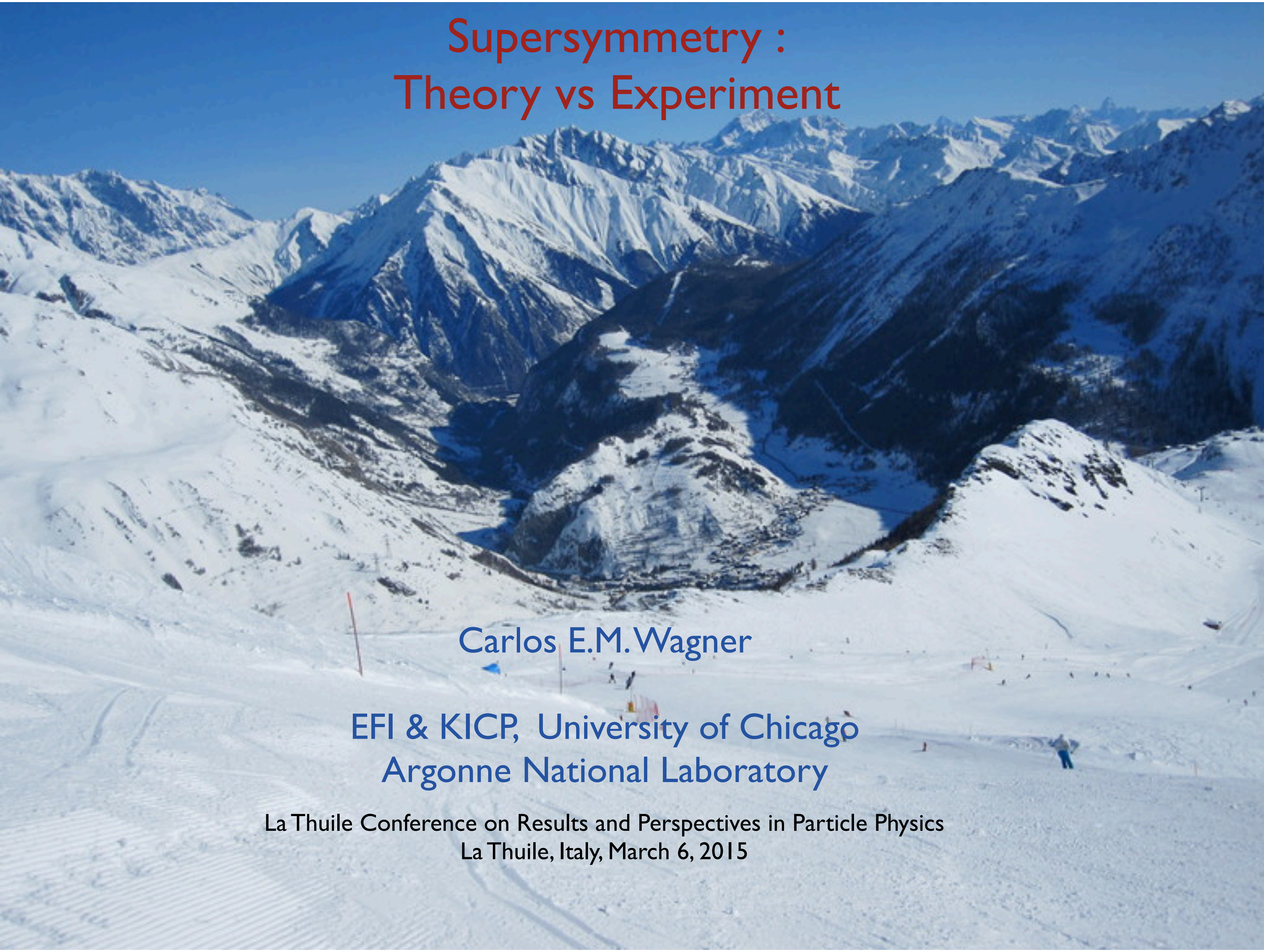
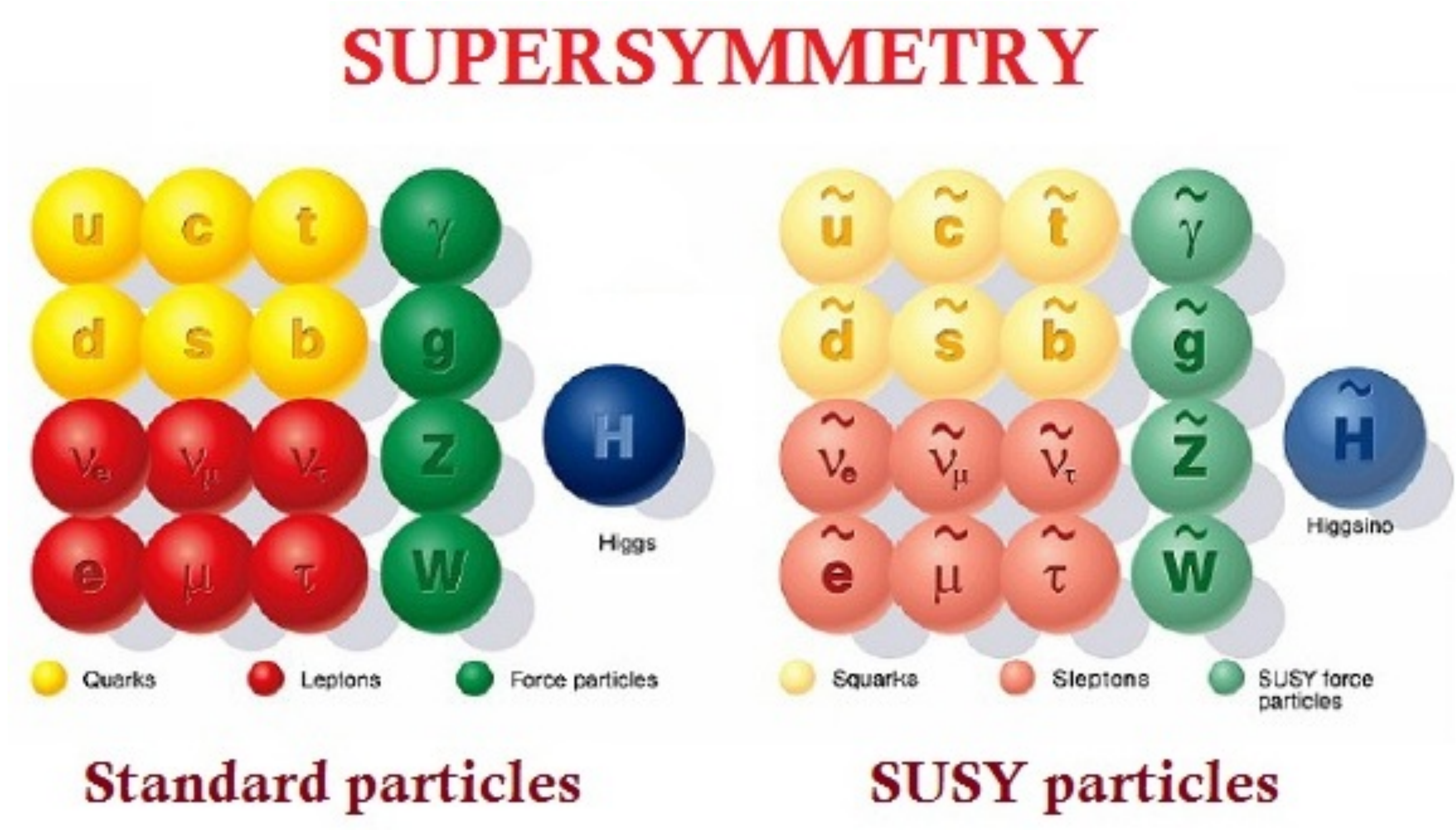
Supersymmetry : Theory vs Experiment



Carlos E.M. Wagner

EFI & KICP, University of Chicago
Argonne National Laboratory

La Thuile Conference on Results and Perspectives in Particle Physics
La Thuile, Italy, March 6, 2015



Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Supersymmetry and Higgs Physics

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A
* tan beta
* the top quark mass
* the stop masses and mixing

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

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 sbotton/stau sectors for large tanbeta]

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

M.Carena, J.R. Espinosa, M. Quiros, C.W. '95
M. Carena, M. Quiros, C.W.'95

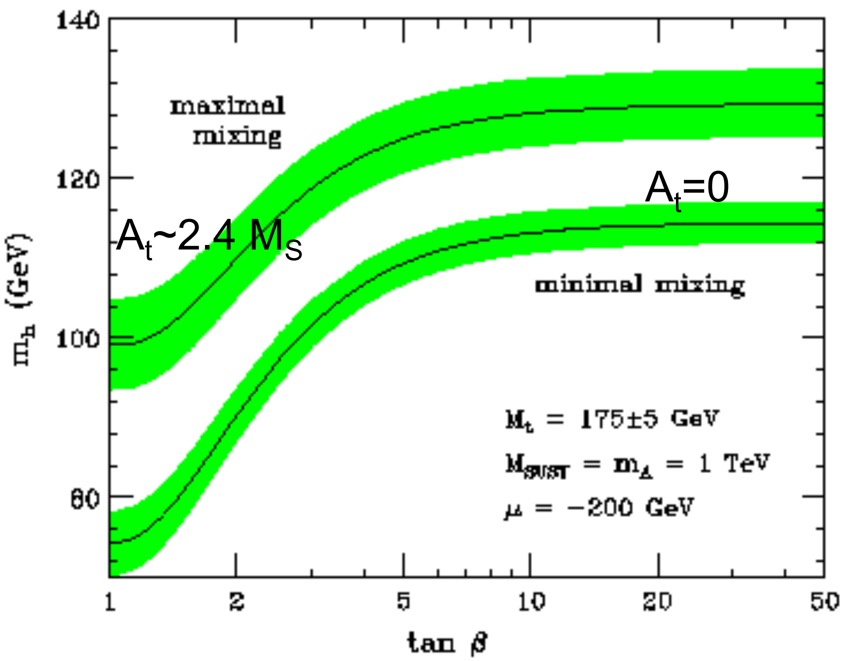
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

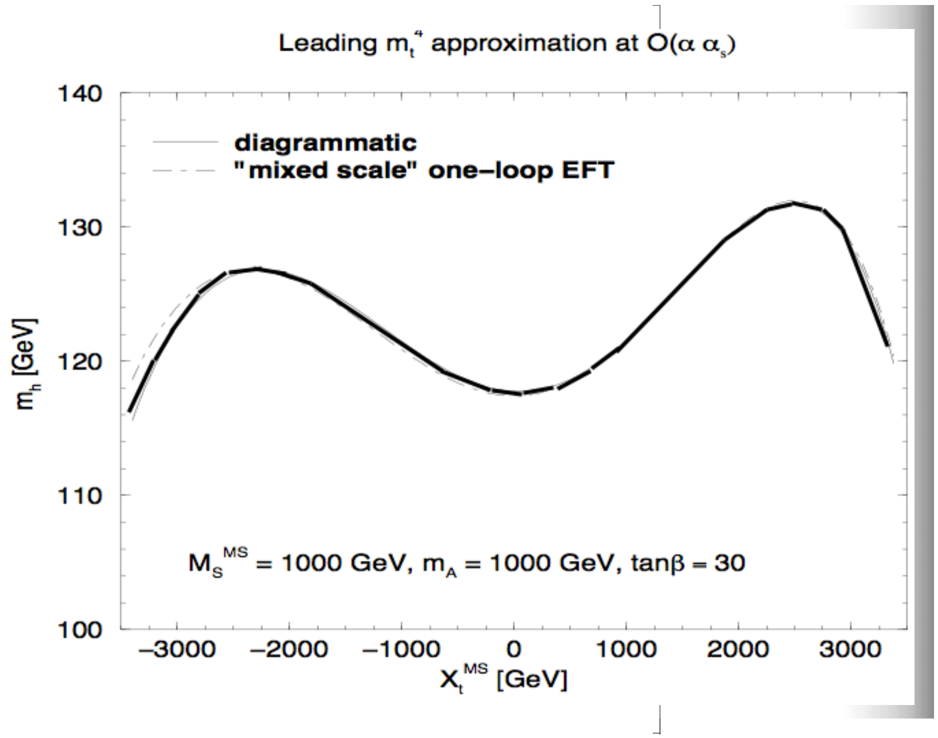
Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

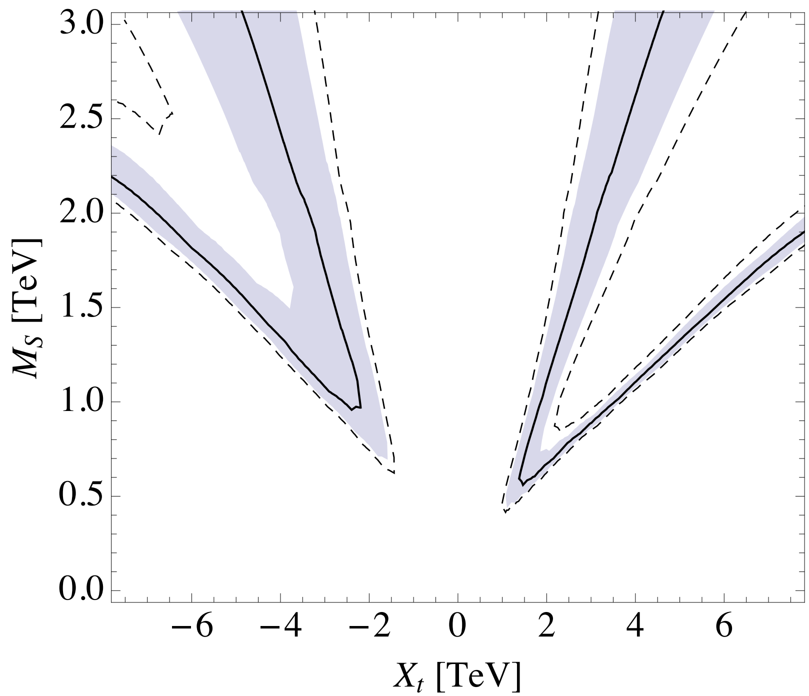
For masses of order 1 TeV, diagrammatic and EFT approach agree well, once the appropriate threshold corrections are included





$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing;} \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

Large Mixing in the Stop Sector Necessary



P. Draper, P. Meade, M. Reece, D. Shih'11
L. Hall, D. Pinner, J. Ruderman'11
M. Carena, S. Gori, N. Shah, C. Wagner'11
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon'11
S. Heinemeyer, O. Stal, G. Weiglein'11
U. Ellwanger'11

This puts strong constraints on, for instance, Gauge Mediated SUSY breaking models, where one expects Xt < Ms, unless the overall scale of stop masses is much larger than 1 TeV.

Higher loop effects and the Stop Mass Scale

Draper, Lee, C.W. '13

The analysis of the three-loop corrections show a high degree of cancellation between the dominant and subdominant contributions

$$\delta_3\lambda = \Big\{ -1728\lambda^4 - 3456\lambda^3 y_t^2 + \lambda^2 y_t^2(-576 y_t^2 + 1536 g_3^2) + \lambda y_t^2(1908 y_t^4 + 480 y_t^2 g_3^2 - 960 g_3^4) + y_t^4(1548 y_t^4 - 4416 y_t^2 g_3^2 + 2944 g_3^4)\Big\} L^3$$

This is a SM effect, since this is the effective theory we are considering.

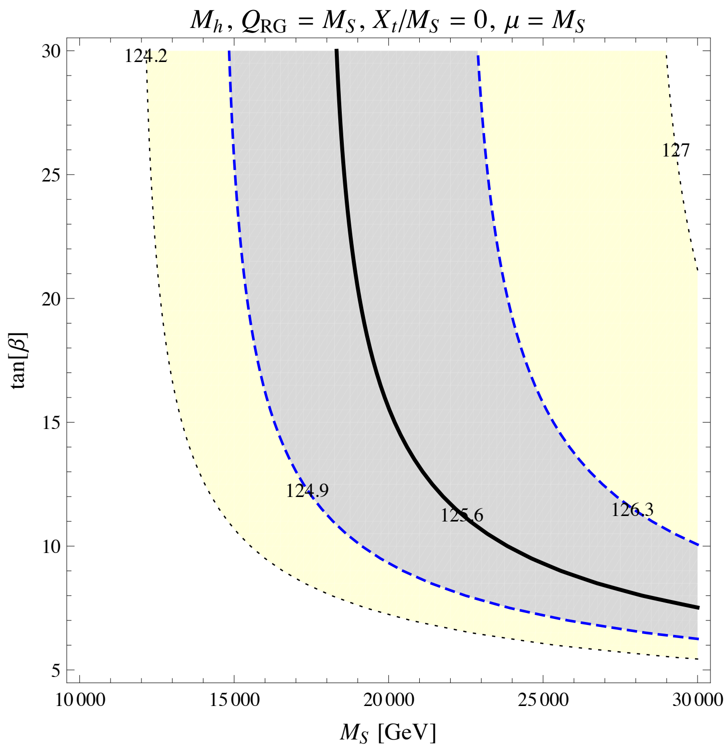
This shows that a partial computation of three loop effects is not justified

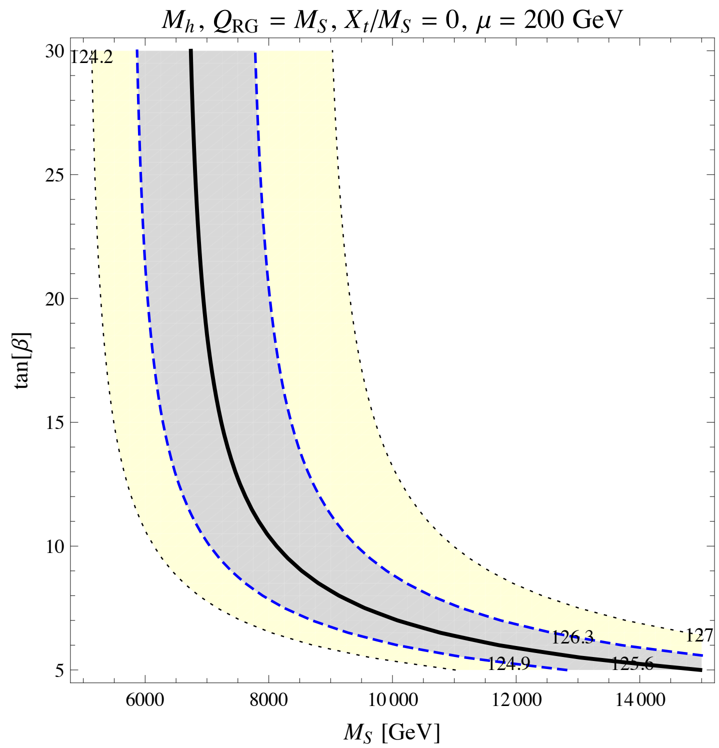
Harlander, Kant, Mihaila, Steinhauser'08,'10

Feng, Kant, Profumo, Sanford'13

Draper, Lee, C.W. '13

Necessary stop mass values to get the proper Higgs mass for Small mixing in the stop sector

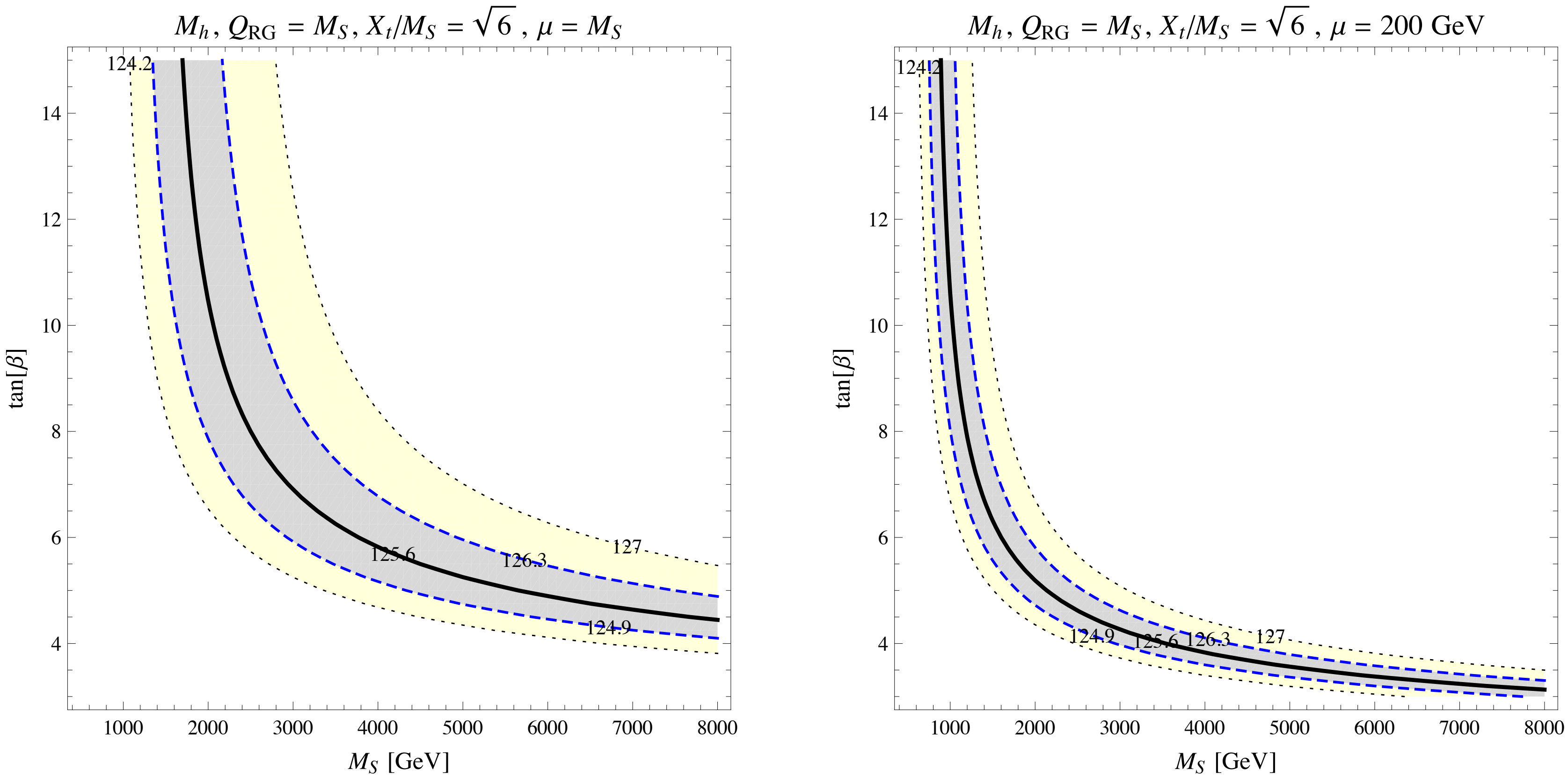




Such heavy stops would be out of the reach of the LHC
A higher energy collider necessary to investigate stop sector

Draper, Lee, C.W. '13

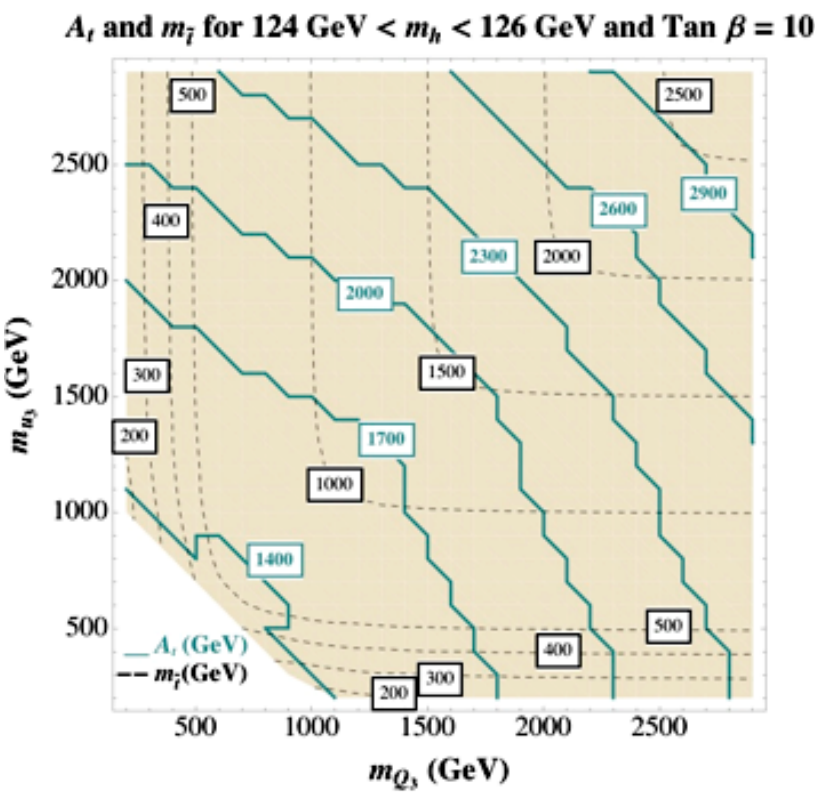
Necessary stop mass values to get the proper Higgs mass for Maximal mixing in the stop sector

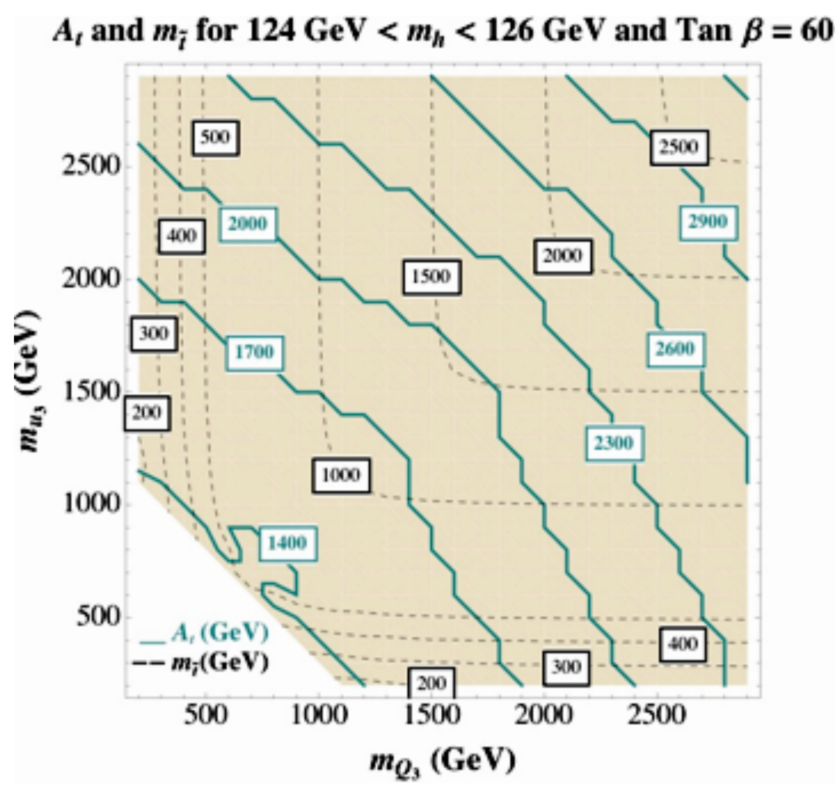


Light Stops at the reach of the LHC for large mixing in the Stop sector and moderate values of tanβ

Splitting the Two Stop Masses
Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842





Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop

Intermediate values of tan beta lead to the largest values of m_h for the same values of stop mass parameters

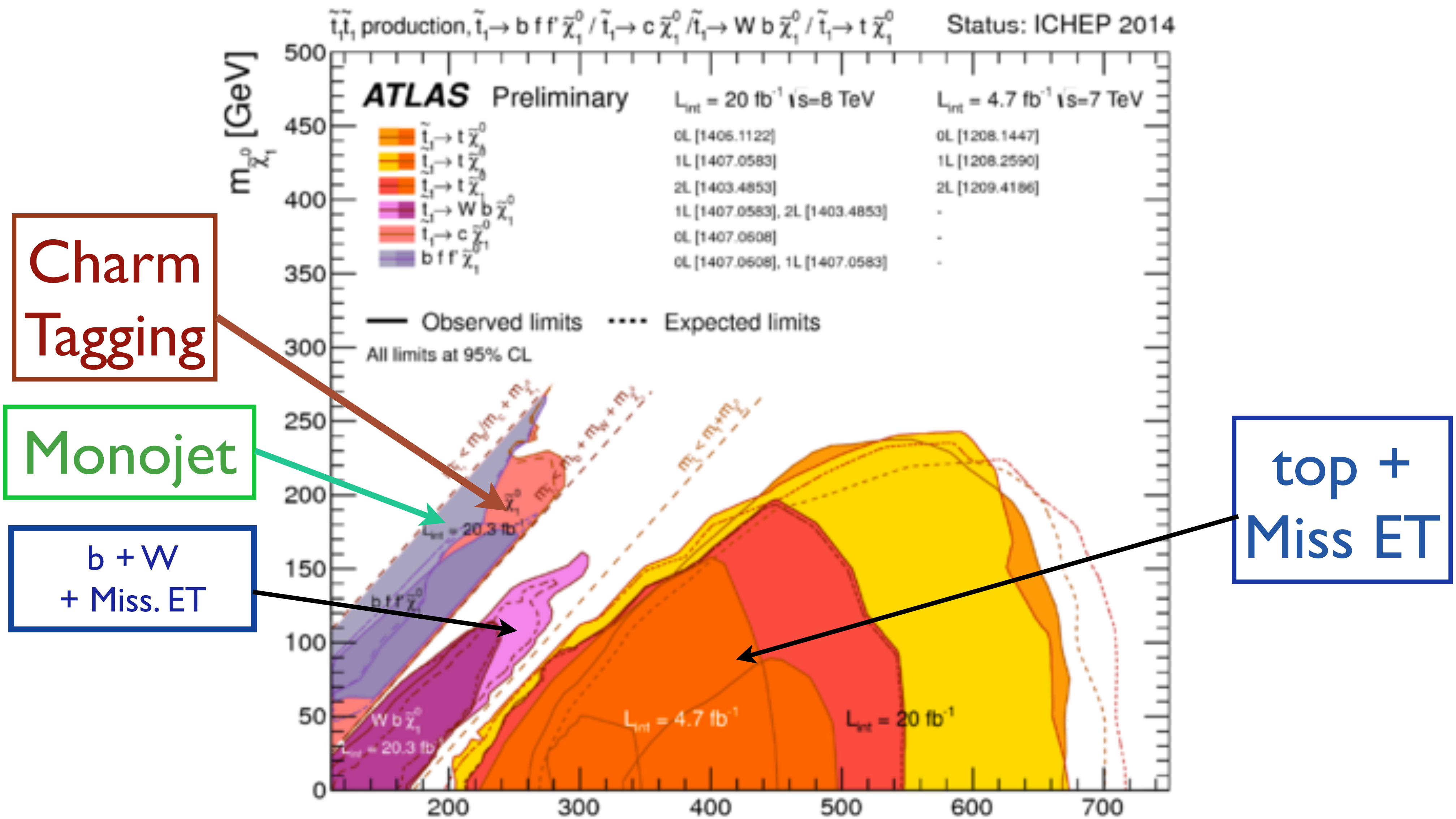
Light stop coupling to the Higgs

$$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

Lightest stop coupling to the Higgs approximately vanishes for $X_t \simeq m_Q$
Higgs mass pushes us in that direction
Modification of the gluon fusion rate milder due to this reason.

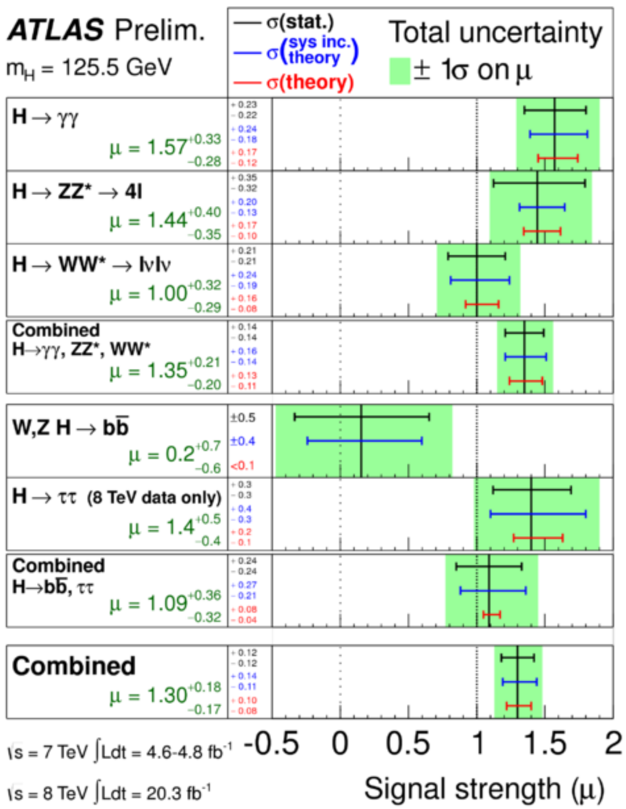
Stop Searches

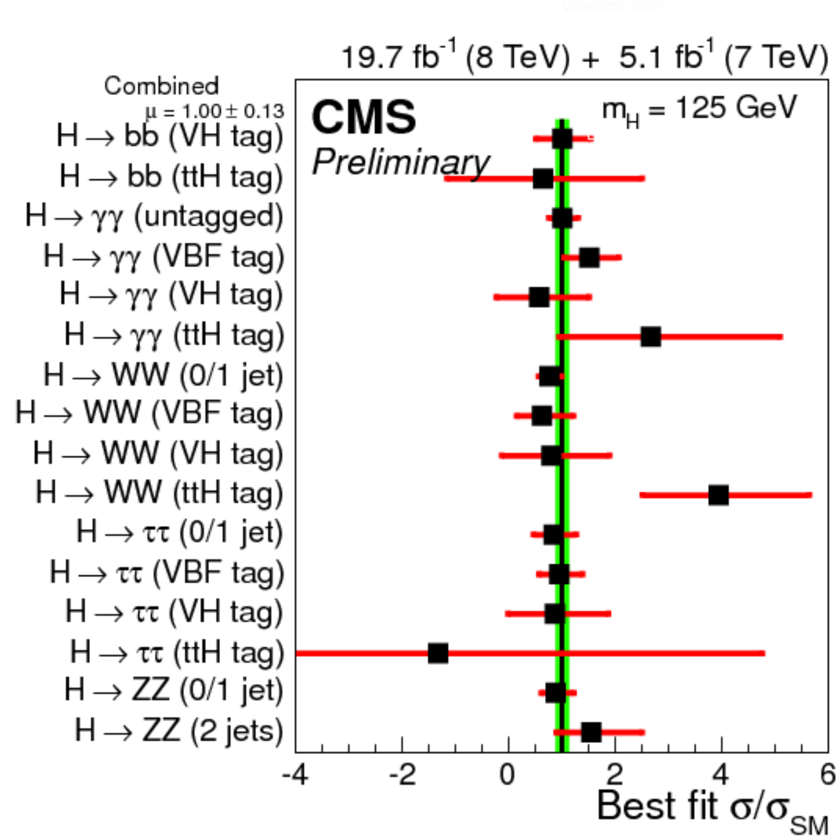
Provided the lightest neutralino (DM) is heavier than about 250 GeV, there are no limits on stops. Even for lighter neutralinos, there are big holes.



The properties of the recently discovered Higgs boson are close to the SM ones

Variations of Higgs couplings are still possible





As these measurements become more precise, they constrain possible extensions of the SM, and they could lead to the evidence of new physics.

It is worth studying what kind of effects one could obtain in well motivated extensions of the Standard Model, like SUSY.

(for an extensive review, see Christensen, Han and Su'13)

Low Energy Supersymmetry : Type II Higgs doublet models

- In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{(-\sin\alpha)}{\cos\beta}, \qquad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{\cos\alpha}{\cos\beta}$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{(\cos\alpha)}{\sin\beta}, \qquad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{\sin\alpha}{\sin\beta}$$

- If the mixing is such that

$$\sin\alpha = -\cos\beta, \qquad \sin(\beta-\alpha) \simeq 1$$

$$\cos\alpha = \sin\beta \qquad (\cos(\beta-\alpha) = 0)$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

- Observe that close to the decoupling limit, the lightest Higgs couplings are SM-like, while the heavy Higgs couplings to down quarks and up quarks are enhanced (suppressed) by a $\tan\beta$ factor. We shall concentrate on this case.

- It is important to stress that the coupling of the CP-odd Higgs boson

$$g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\rm diag}^{\rm dd}}{v} \tan\beta, \qquad g_{Aff}^{uu} = \frac{\mathcal{M}_{\rm diag}^{\rm uu}}{v\tan\beta}$$

Deviations from Alignment

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

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

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

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

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

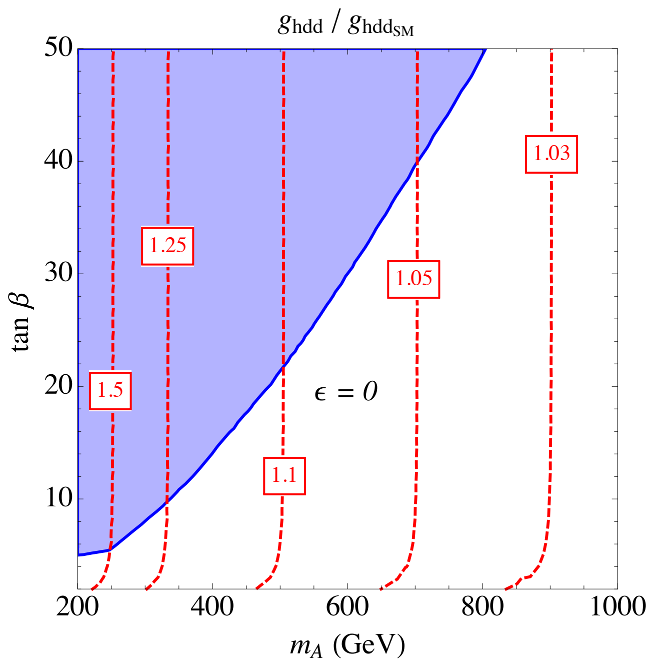
At moderate or large values of $\tan\beta$, it is clear that the only relevant deviations will be in the bottom coupling

Down Couplings in the MSSM for low values of μ

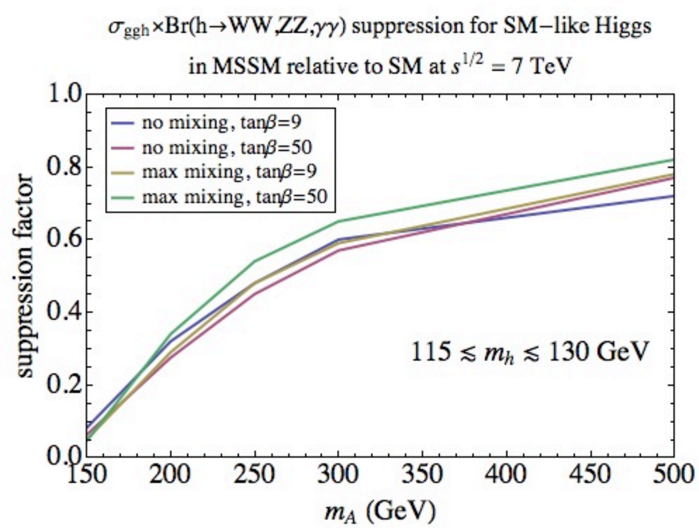
- In this regime, $\lambda_{6,7} \simeq 0$, and

$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{\rm SM} \simeq 0.26$$

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



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



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

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

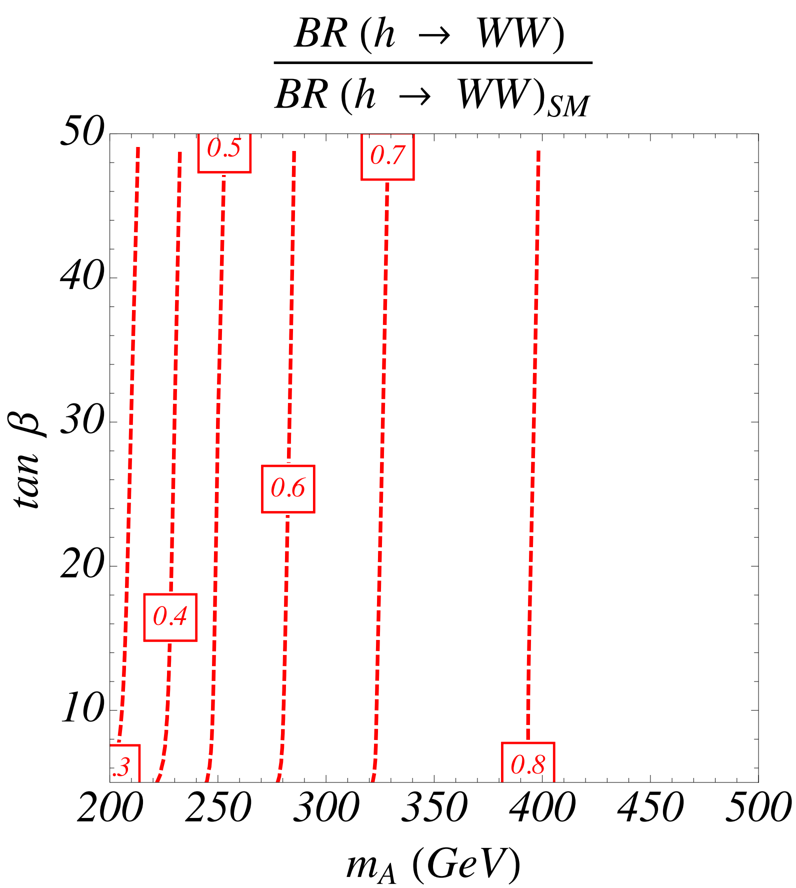
Carena, Haber, Low, Shah, C.W.'14

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

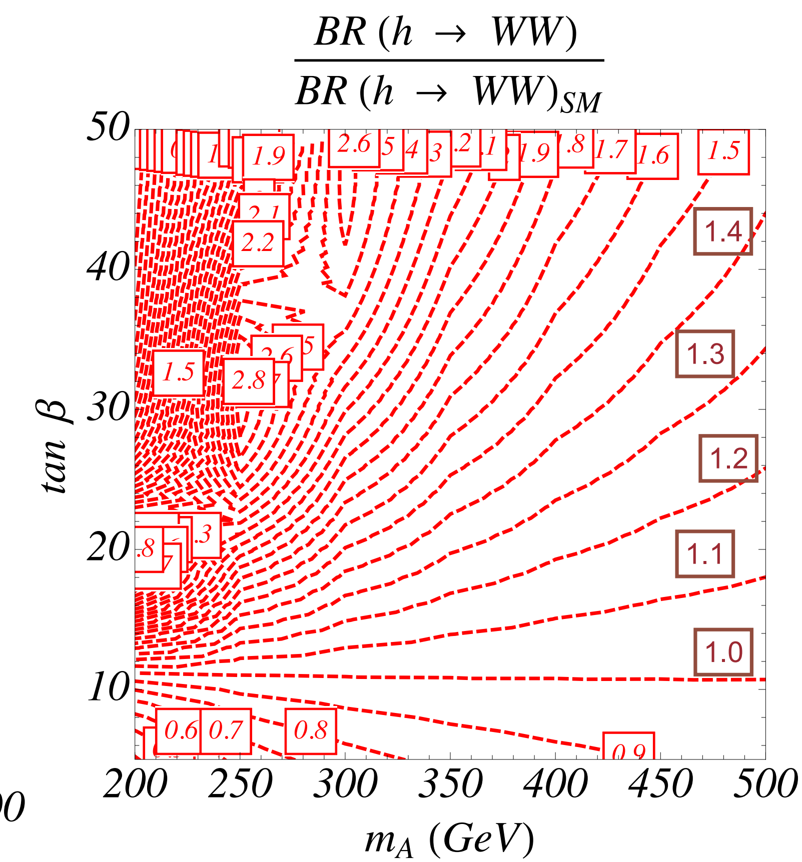
Higgs Decay into Gauge Bosons

Mostly determined by the change of width

Small μ



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

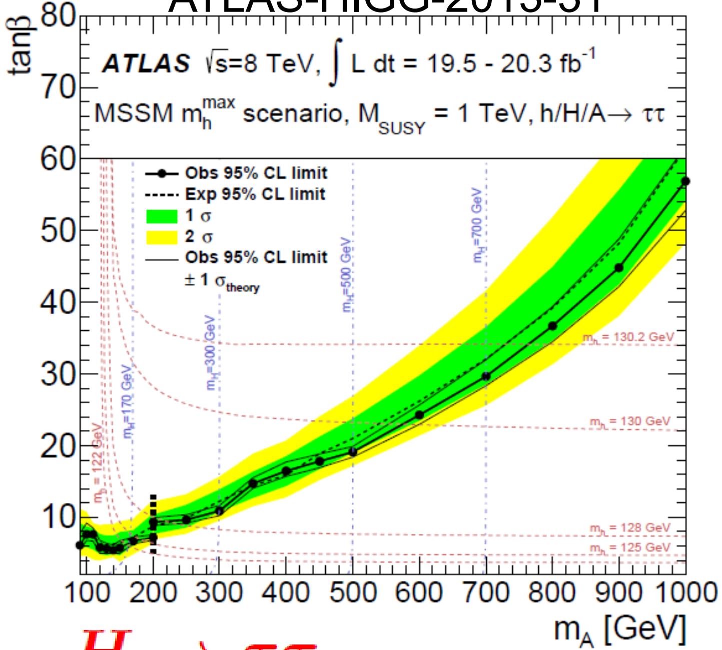


CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

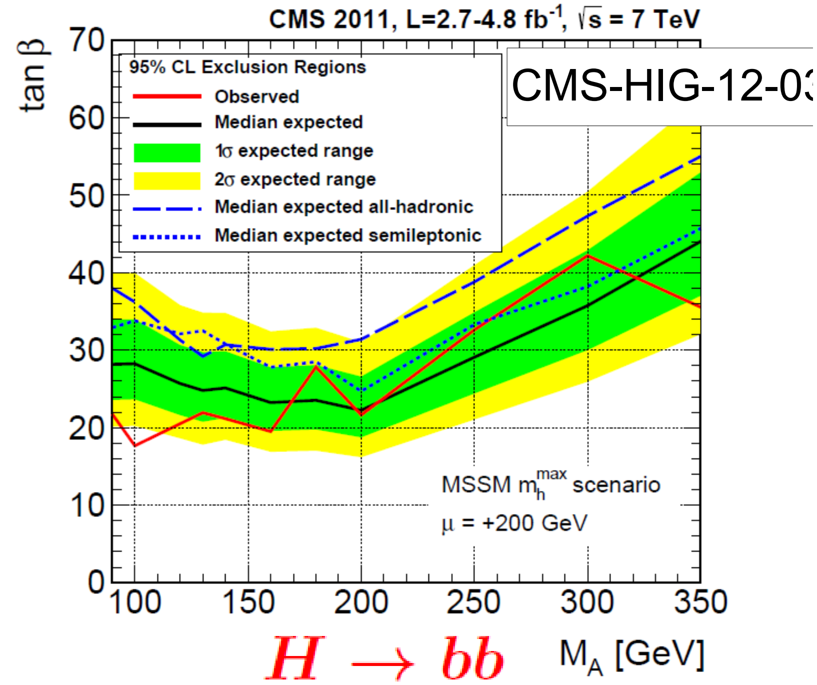
Non-Standard Higgs Searches

Neutral Higgs bosons

ATLAS-HIGG-2013-31



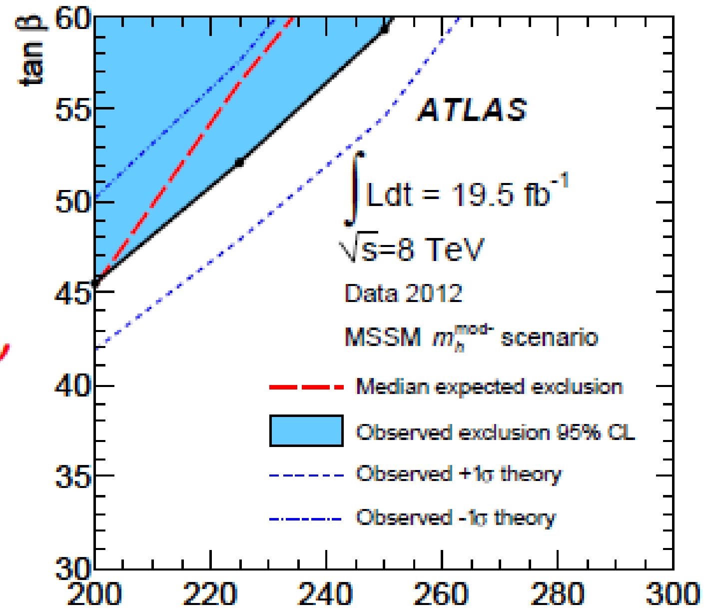
$H \to \tau\tau$



$H \to bb$

Charged Higgs bosons

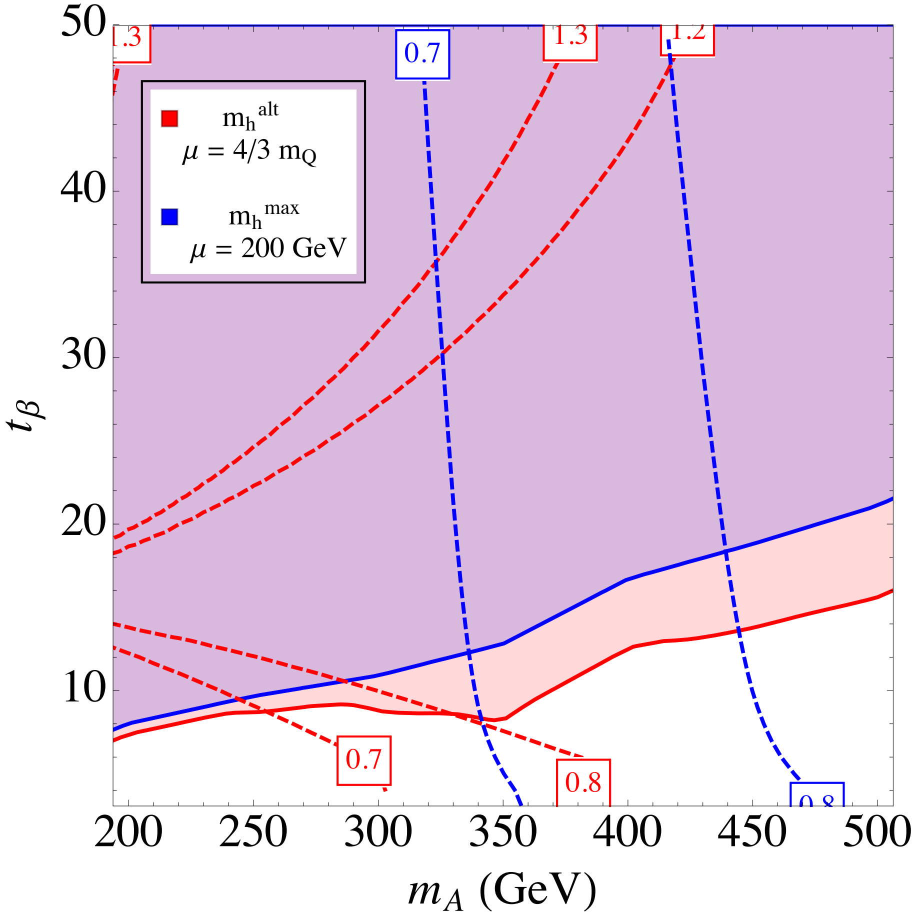
$H^{\pm} \to \tau^{\pm}\nu$



ATLAS-HIGG-2013-30

Complementarity between different search channels

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



Limits coming from measurements of h couplings become weaker for larger values of μ

— $\sum_{\phi_i=A,H}\sigma(bb\phi_i+gg\phi_i)\times BR(\phi_i\to\tau\,\tau)$ (8 TeV)

--- $\sigma(bbh+ggh)\times BR(h\to VV)/SM$

Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

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

- 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,

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

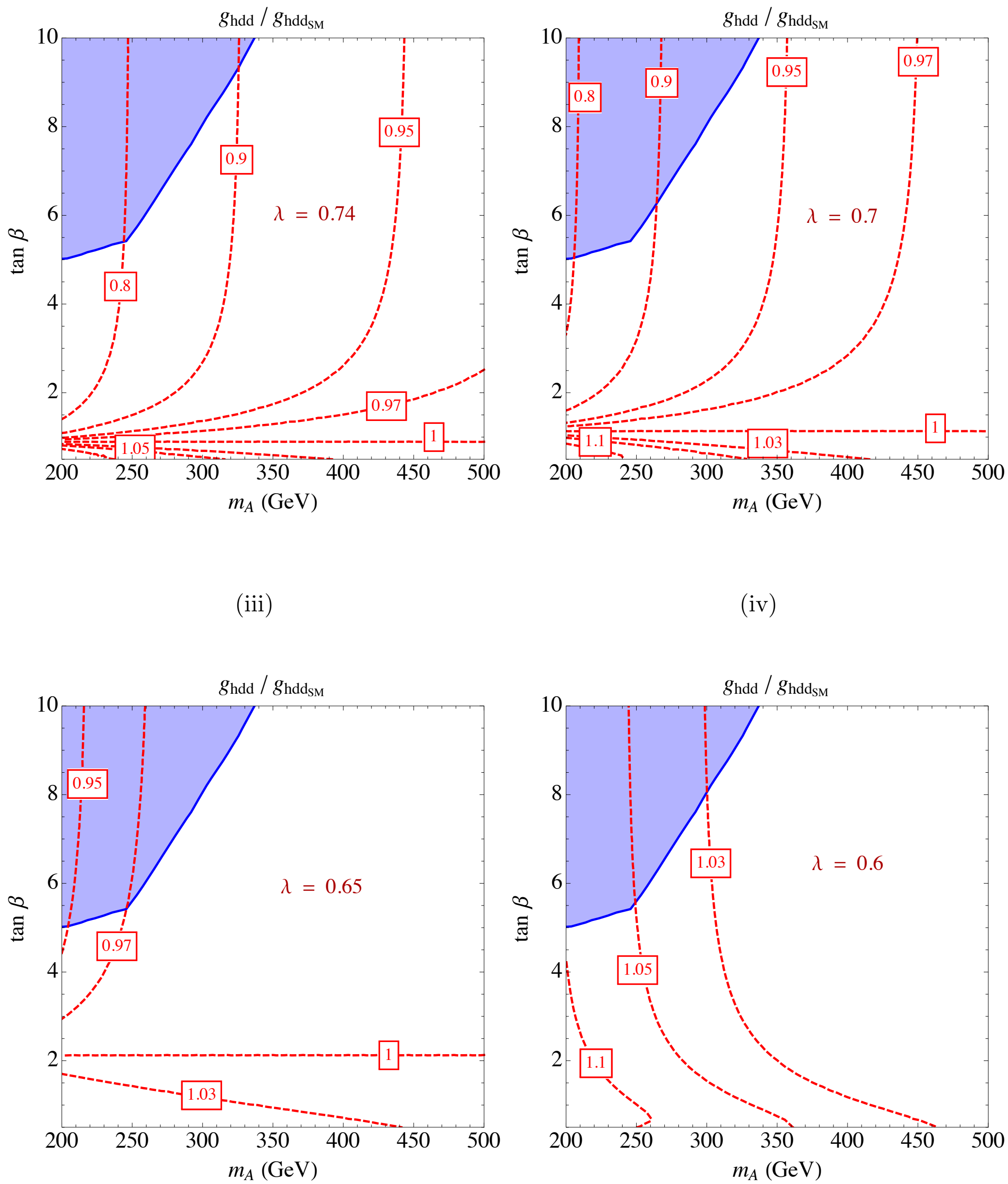
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- So, alignment leads to a determination of lambda,

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for allvalues of tanbeta, 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

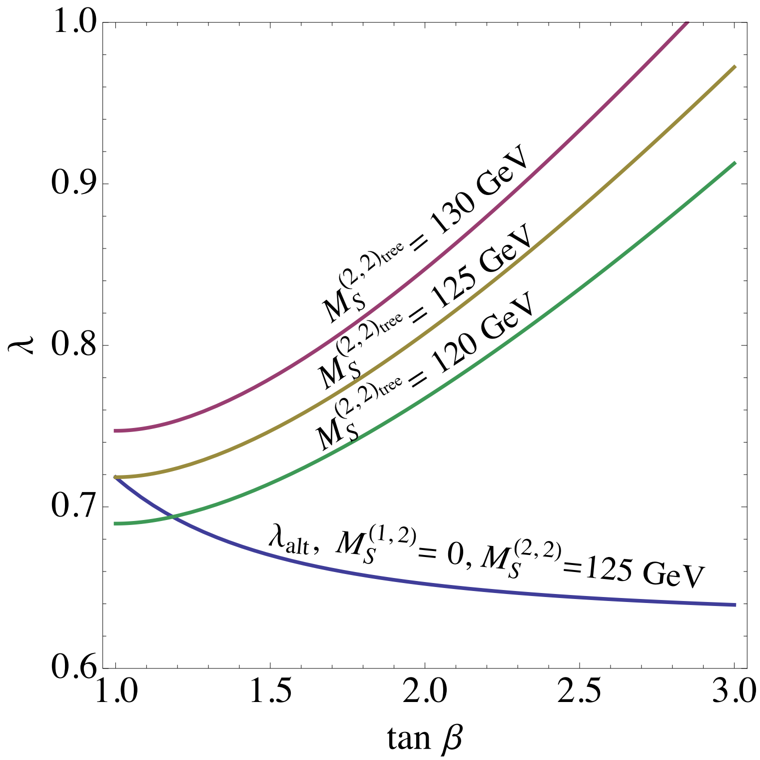
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided lambda is of about 0.65

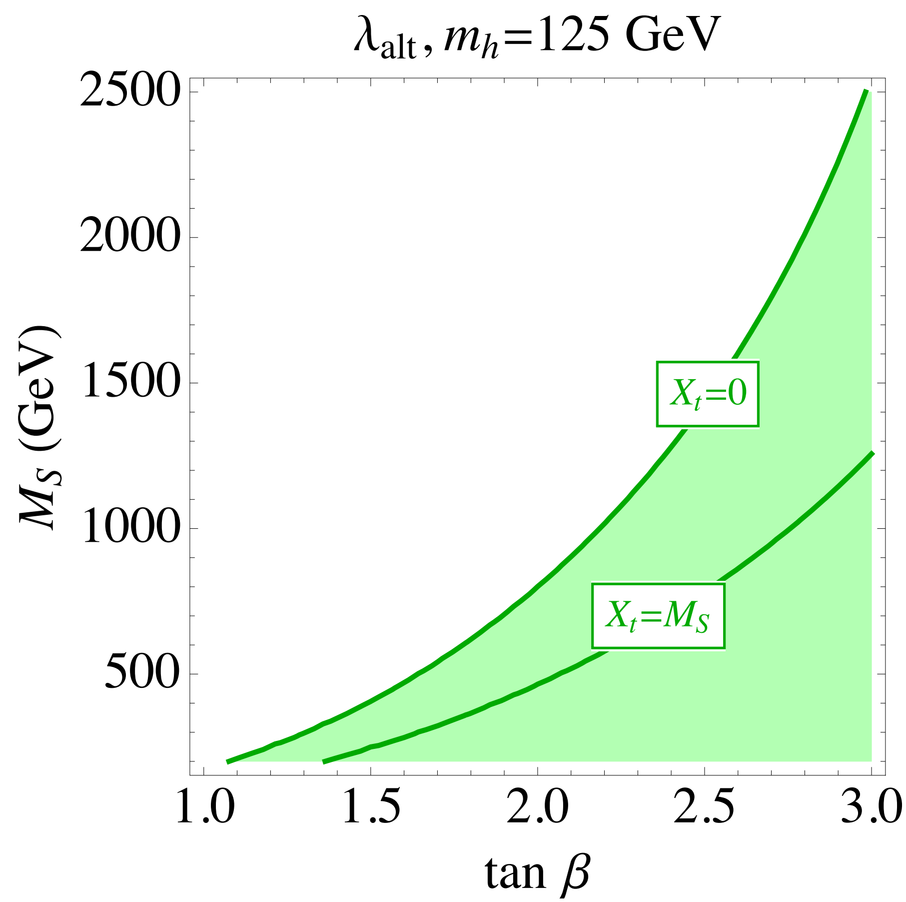
Stop Contribution at alignment

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

Interesting, after some simple algebra, one can show that

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$





For moderate mixing, It is clear that low values of $\tan\beta < 3$ lead to lower corrections to the Higgs mass parameter at the alignment values

Loop Induced Couplings

They may be efficiently computed using effective theory methods

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i 2b_i \frac{\partial}{\partial \log v}\log m_i(v)\right] F_{\mu\nu}F^{\mu\nu}$$

$$\left\{ \begin{aligned} b &= \frac{4}{3} N_c Q^2 \quad \text{for a Dirac fermion },\\ b &= -7 \qquad\quad \text{for the } W \text{ boson },\\ b &= \frac{1}{3} N_c Q_S^2 \quad \text{for a charged scalar }. \end{aligned} \right.$$

where in the Standard Model

$$\frac{g_{hWW}}{m_W^2} = \frac{\partial}{\partial v}\log m_W^2(v) , \qquad \frac{2 g_{ht\bar{t}}}{m_t} = \frac{\partial}{\partial v}\log m_t^2(v)$$

This generalizes for the case of fermions with contributions to their masses independent of the Higgs field. The couplings come from the vertex and the inverse dependence on the masses from the necessary chirality flip (for fermions) and the integral functions.

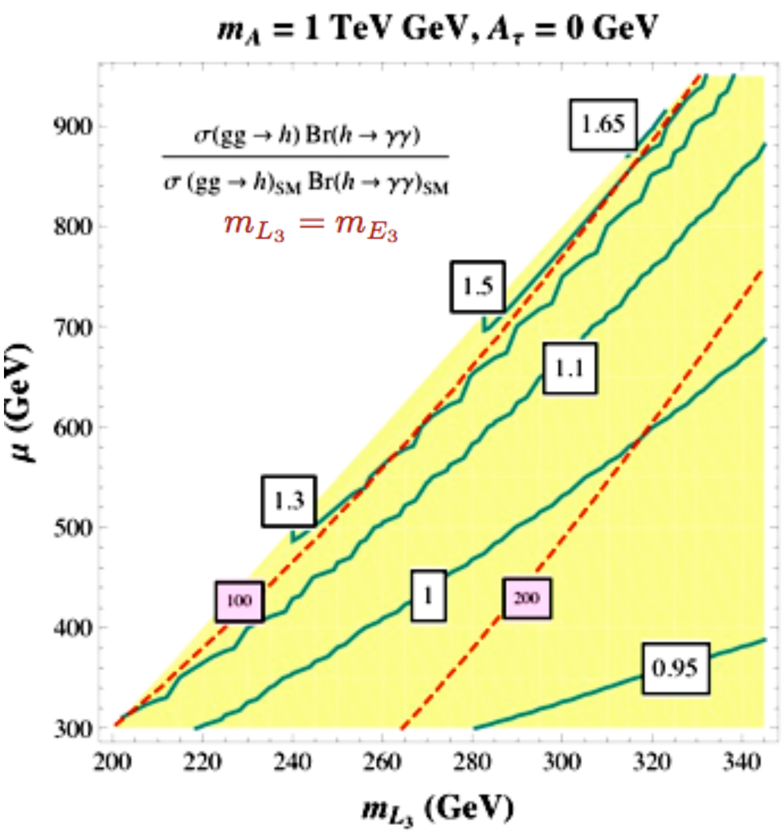
$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{B,i}^2\right)\right] F_{\mu\nu}F^{\mu\nu}$$

M. Carena, I. Low, C.W., arXiv:1206.1082, Ellis, Gaillard, Nanopoulos'76, Shifman, Vainshtein, Voloshin, Zakharov'79

Similar expressions may be obtained for the gluon coupling

Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}_{\tilde{\tau}}^2 \simeq \begin{bmatrix} m_{L_3}^2 + m_\tau^2 + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m_{E_3}^2 + m_\tau^2 + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ **enhancement of the Higgs to di-photon decay rate**

Contours of constant

$$\frac{\sigma(gg \to h)Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{SM} Br(h \to \gamma\gamma)_{SM}}$$

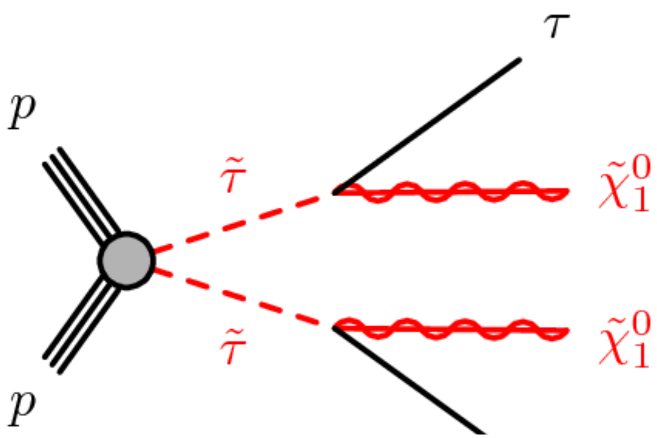
for M_h ~ 125 GeV

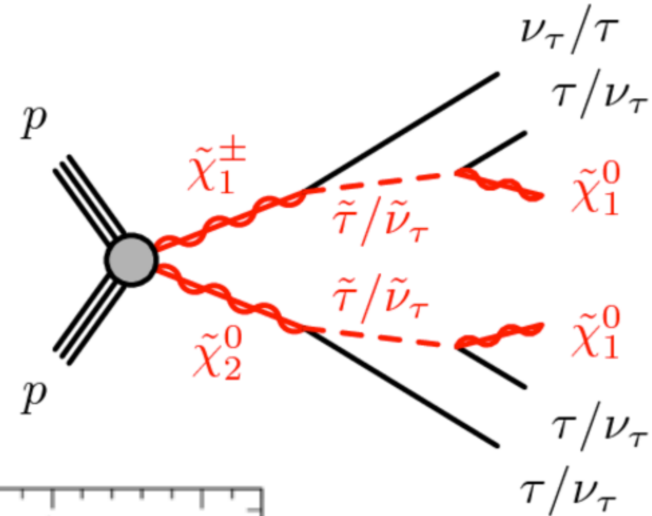
M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T. Wang, arXiv:1205.5842

Decrease for heavy staus explained by stop contribution to gluon fusion process

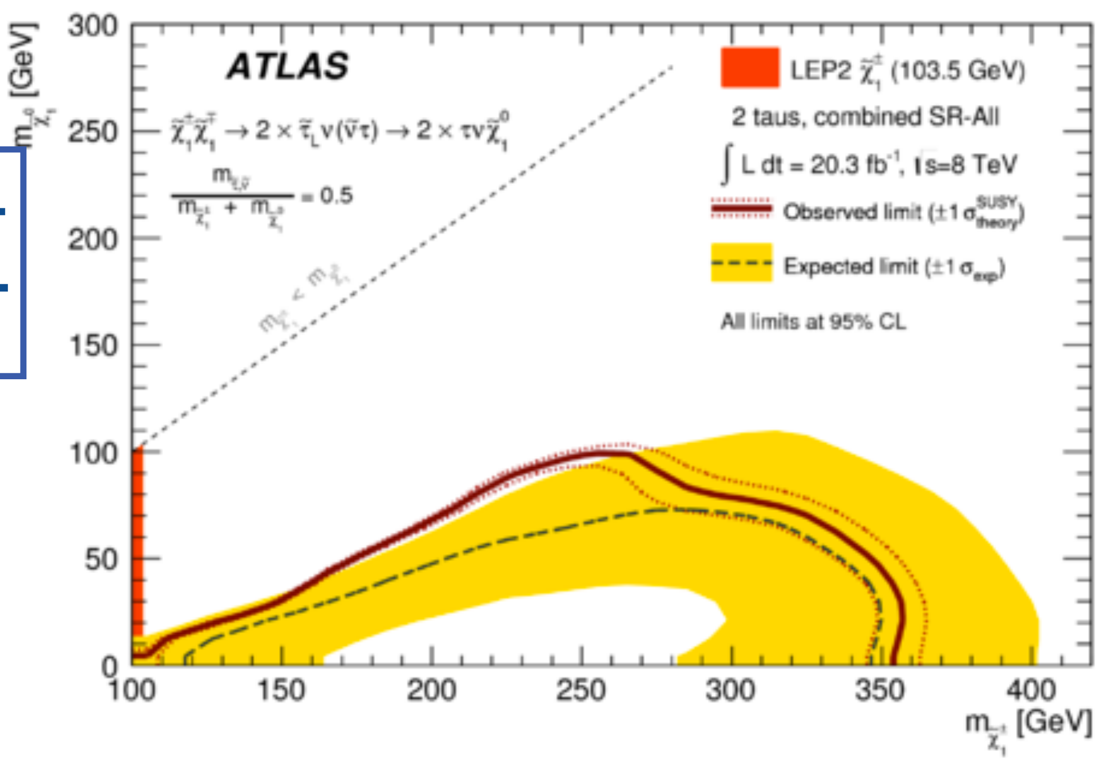
$$\frac{A_{ggh}^{\tilde{t}}}{A_{ggh}^{top}} \simeq \frac{m_t^2}{4} \frac{\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2\right)}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}$$

Stau Searches





2 taus + Miss. ET



Alternative :

Stau-sneutrino production

2 taus + W + Miss. ET

Carena, Gori, Shah, Wang, C.W'13

Direct stau decay into taus quite difficult. No bounds

SUSY and Experimental Anomalies

SUSY and (not very significant) Experimental Anomalies

Summary of LHC Experimental Anomalies

B. Hooberman'15

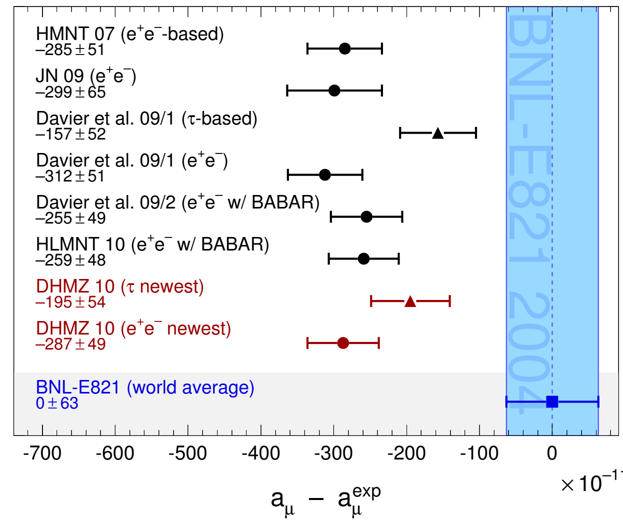
Search	Dataset	**Max Significance**	Reference
Dilepton mass edge	CMS 8 TeV	**2.6σ**	CMS-PAS-SUS-12-019
WW cross section	CMS 7 TeV	**1.0σ**	EPJC 73 2610 (2013)
WW cross section	CMS 8 TeV	**1.7σ**	PLB 721 (2013)
$3\ell+E_T^{miss}$ electroweak SUSY	CMS 8 TeV	**~2σ**	EPJC 74 (2014) 3036
$4\ell+E_T^{miss}$ electroweak SUSY (see backup)	CMS 8 TeV	**~3σ**	PRD 90, 032006 (2014)
Higgs→$\mu\tau$ (lepton flavor violation)	CMS 8 TeV	**2.5σ**	CMS-PAS-HIG-14-005
1st generation leptoquarks (eνjj channel)	CMS 8 TeV	**2.6σ**	CMS-PAS-EXO-12-041
ttH with same-sign muons	CMS 8 TeV	**$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$**	arXiv:1408.1682v1 [hep-ex]
Dijet resonance search	CMS 8 TeV	**~2σ**	arXiv:1501.04198 [hep-ex]
$3\ell+E_T^{miss}$ electroweak SUSY	ATLAS 8 TeV	**2.2σ**	PRD 90, 052001 (2014)
Soft $2\ell+E_T^{miss}$ strong SUSY	ATLAS 8 TeV	**2.3σ**	ATLAS-CONF-2013-062
WW cross section	ATLAS 7 TeV	**1.4σ**	PRD 87, 112001 (2013)
WW cross section	ATLAS 8 TeV	**2.0σ**	ATLAS-CONF-2014-033
Monojet search	ATLAS 8 TeV	**1.7σ**	arXiv:1502.01518 [hep-x]
H→h(bb)h(γγ)	ATLAS 8 TeV	**2.4σ**	arXiv:1406.5053 [hep-ex]

Muon Anomalous Magnetic Moment

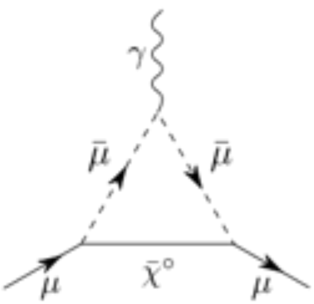
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

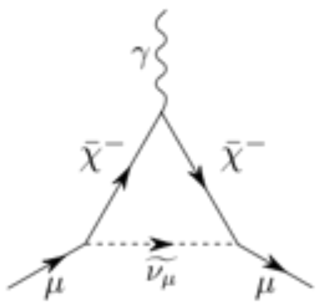
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287\ (63)(49) \times 10^{-11}$$

3.6σ Discrepancy



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





$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100 \text{ GeV}}{\tilde{m}}\right)^2 \tan\beta$$

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

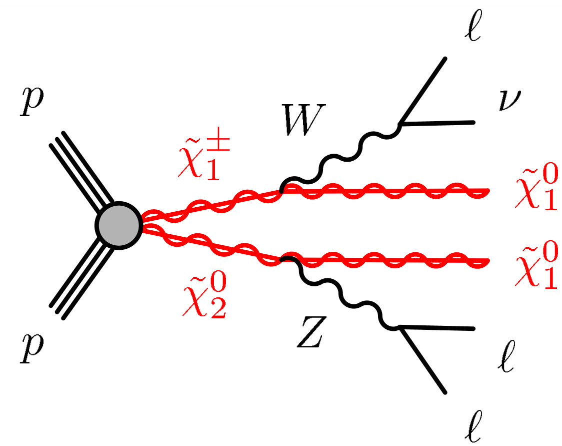
Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

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

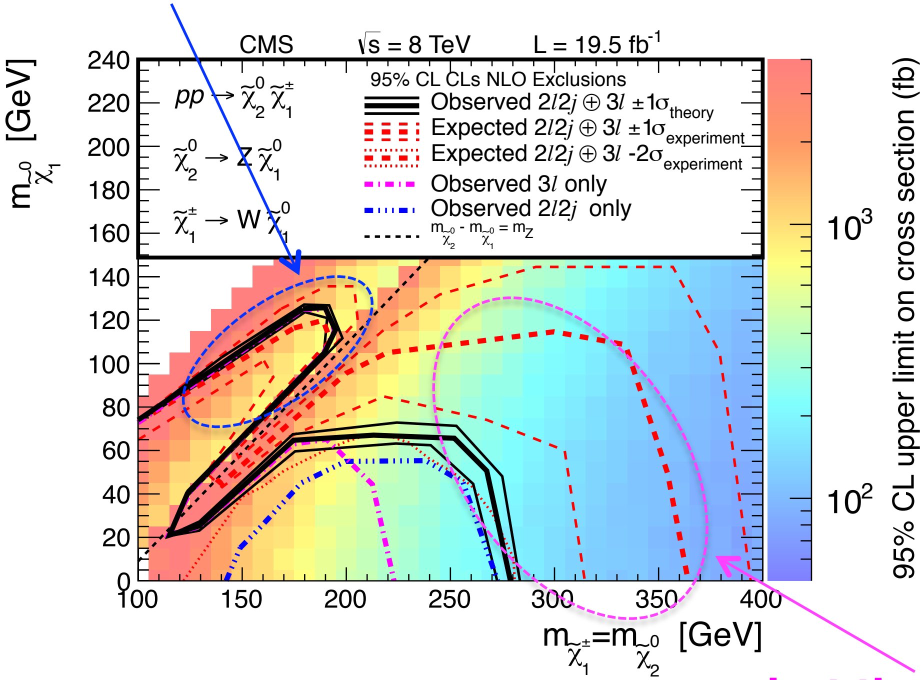
Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

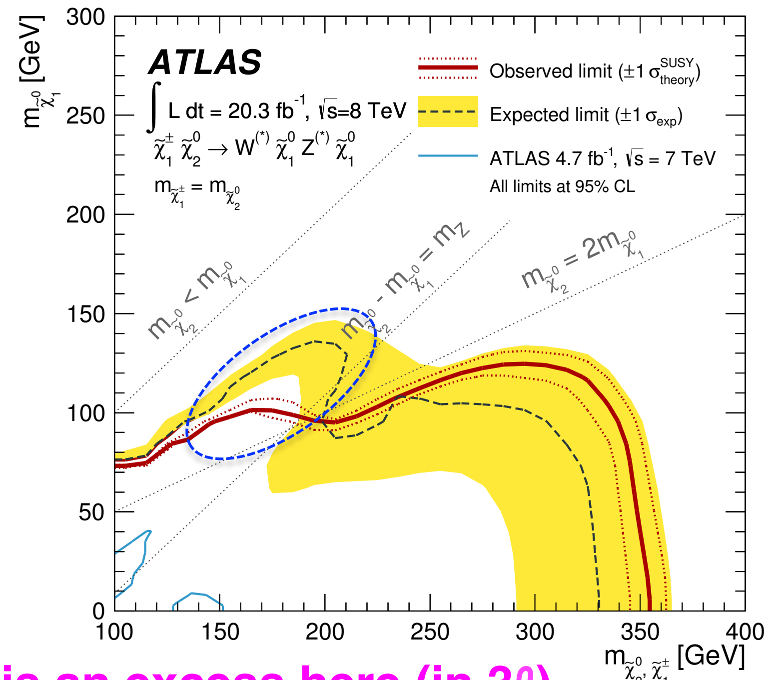
Trilepton Excess ?

- CMS search for $\chi^+\chi^0 \longrightarrow WZ+E_T^{miss}$
  - Search in $WZ \longrightarrow 3\ell$ and $WZ \longrightarrow (jj)(\ell\ell)$ channels



no excess here



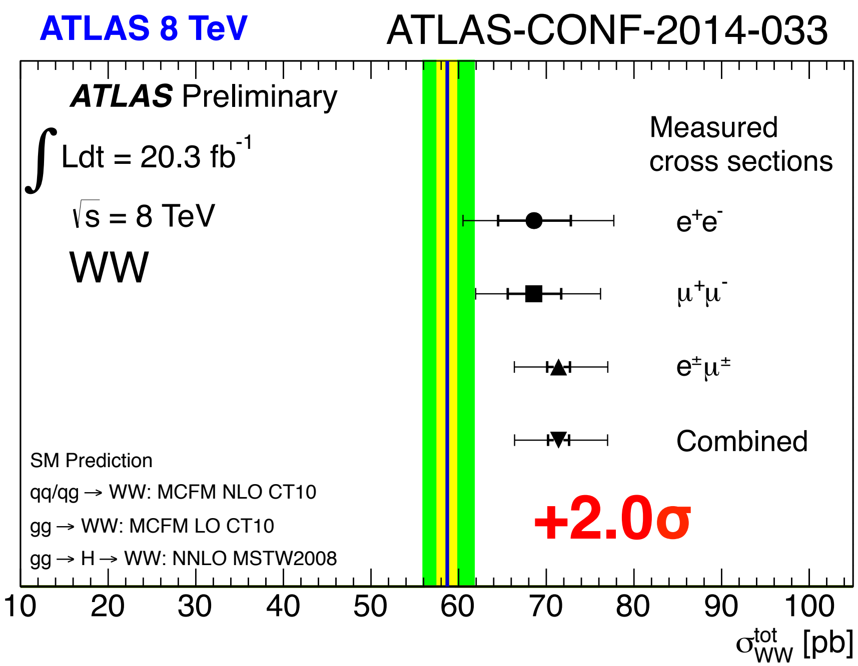


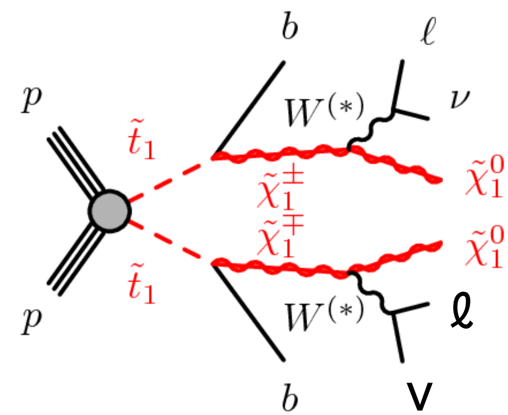
… but there is an excess here (in 3ℓ)

CMS, EPJC 74 (2014) 3036

B. Hooberman'15

WW Excess ?





$$m_{\tilde{t}_1} = 202^{+35}_{-25}\ \text{GeV},$$
$$m_{\tilde{\chi}_1^0} = 140^{+25}_{-15}\ \text{GeV}$$
$$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = m_{\tilde{t}} - 7\ \text{GeV}$$

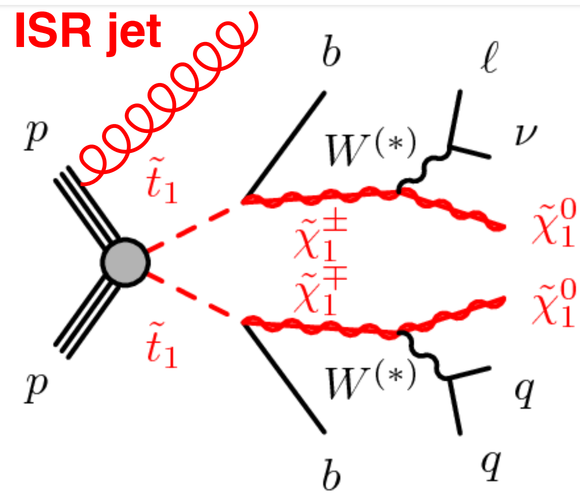
See K. Bachas, J. Gao and M. Grazzini talks
NNLO Effects relevant, reduce effect to one σ

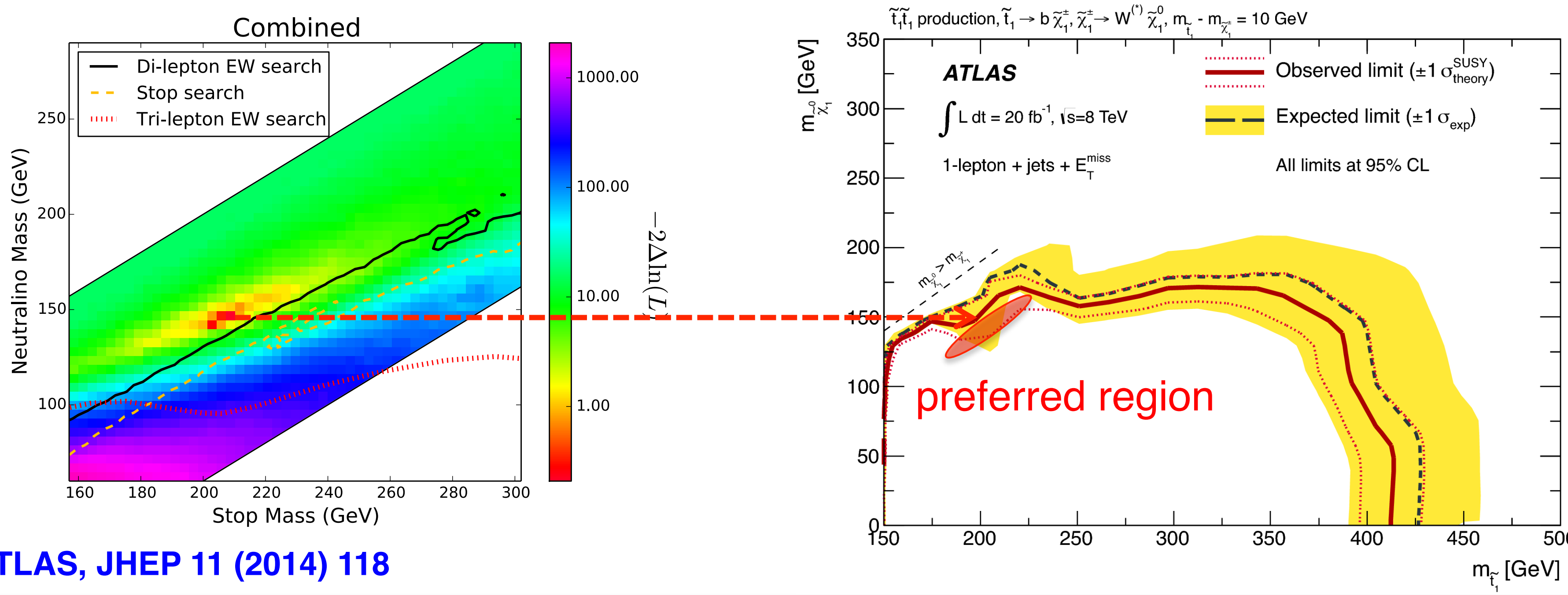
Light Stop solution proposed by
Curtin, Meade, Tien; Kim, Robiecki and Sakurai '14

Could contribute to ATLAS 3l excess...

Further Probes of Relevant Parameter Space

- ATLAS 1ℓ stop search probes this model using ISR jet selection
- Preferred region is excluded, but at edge of sensitivity





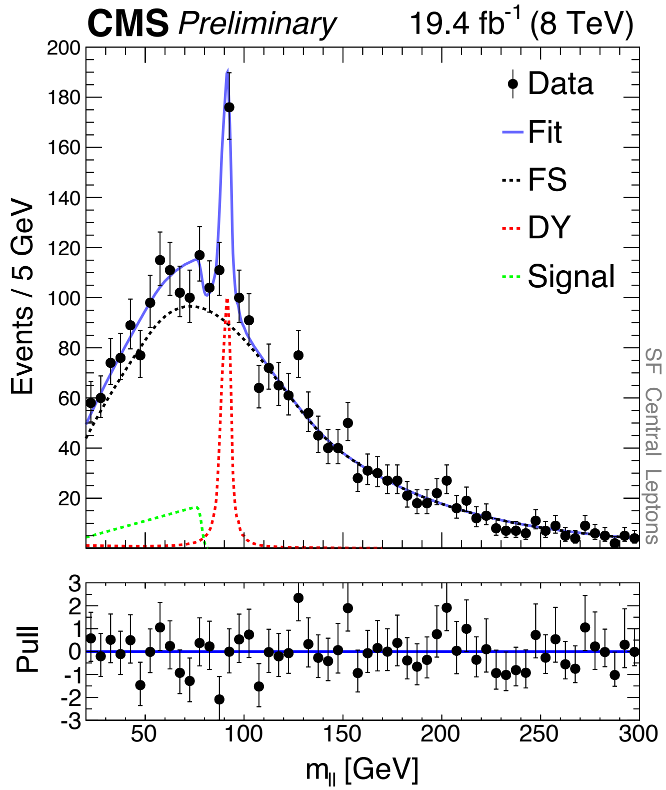
ATLAS, JHEP 11 (2014) 118

Hooberman '15

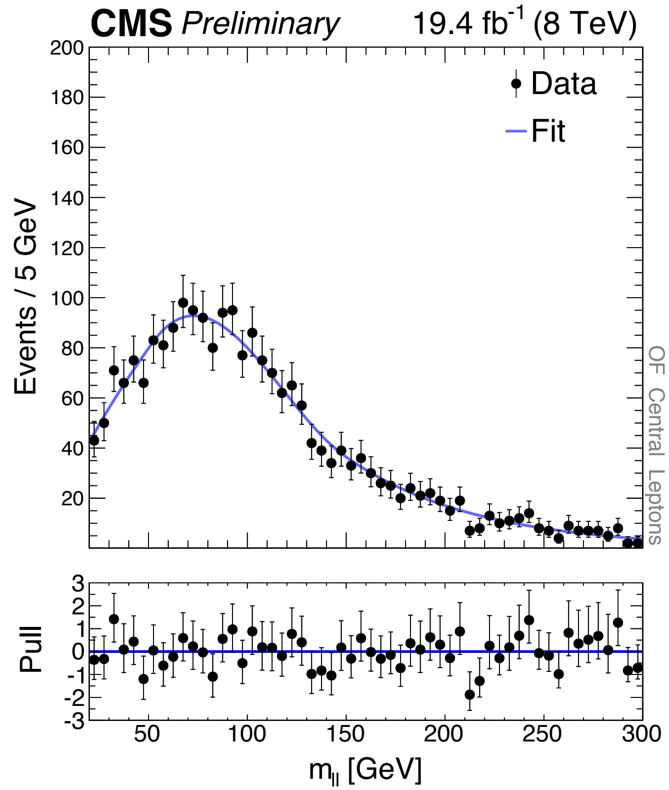
Edge in the invariant mass distribution of leptons

2 e/μ leptons with $p_T > 20$ GeV and $|\eta| < 1.4$
($n_{jets} \geq 2$ AND $E_T^{miss} > 150$ GeV) OR
($n_{jets} \geq 3$ AND $E_T^{miss} > 100$ GeV)

ee+μμ search region

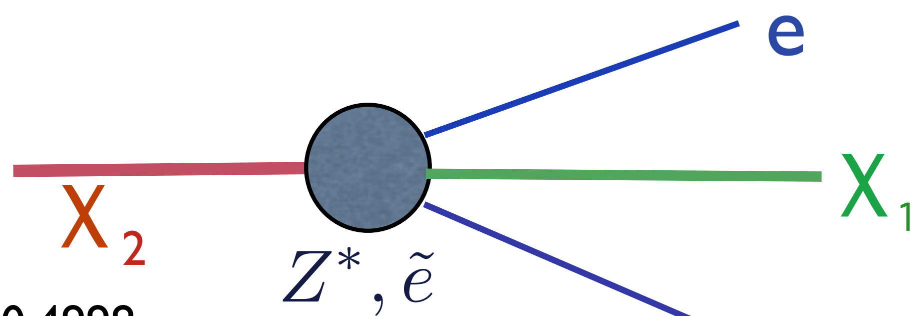


eμ control region



$$\tilde{b} \to b\ \chi_2^0$$

$$\tilde{b} \to b\ \chi_2^0 \to b\ e^+ e^- \chi_1^0$$



$m_{\tilde{b}} \simeq 390\text{GeV}$

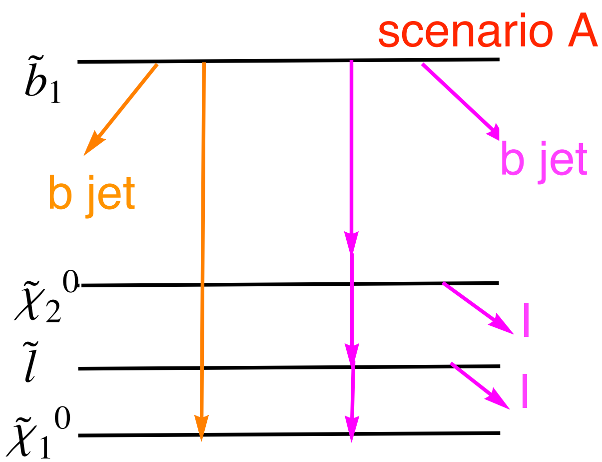
$m_{\tilde{\chi}_2^0} \simeq 340\text{GeV}$

$m_{\tilde{\chi}_1^0} \simeq 260\text{GeV}$

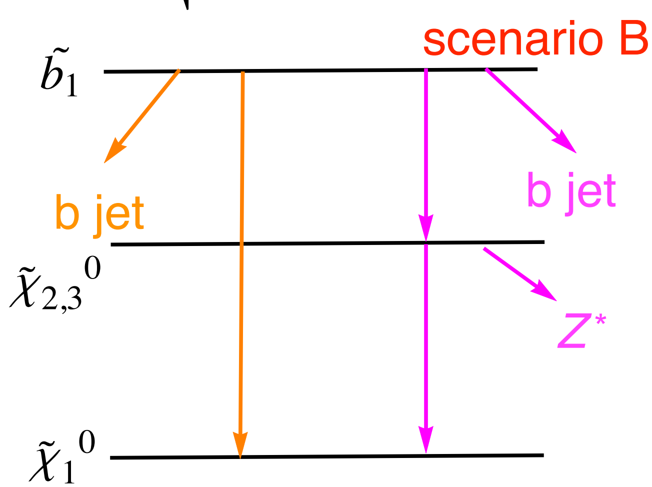
P. Huang, C.W., arXiv:1410.4998

Two Possible Scenarios

P. Huang, C.W. , arXiv:1410.4998



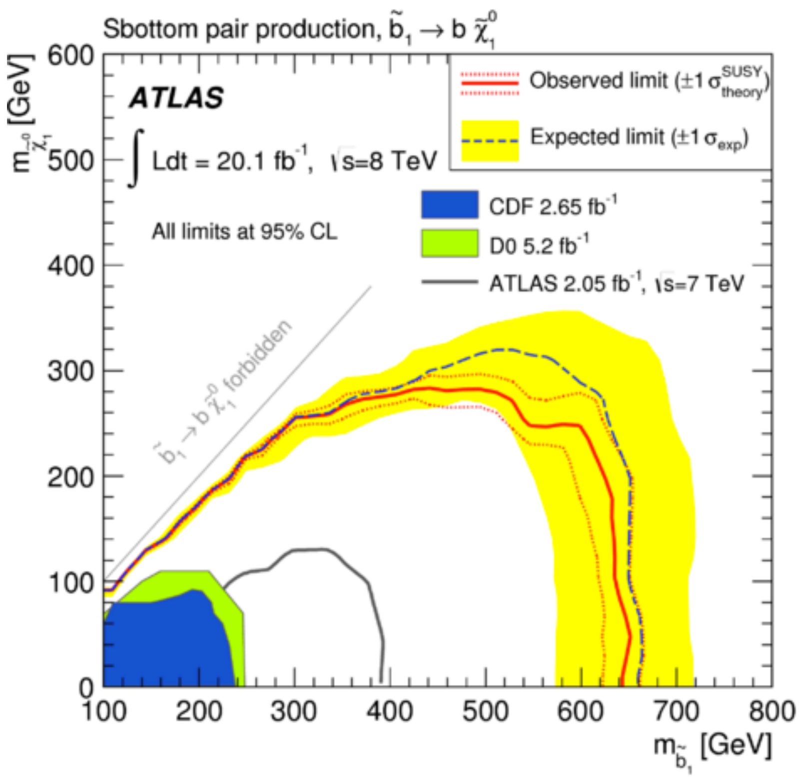
$$m_{ll}^{edge} = \sqrt{\frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}}}}$$

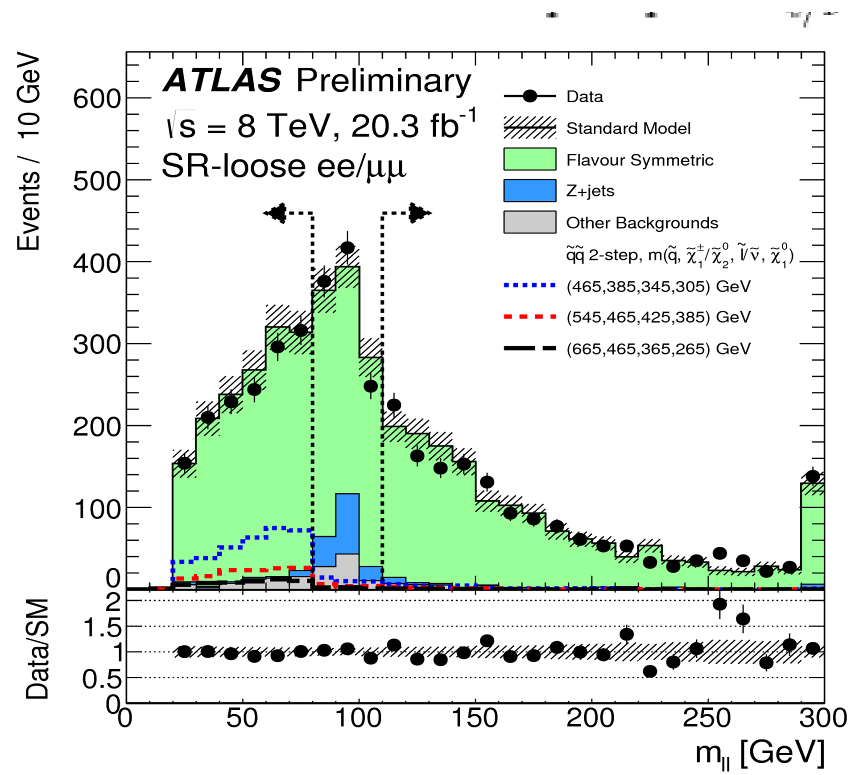


$$m_{ll}^{edge} = m_{\tilde{\chi}^0_2,\tilde{\chi}^0_3} - m_{\tilde{\chi}^0_1}$$

parameter	scenario A	scenario B
$m_{\tilde{b}_1}$ (GeV)	390	330
$m_{\tilde{\chi}^0_1}$ (GeV)	260	212
$m_{\tilde{\chi}^0_2}$ (GeV)	340	288
$m_{\tilde{\chi}^0_3}$ (GeV)	$\sim$ 500	290
$m_{\tilde{l}}$ (GeV)	297	500
$\tan\beta$	25	50
$\sigma(pp \to \tilde{b}_1\tilde{b}_1)$ (pb)	0.42	1.14
BF$(\tilde{b}_1 \to b\tilde{\chi}^0_1)$	0.93	0.56
BF$(\tilde{b}_1 \to b\tilde{\chi}^0_2)$	0.07	0.25
BF$(\tilde{b}_1 \to b\tilde{\chi}^0_3)$	0	019
Δa_μ	2.0×10^{-9}	2.7×10^{-9}
Ωh^2	0.11	0.11

Constraint from ATLAS :
1) Sbottom Searches in events with bottoms and Missing Energy
2) Searches for a similar edge in the invariant mass distribution
No excess found !



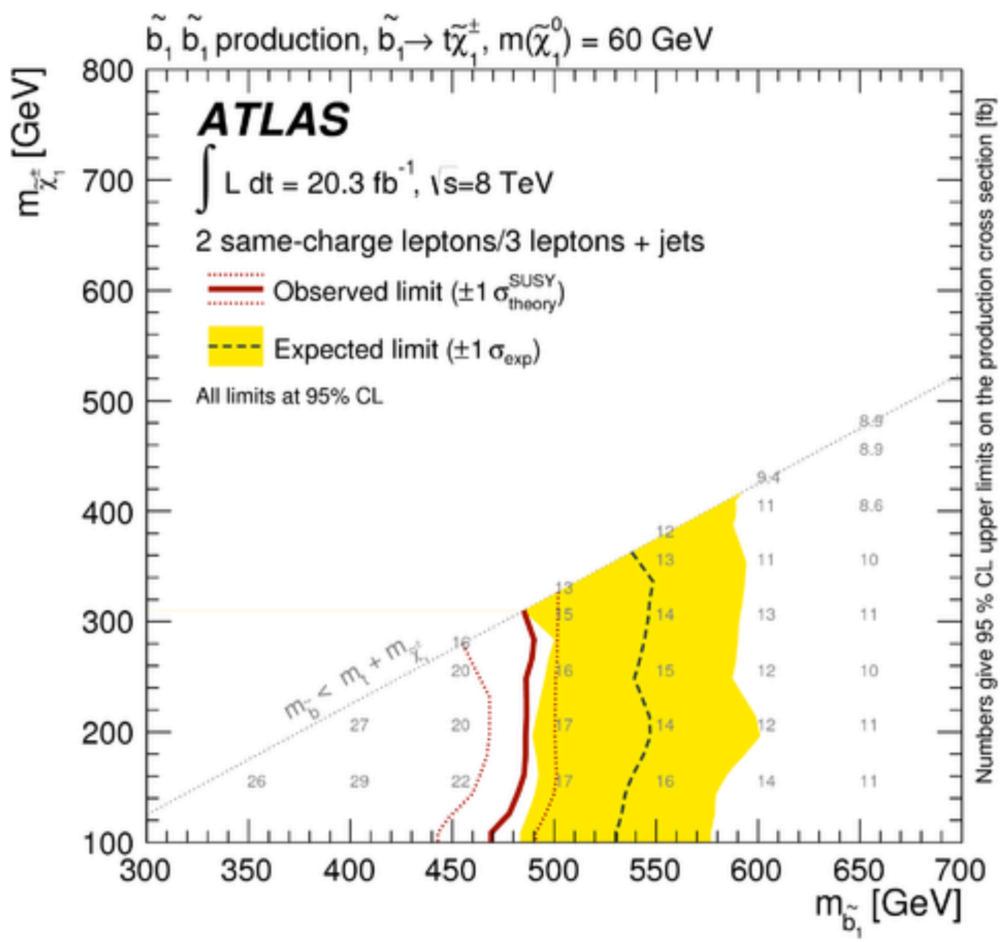


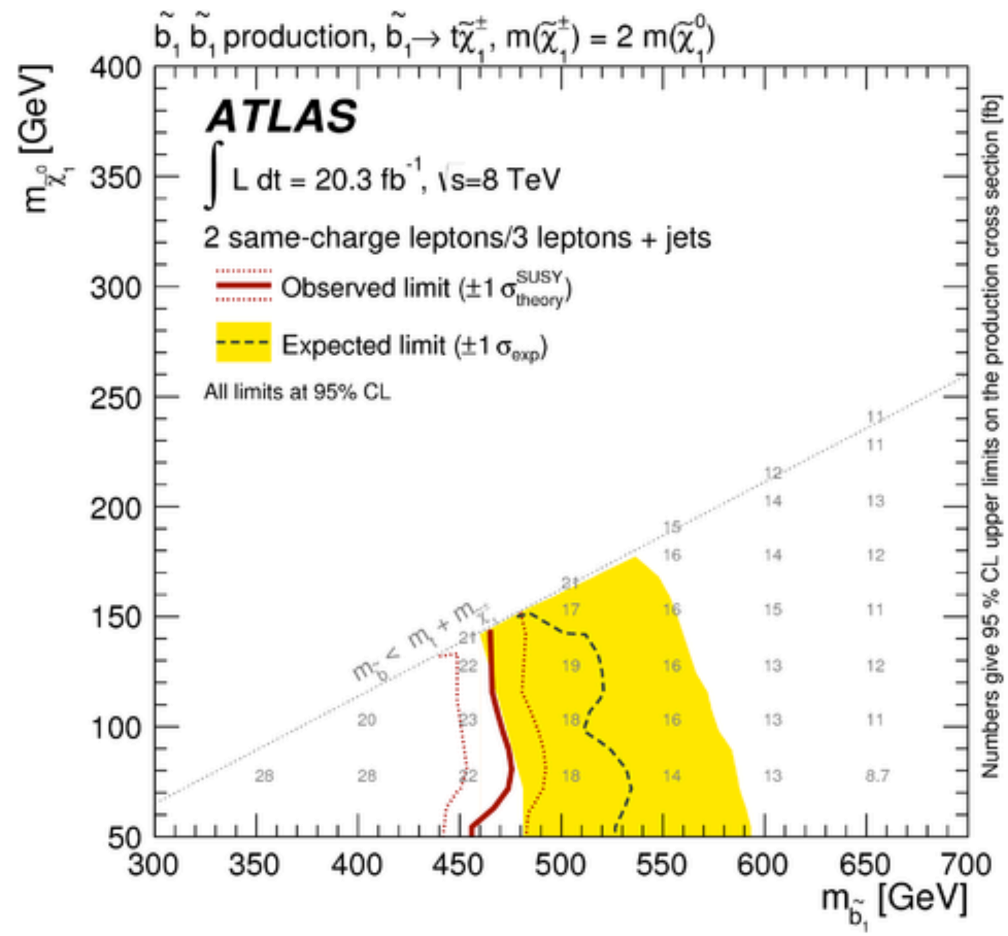
	Dilepton edge	Z+MET
ATLAS	No excess	3.0σ
CMS	2.6σ	No excess

The ATLAS and CMS edge selections are the same (by design) but the Z+MET are different, only ~30% of our events enter the CMS selection

Sbottom Searches

Small excess observed in 2 bottoms plus
equal sign leptons or tripleptons

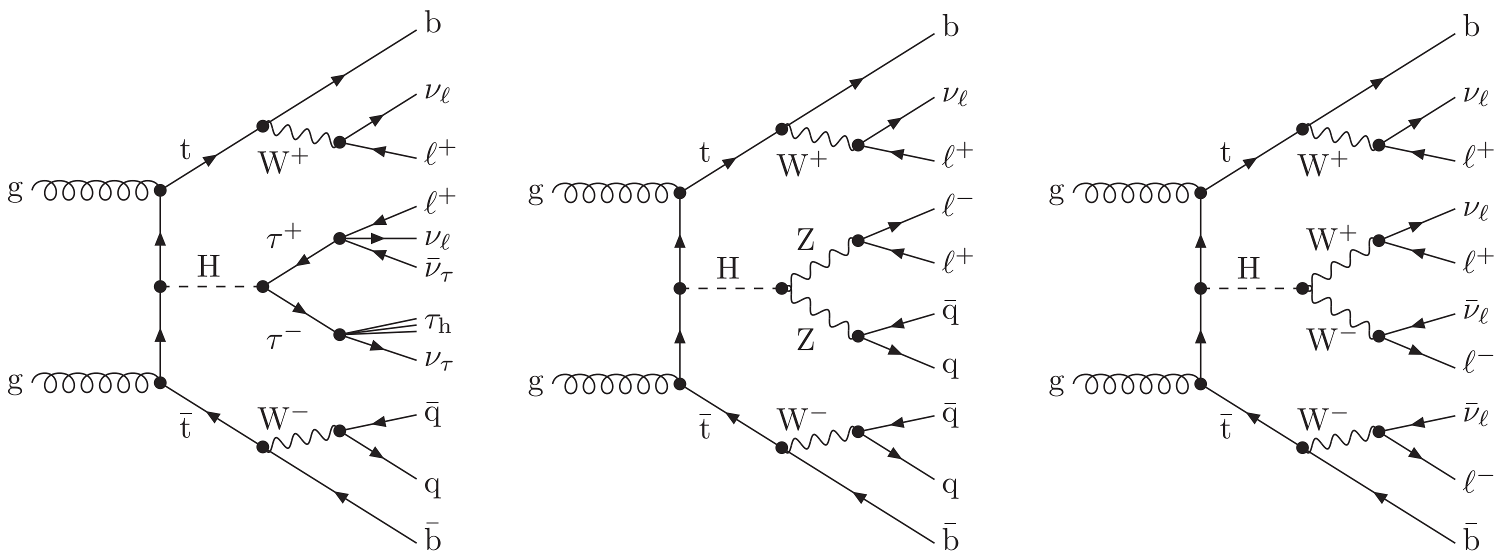




2 b + 4 W + Missing ET

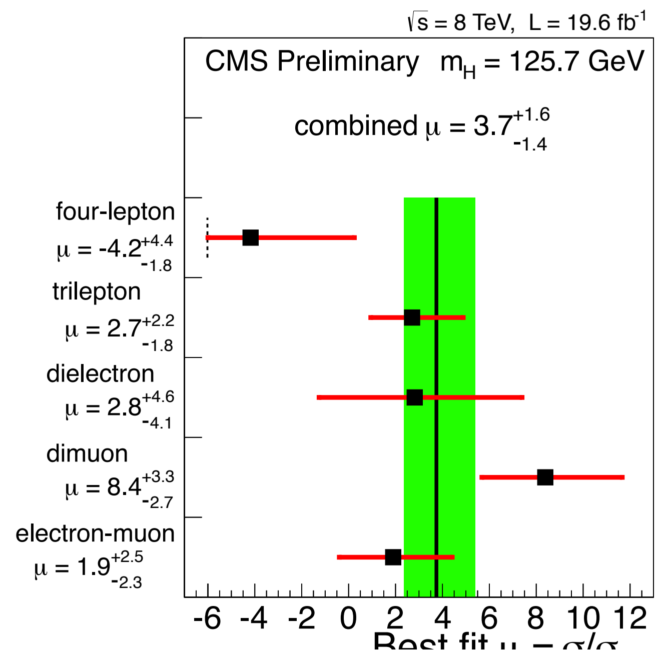
$ttH, H \rightarrow WW$

CMS-Hig13-020



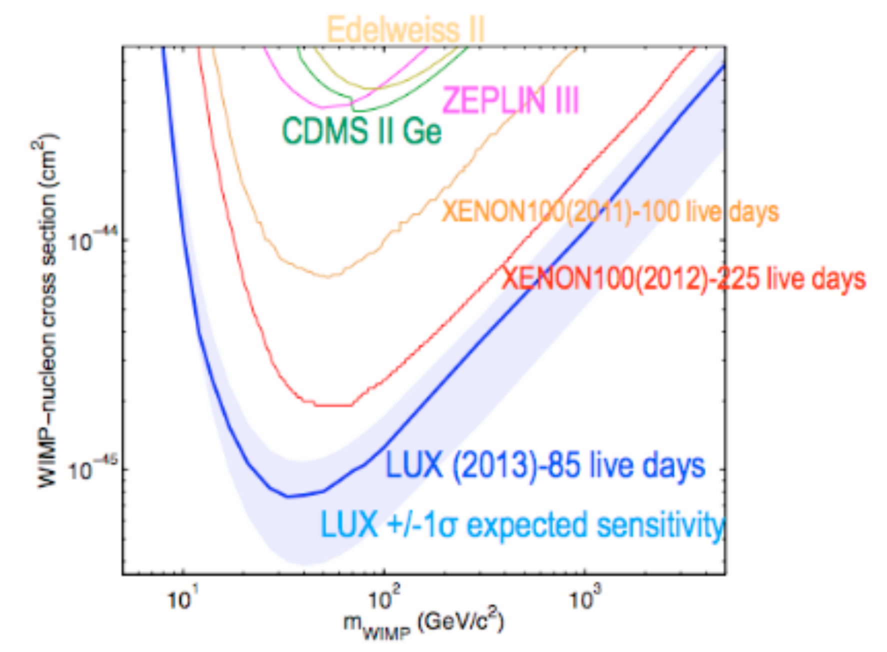
Most relevant channels : 2 bottom-quarks and equal sign leptons/trileptons

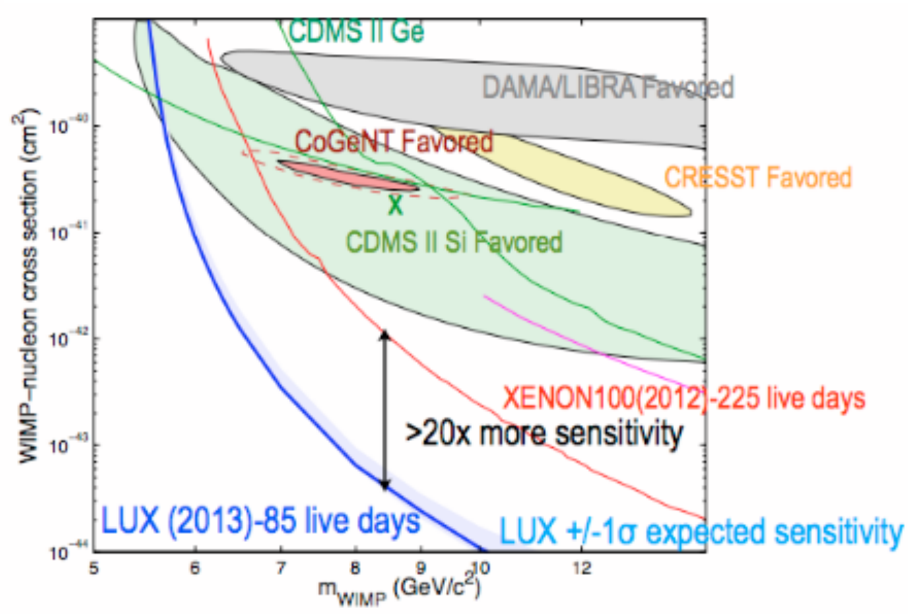
	$\mu\mu$	ee	eμ	3ℓ	4ℓ
$t\bar{t}H$, $H \rightarrow WW$	2.0 ± 0.3	0.9 ± 0.1	2.7 ± 0.4	3.2 ± 0.6	0.28 ± 0.05
$t\bar{t}H$, $H \rightarrow ZZ$	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \rightarrow \tau\tau$	0.6 ± 0.1	0.3 ± 0.0	0.9 ± 0.1	1.0 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	8.2 ± 1.5	3.4 ± 0.6	13.0 ± 2.2	9.2 ± 1.9	-
$t\bar{t}Z/\gamma^*$	2.5 ± 0.5	1.6 ± 0.3	4.2 ± 0.9	7.9 ± 1.7	1.25 ± 0.88
$t\bar{t}WW$	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	-	1.3 ± 0.3	1.9 ± 0.5	2.9 ± 0.8	-
WZ	0.8 ± 0.9	0.5 ± 0.5	1.2 ± 1.3	4.2 ± 0.9	-
ZZ	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.4 ± 0.1	0.45 ± 0.09
rare SM bkg.	1.1 ± 0.0	0.4 ± 0.0	1.5 ± 0.0	0.8 ± 0.0	0.01 ± 0.00
non-prompt	10.8 ± 4.8	8.9 ± 4.5	21.2 ± 8.1	33.2 ± 12.3	0.53 ± 0.32
charge flip	-	1.9 ± 0.6	2.4 ± 0.8	-	-
all signals	2.7 ± 0.4	1.2 ± 0.2	3.7 ± 0.6	4.4 ± 0.8	0.52 ± 0.09
all backgrounds	23.7 ± 5.2	18.0 ± 4.7	45.9 ± 8.6	58.9 ± 12.7	2.28 ± 0.94
data	41	19	51	68	1



Work correlating these signals in progress :
S. Gori, A. Ismail, P. Huang, I. Low, C.W.'15

Direct Dark Matter Detection





Non-observation of any Spin Independent Signal

Ellis, Ferstl, Olive'00, Ellis et al'05, Baer et al'07
Cheung, Hall, Pinner, Rudermann '13
Huang, C.W. '14

Blind Spots for Gaugino--Higgsino Mixed Dark Matter

$$2\ (m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq -\ \mu \tan\beta \frac{1}{m_H^2}$$

Not covered, but may be interesting : Gamma-Ray Galactic center Excess

- Interesting excess of gamma rays with energies in the few to tens of GeV
- Dark Matter annihilation cross section necessary to explain these events consistent with the one necessary to generate thermal relic density
- Most plausible explanation within supersymmetry via the resonance annihilation from pseudoscalars. Difficult in the MSSM but possible in NMSSM

See, for instance, Cheung, Papucci, Sanford, Shah, Zurek'14

- Annihilation into W pairs also possible, although does not provide equally good fit

See, for instance, Agrawal, Batell, Fox, Harnik'15

Conclusions

- Low energy supersymmetry provides a very predictive framework for the computation of the Higgs phenomenology.
- The properties of the lightest and heavy Higgs bosons depend strongly on radiative corrections mediated by the stops.
- Alignment in the MSSM appears for large values of mu, for which decays into charginos and neutralinos are suppressed, making the bounds coming from decays into SM particles stronger.
- Complementarity between precision measurements and direct searches will allow to probe efficiently the MSSM Higgs sector
- In the NMSSM, alignment occurs in regions of parameter space in which the naturalness conditions are fulfilled.
- Few experimental anomalies may be pointing to an unexpected low energy spectrum, that may be tested at the next LHC run