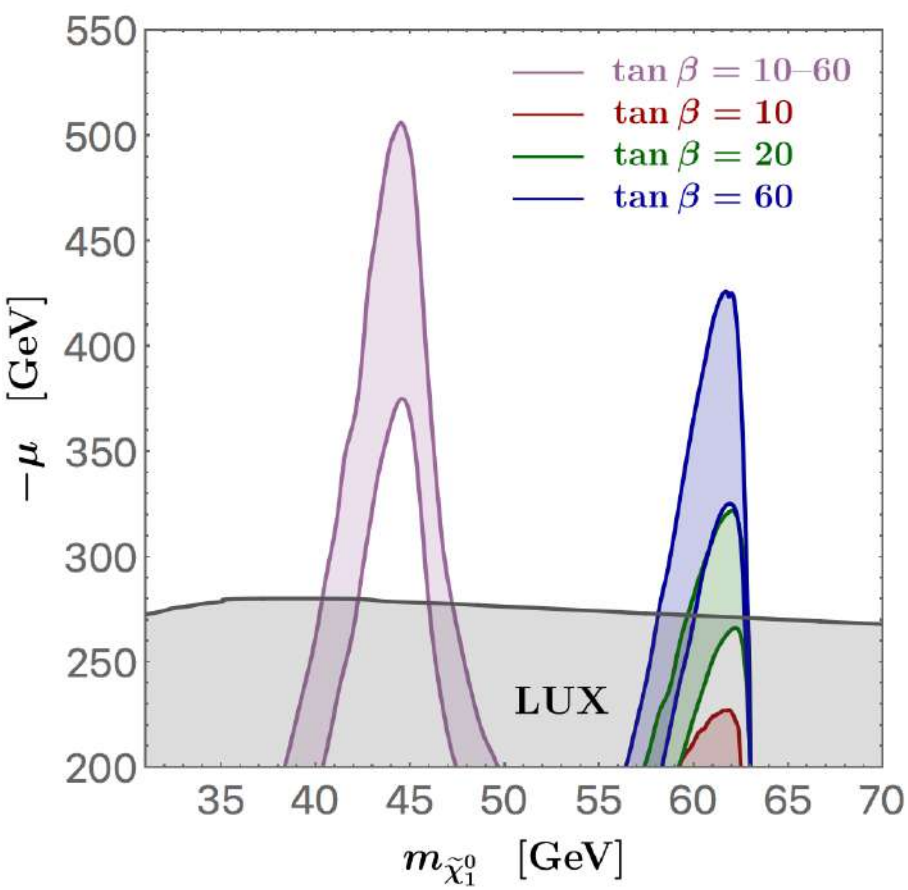
$$\sigma_p^{\rm SI} = 6.82 \times 10^{-13} \text{ pb}\,, \qquad \sigma_p^{\rm SD} = 1.70 \times 10^{-5} \text{ pb}\,,$$
$$\sigma_n^{\rm SI} = 4.70 \times 10^{-13} \text{ pb}\,, \qquad \sigma_n^{\rm SD} = 1.33 \times 10^{-5} \text{ pb}\,.$$

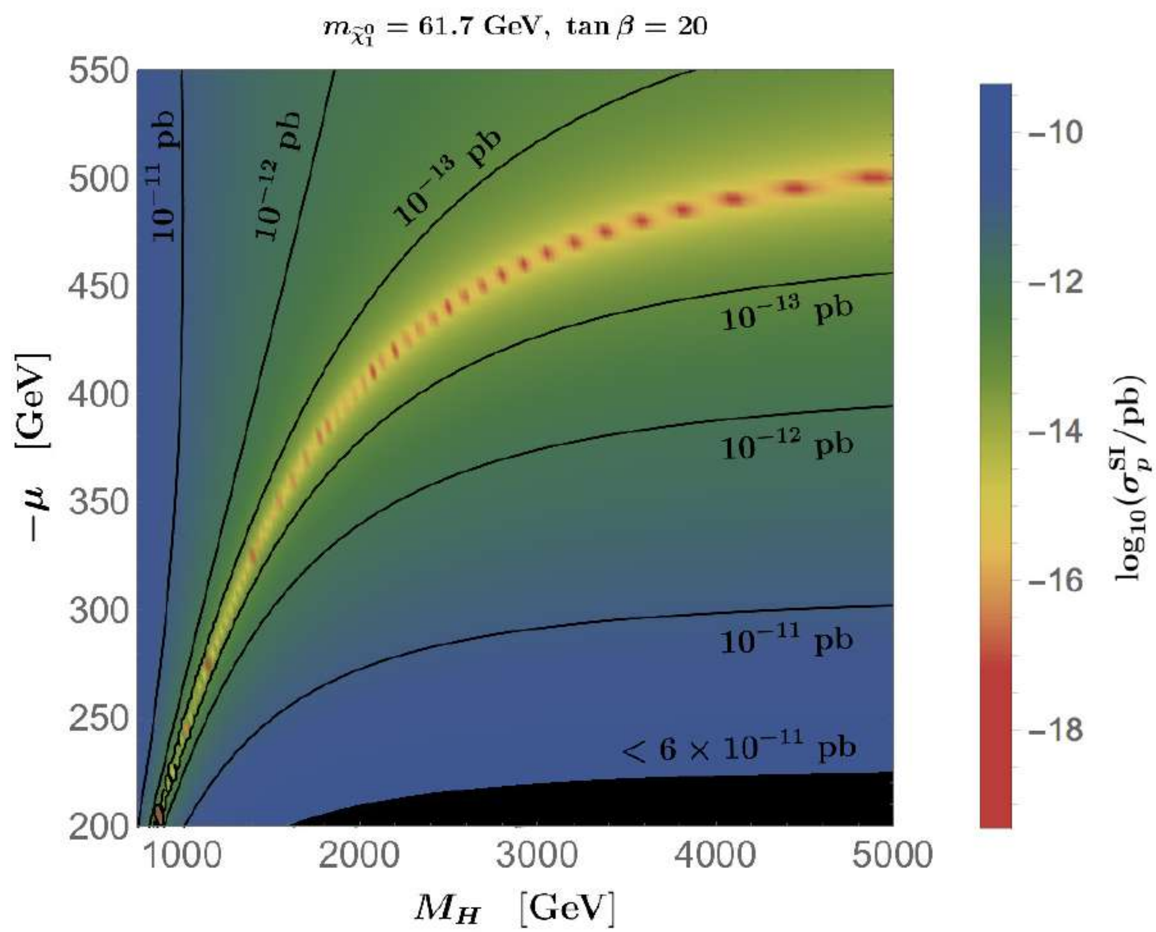
Carena, Osborne, Shah, C.W. ‘18

ATLAS Excess : 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.



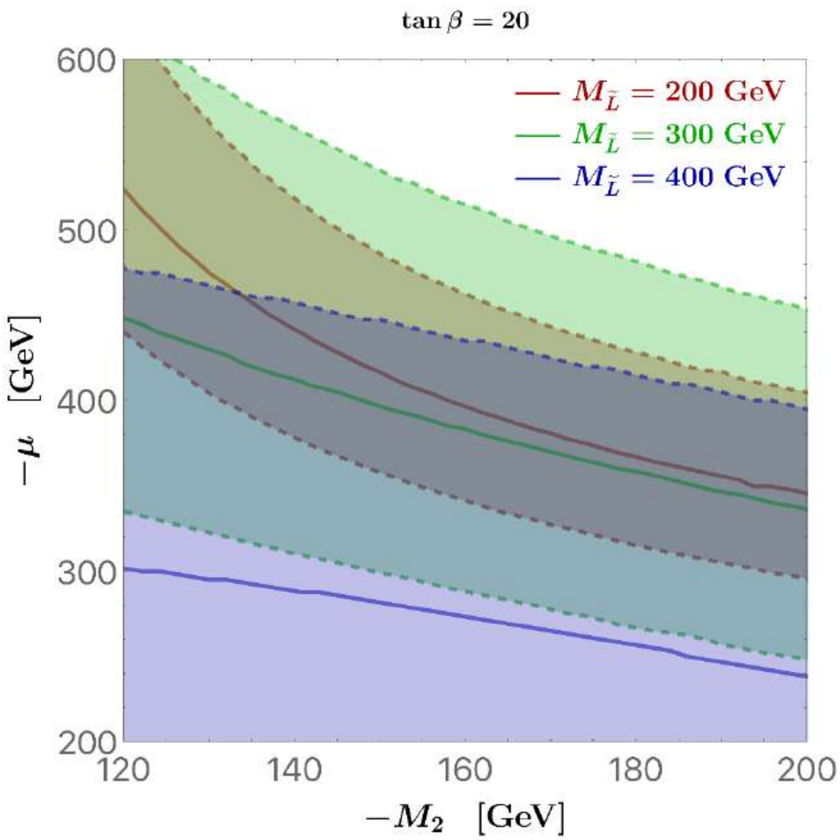


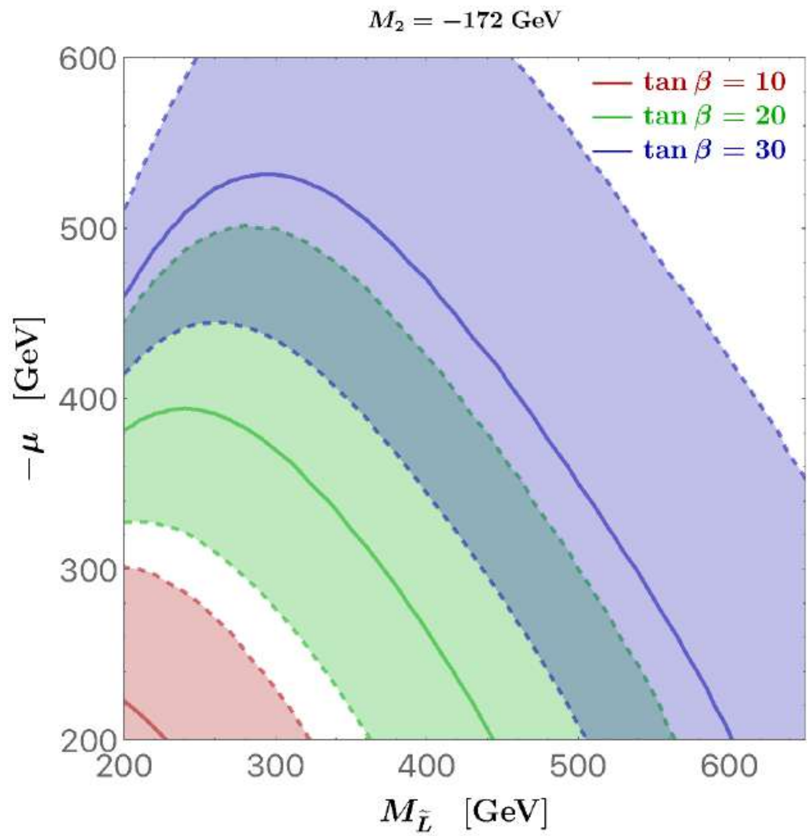
Carena, Osborne, Shah, C.W. ‘18

ATLAS Excess : Anomalous Magnetic Moment $(g-2)_\mu$

As expected, s-leptons with masses of the order of 400 GeV lead to an explanation of g-2 for the benchmark point.

Dependence on tan(beta) follows the expected behavior



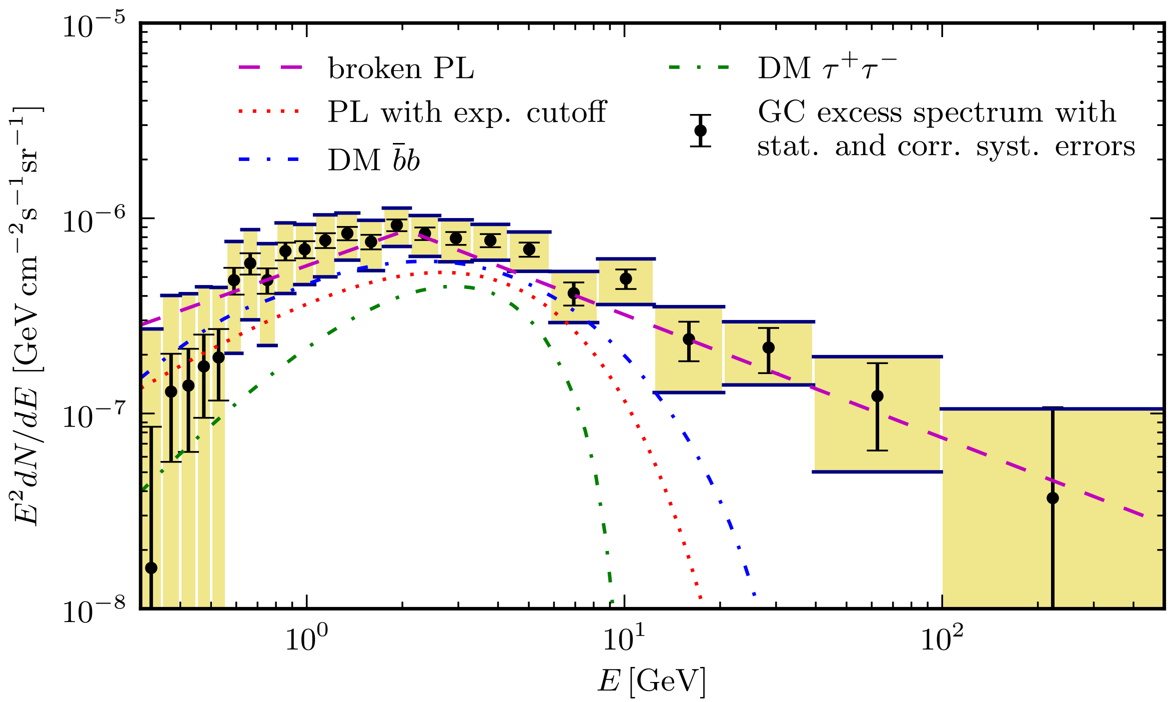


Galactic Center Gamma Ray Excess

Significant Excess of Gamma Rays at the Center of the Galaxy
Could be due to either Dark Matter annihilation or Astrophysical sources.

Four years ago a detailed analysis revealed preference towards Astrophysics.
arXiv:1506.05124

However, some of the same authors discovered last systematics in the previous analysis, implying that the Dark Matter annihilation explanation becomes possible
arXiv:1904.08430



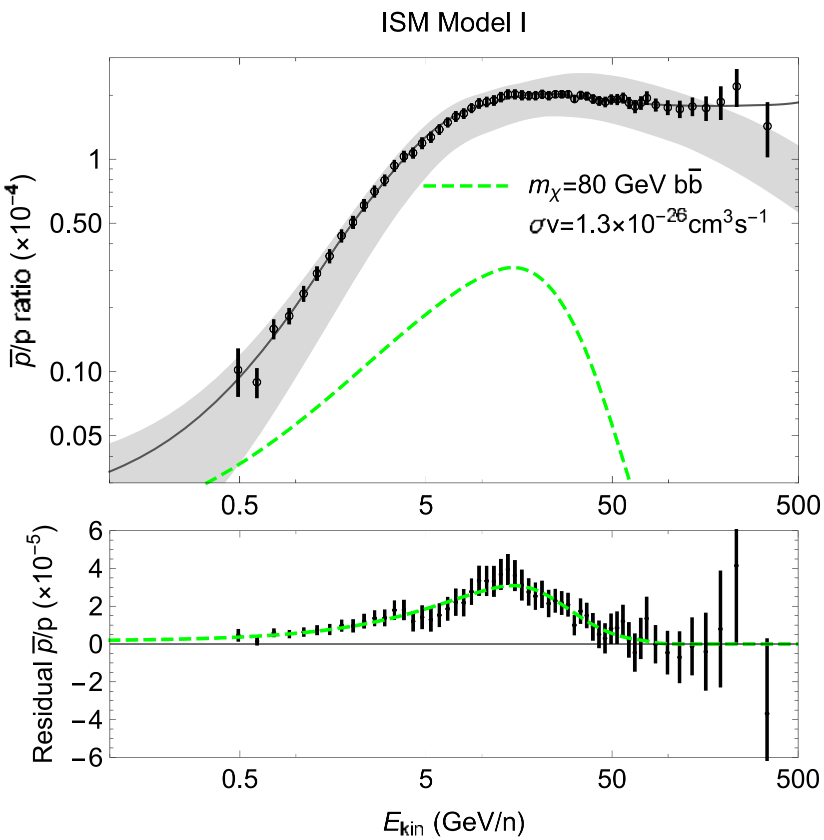
Fermi-LAT arXiv:1409.0042

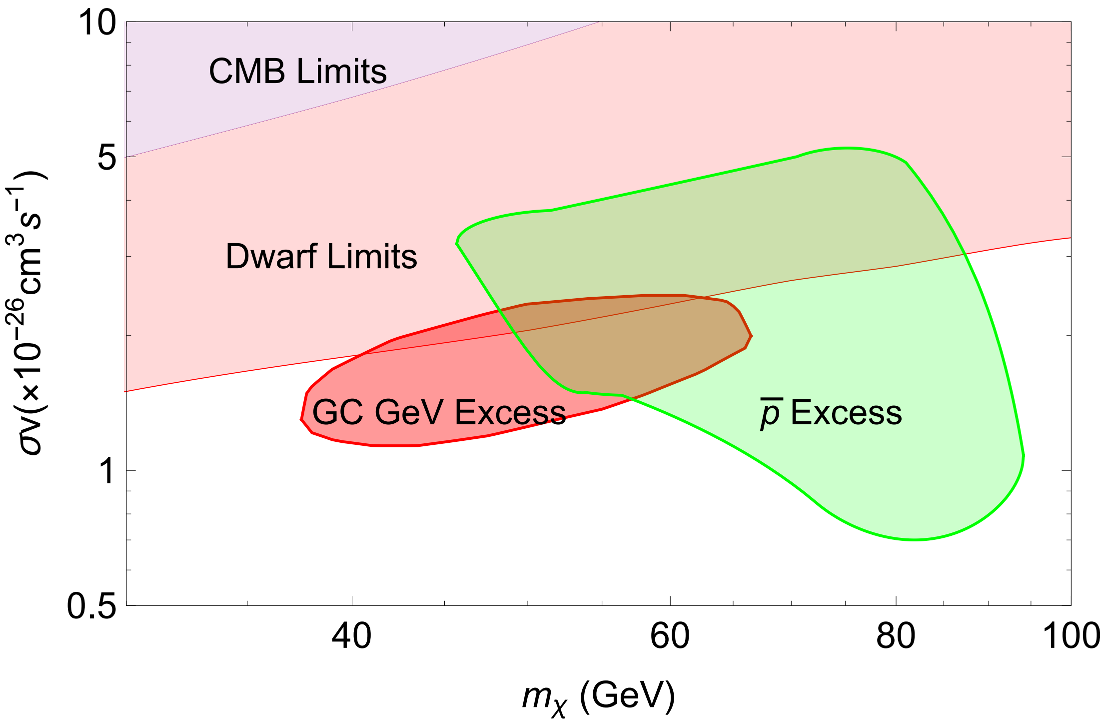
Galactic Center Excess and Antiproton Excess

AMS02 measured the antiproton cosmic ray flux, leading to evidence of an excess with respect to expectations.

Intriguingly, both the Galactic Center Excess and the Antiproton excess may be explained through the annihilation of a Dark Matter candidate of mass 60 GeV. Similar o the value coming from collider searches

This motivated us to explore a possible common origin of these excesses within the MSSM and the NMSSM.





AMS02- Phys.Rev.Lett. (2017), I. Cholis, T. Linden D. Hooper, arXiv:1903.02549

M. Carena, J. Osborne, N.R. Shah and C.E.M. Wagner, arXiv:1905.13768

CP-Violating Benchmark Scenario

A mass of 60 GeV open the possibility of fixing the DM relic density via annihilations with the Standard Model Higgs boson. However, our previous scenario would lead to p-wave suppression. The addition of CP-violation in the Bino sector leads to a pseudo-scalar coupling of the Higgs to Dark Matter and also to a sizable indirect signal.

Param.	Value	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
$\arg[M_1]$	5.8°	μ	-300	M_3	3000	A_t	2500
$\tan\beta$	20	M_1	63.425	$M_{\widetilde{L}}$	3000	A_b	2500
$M_{H^\pm}$	1500 GeV	M_2	-185	$M_{\widetilde{Q}}$	3000	A_τ	1000

Using CPsuperH as spectrum generator, one gets

Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	125.5	$\widetilde{\chi}_1^\pm$	165.2	$\widetilde{\nu}_e$	2999.3	$\widetilde{u}_R$	2999.8
H_2	1497.9	$\widetilde{\chi}_2^\pm$	331.9	$\widetilde{\nu}_\mu$	2999.3	$\widetilde{u}_L$	2999.5
H_3	1497.9	$\widetilde{\tau}_1$	2998.4	$\widetilde{\nu}_\tau$	2999.3	$\widetilde{d}_R$	3000.1
$H^\pm$	1500.0	$\widetilde{\tau}_2$	3002.3	$\widetilde{g}$	3000.0	$\widetilde{d}_L$	3000.6
$\widetilde{\chi}_1^0$	62.7	$\widetilde{e}_R$	3000.3	$\widetilde{t}_1$	2945.8	$\widetilde{s}_R$	3000.1
$\widetilde{\chi}_2^0$	165.0	$\widetilde{e}_L$	3000.4	$\widetilde{t}_2$	3058.4	$\widetilde{s}_L$	3000.6
$\widetilde{\chi}_3^0$	309.6	$\widetilde{\mu}_R$	3000.3	$\widetilde{b}_1$	2997.6	$\widetilde{c}_R$	2999.8
$\widetilde{\chi}_4^0$	329.0	$\widetilde{\mu}_L$	3000.4	$\widetilde{b}_2$	3003.1	$\widetilde{c}_L$	2999.5

M. Carena, J. Osborne, N.R. Shah and C.E.M. Wagner, arXiv:1905.13768

Experimental Predictions

Relic density together with an annihilation into bottom-quark pairs of the proper order of magnitude to explain the galactic center and antiproton excesses are obtained. This is achieved keeping the SI and SD detection cross sections small.

$$\Omega h^2 = 0.119, \qquad \sigma^p_{\rm SI} = 2.17 \times 10^{-12}\ {\rm pb}, \qquad \sigma^n_{\rm SI} = 1.84 \times 10^{-12}\ {\rm pb},$$
$$\sigma v|_{v=0} = 2.69 \times 10^{-26}\ {\rm cm}^3/{\rm s}, \qquad \sigma^p_{\rm SD} = 1.76 \times 10^{-5}\ {\rm pb}, \qquad \sigma^n_{\rm SD} = 1.36 \times 10^{-5}\ {\rm pb}. \quad (2.3)$$

$$BR(h \to b\bar{b}) \sim 58\%, \qquad BR(h \to WW) \sim 22\%,$$

$$\sigma v(\chi\chi \to b\bar{b}) \sim 1.5 \times 10^{-26} {\rm ecm}$$

$$BR(h \to gg) \sim 8\%, \qquad BR(h \to \tau^+\tau^-) \sim 7\%$$

Interestingly enough, this scenario leads to one and two loop contributions to the electric dipole moment. As Prof. Nath and collaborators investigated years ago, there are interesting cancellations between the one and two loop contributions.

Ibrahim and Nath, arXiv:0705.2008

$$d_e = 1.8 \times 10^{-30} {\rm e\ cm}$$

$$d_e = 1.1 \times 10^{-30} {\rm e\ cm\ for\ slepton\ masses\ at\ 2\ TeV}$$ (Current experimental limit)

Almost exact cancellation for slepton masses of about 4 TeV !

M. Carena, J. Osborne, N.R. Shah and C.E.M. Wagner, arXiv:1905.13768

NMSSM Benchmark Scenario

Alternatively, one can add a light CP-odd scalars, like can be obtained in the NMSSM.

This allows to avoid the p-wave suppression, by using the DM annihilation with this Higgs boson.

The rest of the scenario is as before. choosing kappa larger than lambda allows to push all other singlet states to large values. For instance,

Param.	Value	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
$\tan\beta$	20	$\mu_{\rm eff}$	-300	M_3	3000	A_λ	-1260
λ	0.15	M_1	62.62	$M_{\widetilde{L}}$	450	A_κ	-10.8
κ	-0.55	M_2	-171.	$M_{\widetilde{Q}}$	3000	A_t	4000

With these parameters one obtains

Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	124.8	$\widetilde{\chi}_1^\pm$	165.2	A_1	120.8	$\widetilde{u}_R$	3100.7
H_2	969.6	$\widetilde{\chi}_2^\pm$	336.7	A_2	974.1	$\widetilde{u}_L$	3100.5
H_3	2185.5	$\widetilde{\tau}_1$	438.3	$\widetilde{\nu}_{e,\mu,\tau}$	445.7	$\widetilde{d}_R$	3101.0
$H^\pm$	972.9	$\widetilde{\tau}_2$	465.5	$\widetilde{g}$	3198.1	$\widetilde{d}_L$	3101.5
$\widetilde{\chi}_1^0$	60.7	$\widetilde{e}_R$	452.0	$\widetilde{t}_1$	2955.6	$\widetilde{s}_R$	3101.0
$\widetilde{\chi}_2^0$	165.0	$\widetilde{e}_L$	452.3	$\widetilde{t}_2$	3120.5	$\widetilde{s}_L$	3101.5
$\widetilde{\chi}_3^0$	315.8	$\widetilde{\mu}_R$	452.0	$\widetilde{b}_1$	3076.3	$\widetilde{c}_R$	3100.7
$\widetilde{\chi}_4^0$	333.9	$\widetilde{\mu}_L$	452.3	$\widetilde{b}_2$	3077.8	$\widetilde{c}_L$	3100.5

M. Carena, J. Osborne, N.R. Shah and C.E.M. Wagner, arXiv:1905.13768

Experimental Predictions

The experimental predictions of this scenario with respect to the DM phenomenology are similar to the CP violating case. One obtains the proper relic density and a large enough cross section into bottom quark pairs to explain the galactic center and antiproton excesses. The SI and SD direct detection cross sections remain small.

$$\Omega h^2 = 0.119, \qquad \sigma_{\rm SI}^p = 5.6 \times 10^{-12}\ \text{pb}, \qquad \sigma_{\rm SI}^n = 7.23 \times 10^{-12}\ \text{pb},$$
$$\sigma v|_{v=0} = 2.25 \times 10^{-26}\ \text{cm}^3/\text{s}, \qquad \sigma_{\rm SD}^p = 1.59 \times 10^{-5}\ \text{pb}, \qquad \sigma_{\rm SD}^n = 1.23 \times 10^{-5}\ \text{pb}.$$

$BR(A_1 \to b\bar{b}) \sim 90\%$ and $BR(A_1 \sim \tau^+\tau^-) \sim 10\%$, $\qquad \sigma v(\chi\chi \to b\bar{b}) \sim 2 \times 10^{-26}\text{cm}^3/s$

One difference between the CP-violating and CP-conserving scenario is that in the latter case one can push the slepton masses to values of the order of a few hundred GeV, implying the possibility of obtaining a large value of the anomalous magnetic moment of the muon. Indeed, for the benchmark choice one obtains values consistent with current experimental observations.

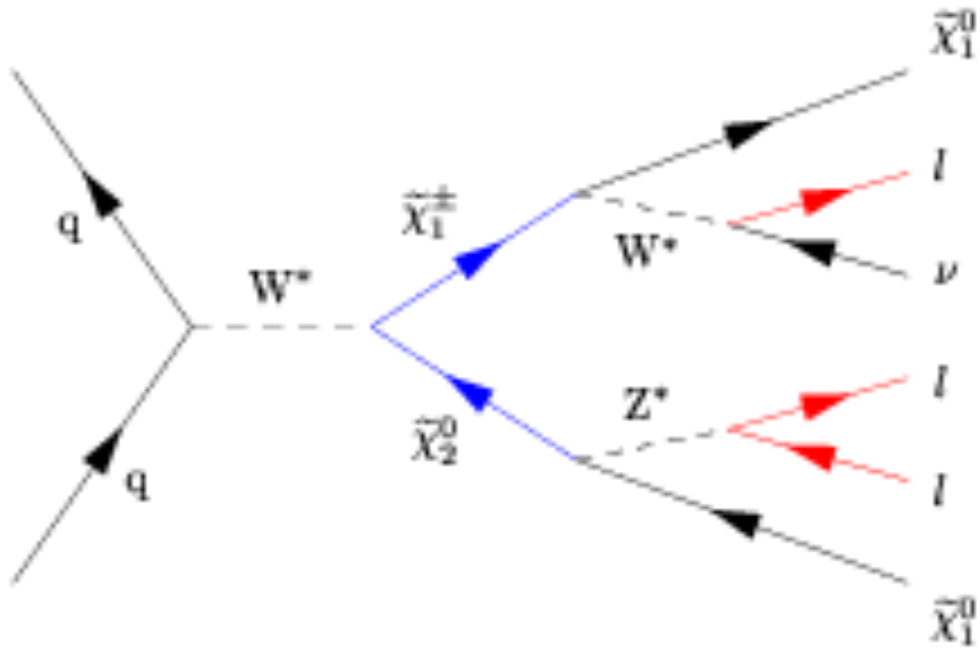
$$a_\mu = 217 \times 10^{-11}$$

Conclusions

- No clear deviation of Higgs coupling from SM expectations
- Strongly interacting particles are restricted to be heavier than about 1 TeV
- We are just starting to constrain the region of masses consistent with the MSSM Higgs mass determination !
- Case of low energy SUSY : Clearly there is still a chance !
- One thing is for sure : If there is SUSY at the weak scale, it could lead to a solution of the DM problem without any tension with present experimental constraints.
- g-2 can also be explained. There could be implications for e.d.m.'s
- Astrophysics and cosmic ray excesses may be addressed.
- Not to mention all the "benefits" of SUSY

Backup

Chargino-Neutralino Production



- For values of the wino and Higgsino masses larger than the weak scale, the mixing between them is small.
- Winos, in the adjoint representation of SU(2), are produced at a stronger rate than Higgsinos.
- The cross section for Wino production is about a factor 4 larger than the one for Higgsino production.
- Mixing increases for smaller mass differences, leading to a reduction of the wino cross section, and to the addition of new channels, some of them mixed “Wino-Higgsino”.

MSSM Cross Sections

Carena, Osborne, Shah, C.W. ‘18

Strong dependence on M2

Weak Dependence on mu.

Wino cross section larger by about a factor 4 than the Higgsino one.

Values of $\mu \simeq 300$ GeV lead to the desired cross sections.