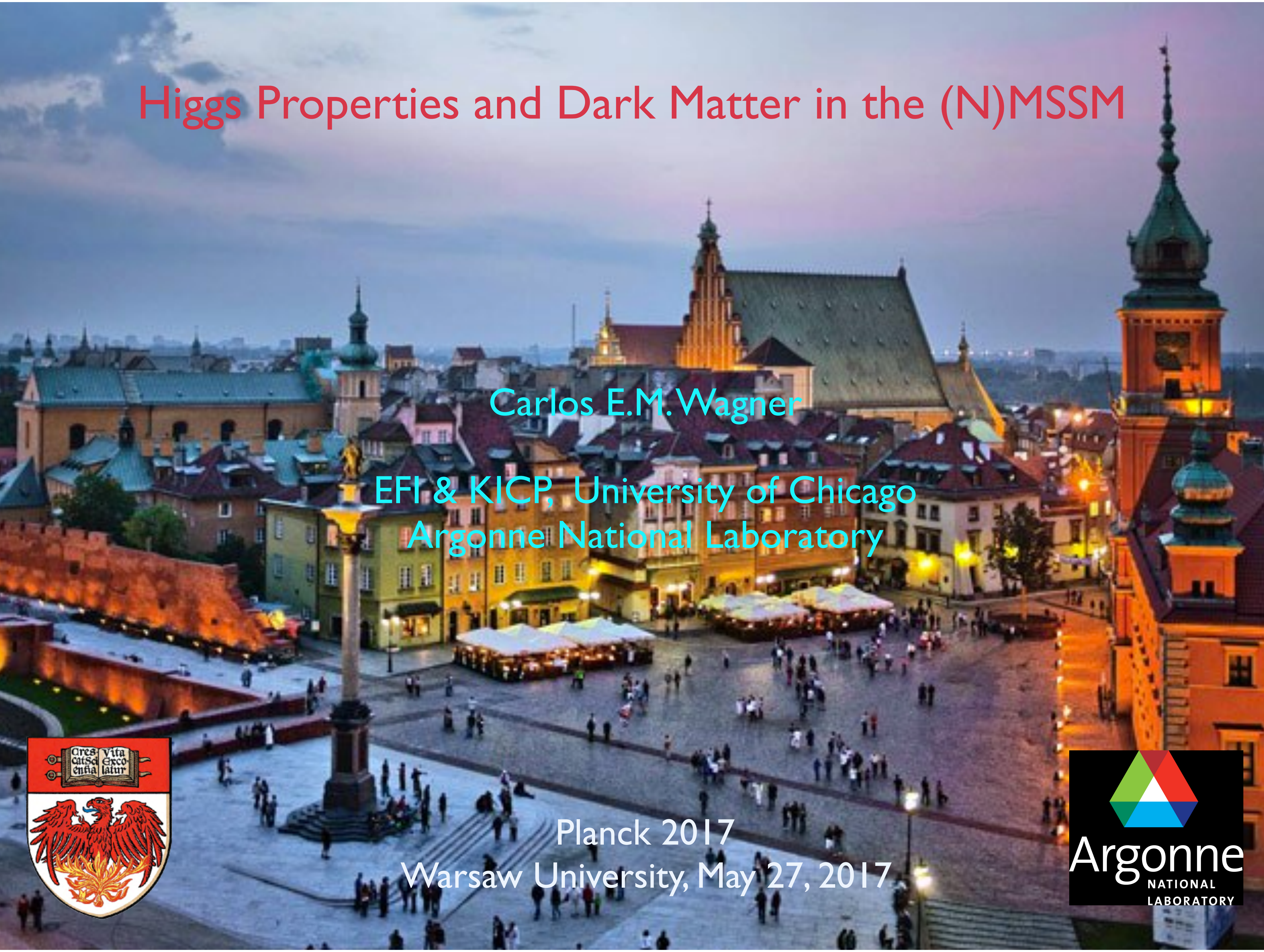


Higgs Properties and Dark Matter in the (N)MSSM

Carlos E.M. Wagner

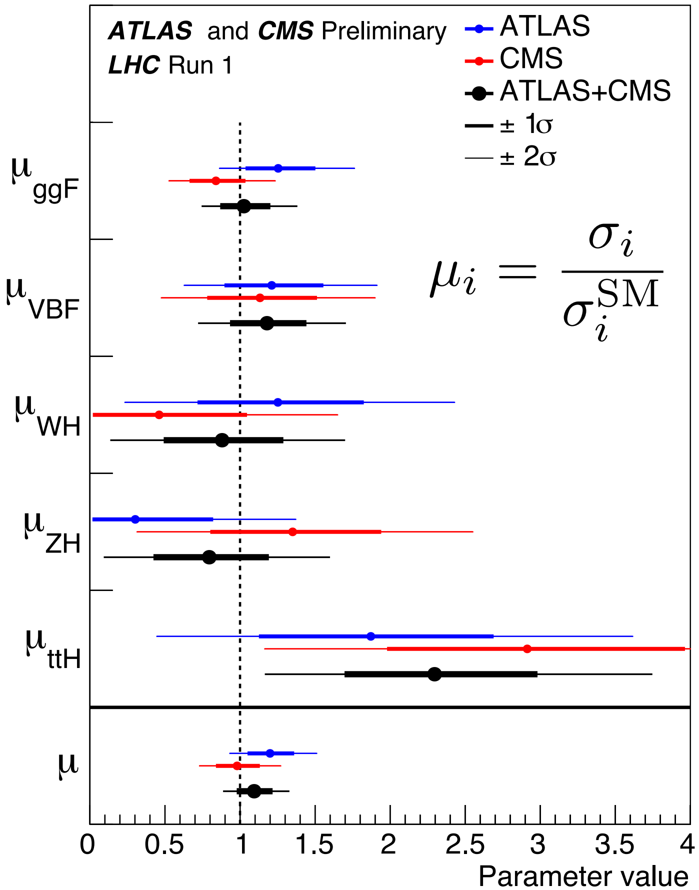
EFI & KICP, University of Chicago
Argonne National Laboratory

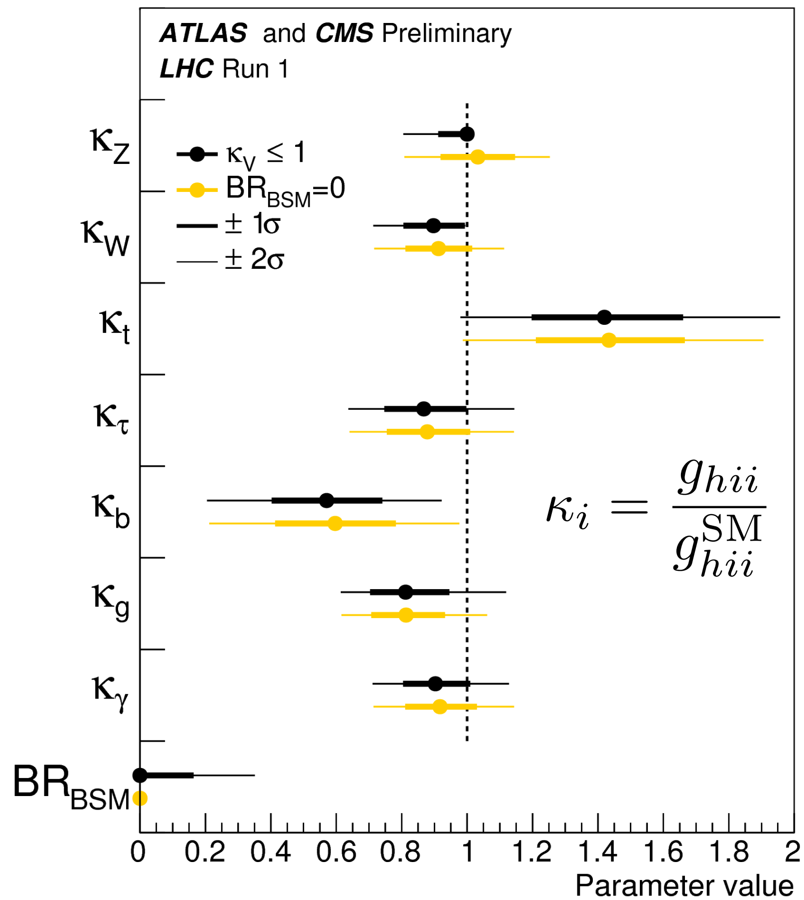
Planck 2017
Warsaw University, May 27, 2017

Higgs Properties

ATLAS and CMS Combination

Very good agreement of production rates with SM predictions





Assuming no strict correlation between gluon and top couplings

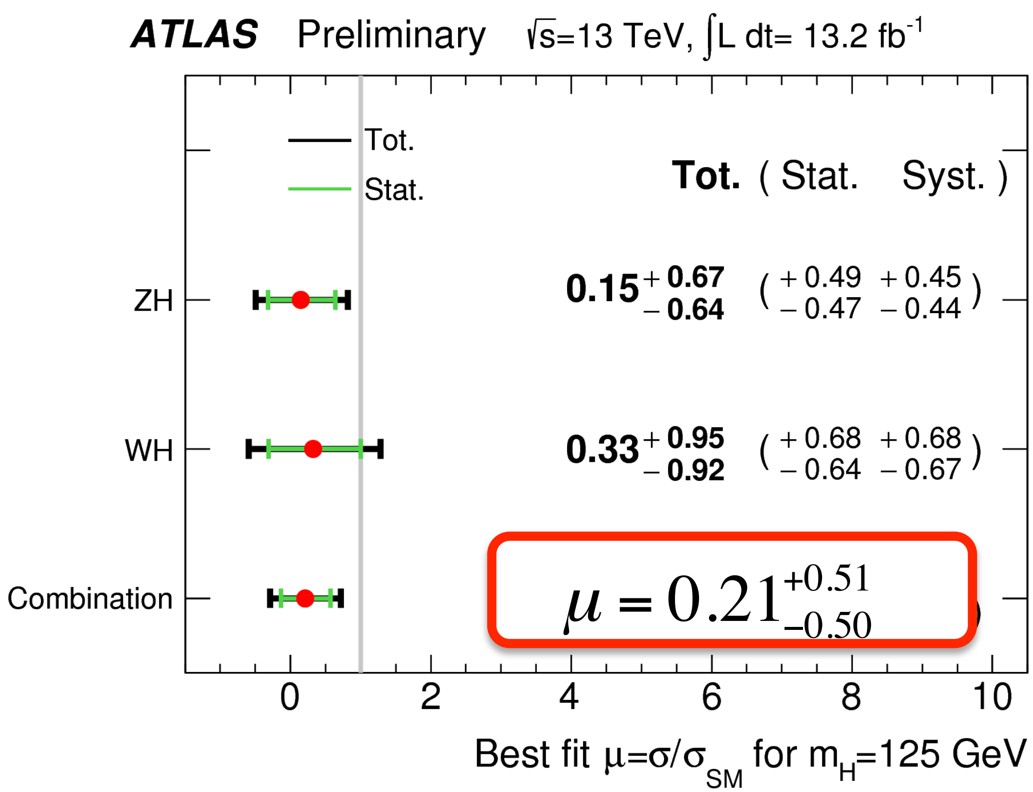
Direct Measurement of Bottom and Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible

Badziak, C.W.'16

Low bottom coupling has a major impact on the fit to the rest of the couplings.

Bottom Coupling Suppression ?

ATLAS-CONF-2016-091



	Significance (expected)
ATLAS (13 TeV)	0.4σ (1.94σ)
ATLAS+CMS (8 TeV)	2.6σ (3.7σ)
Tevatron	2.8σ

Fit tested on SM

	W(Z)Z(→bb)
Observed μ	0.91 ± 0.17(stat) $^{+0.32}_{-0.27}$(syst)
Significance	3.0σ (expected 3.2σ)

The tendency still persists in recent data,

It is important to stress that a suppression of the bottom coupling would affect all Higgs BRs in a relevant way. Persistence of signal strengths would demand suppression of gluon fusion rate

M. Badziak and C.W. ‘1602.06198

Away from Alignment : Modifying the top and bottom couplings in two Higgs Doublet Models

- The combination of Run I data has shown deviations of the third generation couplings to fermions.
- The enhancement on the top coupling is somewhat weaker in the 13 TeV data, although question is still open. Suppression of the bottom coupling still strong.
- Suppressing the bottom coupling is simple in type II 2HDM, and the top-quark coupling is modified as well in an opposite direction

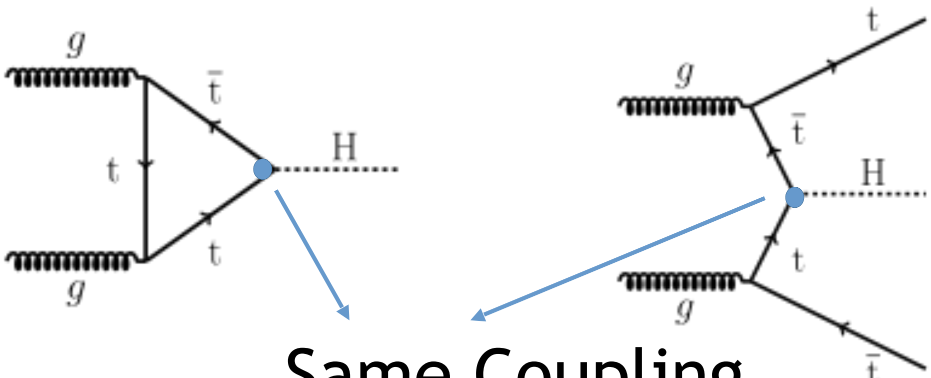
$$h = -\sin\alpha H_d^0 + \cos\alpha H_u^0$$
$$H = \quad \cos\alpha H_d^0 + \sin\alpha H_u^0$$
$$\tan\beta = \frac{v_u}{v_d}$$

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

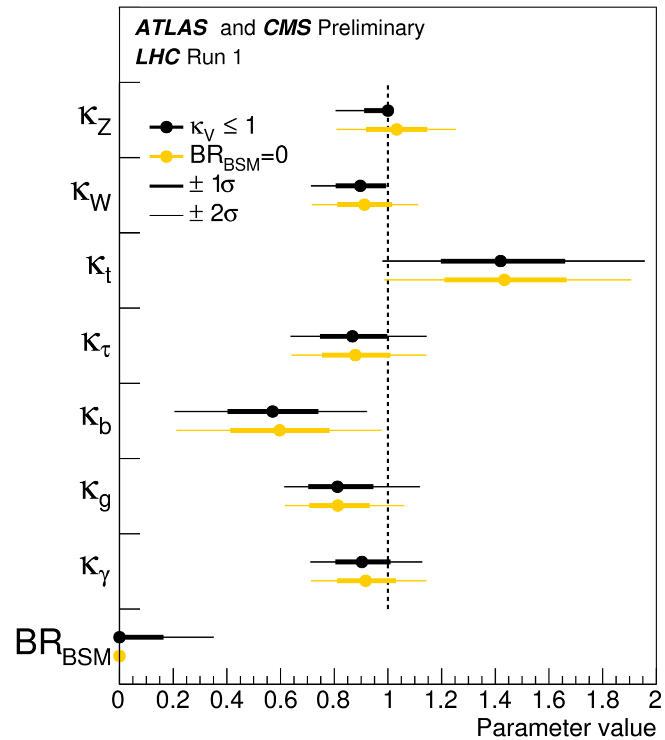
- This tendency is in agreement with the one present in the current data

What is the problem in 2HDM ?

Suppression of the gluon fusion rate ?



Same Coupling



Would expect top rate to be suppressed as well !

Additional contributions necessary to suppress the ggh coupling, as reflected in the best fit.

M. Badziak and C.W. ‘1602.06198, 1611.03253

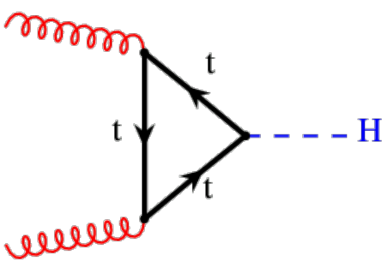
The Gluon Fusion Rate

- Suppression of the bottom coupling would demand some suppression of the gluon-Higgs coupling.

- Problem is even more severe when the top coupling is enhanced, since we have to compensate for this potential source of ggh enhancement

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

- However, the gluon fusion cross section could also be modified in the presence of extra color particles. For instance, for scalar tops,



$$\frac{\kappa_g}{\kappa_g^{\rm SM}} \simeq \kappa_t \left[1 + \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)\right]$$

- Can be done, but demands large mixing/light stops. Can be done in minimal composite models, but only for suppressed top couplings

Da Liu, Ian Low, C.W. arXiv: 1703.07791

Generic predictions of such strong modification of couplings within an extension of the SM

- Light charged and neutral scalars, decaying in standard as well as non-standard channels (flavor physics constraints may be avoided)
- Relatively light color states, contributing to gluon fusion
- Modification of all SM Higgs branching ratios in a correlated way
- In many cases, light electroweak particles to allow the new color particles to decay
- All these are being looked for by the LHC, but will be tested at higher luminosities !

Coupling of the Higgs to vector bosons and quarks within type II Higgs doublet models.

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

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

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

If the condition $\cos(\beta-\alpha) = 0$ is fulfilled, then the properties of the Higgs are the same as the SM ones. We denote this situation alignment. Namely, the mixing should vanish if we perform a β rotation

Alignment in general two Higgs Doublet Models

Haber and Gunion'03

$$\begin{aligned} V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &\quad + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &\quad + \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} , \end{aligned}$$

- From here, one can minimize the effective potential and derive the expression for the CP-even Higgs mass matrix in terms of a reference mass, that we will take to be mA

Carena, Low, Shah, C.W.'13, Carena, Haber, Low, Shah, C.W.'14

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

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

$$m_h^2 = (\lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2\tilde{\lambda}_3 s_\beta^2 c_\beta^2 + 4\lambda_7 s_\beta^3 c_\beta + 4\lambda_6 c_\beta^3 s_\beta) v^2$$

MSSM :

$$\begin{aligned} \lambda_1 &= -\tilde{\lambda}_3 = \frac{M_Z^2}{v^2} \\ \lambda_2 &= \lambda_1 + \delta_t \\ \lambda_7 &\simeq -\frac{3 h_t^4 A_t \mu}{16\pi^2 M_S^2} \left(1 - \frac{A_t^2}{6 M_S^2} \right) \end{aligned}$$

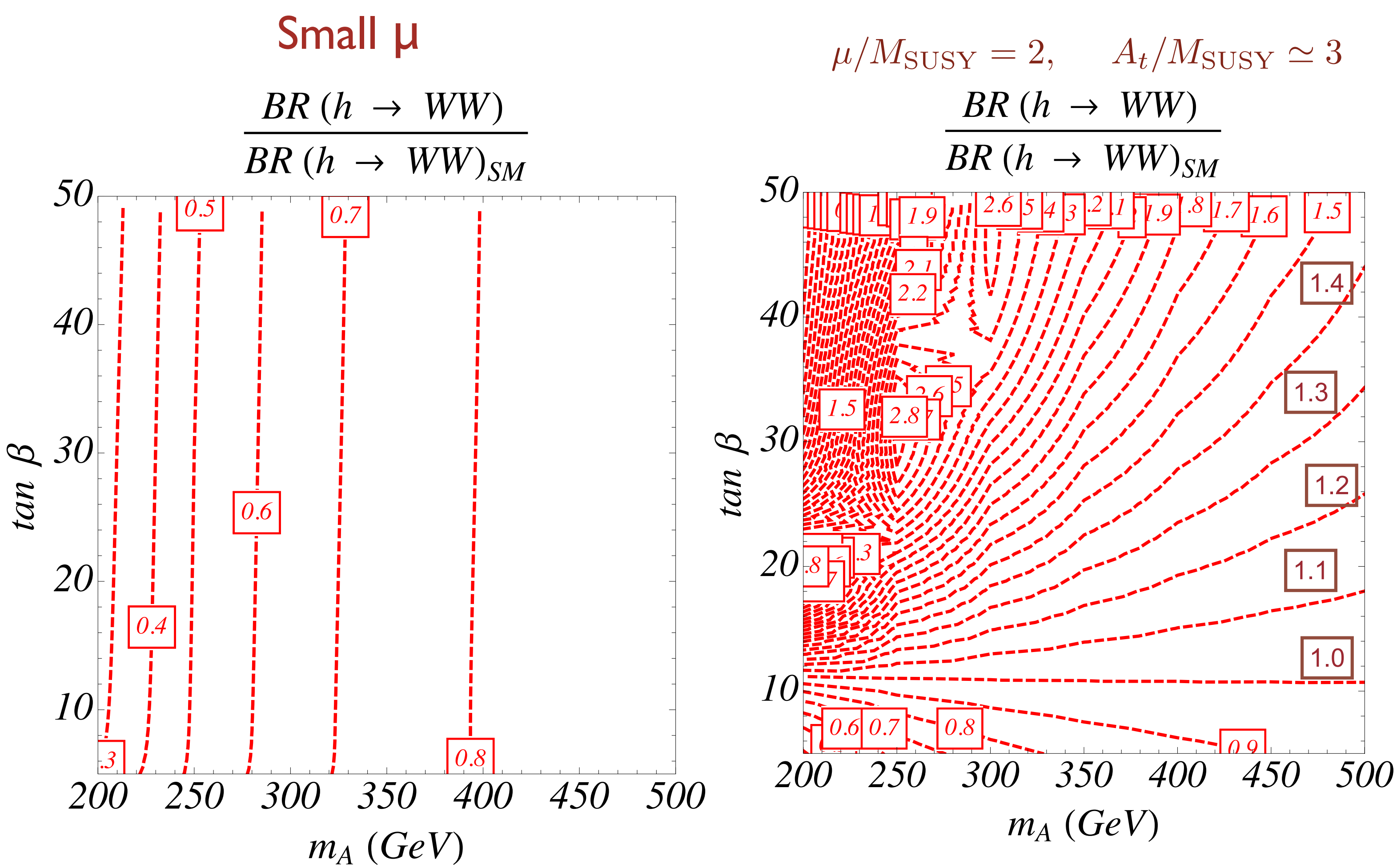
Large Supersymmetry breaking trilinear mass parameters and large tanβ necessary !
(not possible at "maximal mixing")

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

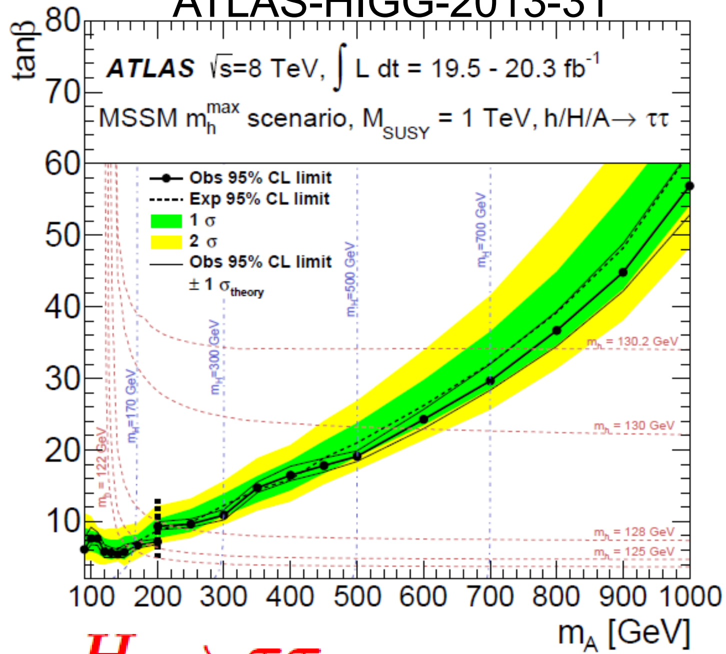


CP-odd Higgs masses of order 200 GeV and tanβ = 10 OK in the alignment case

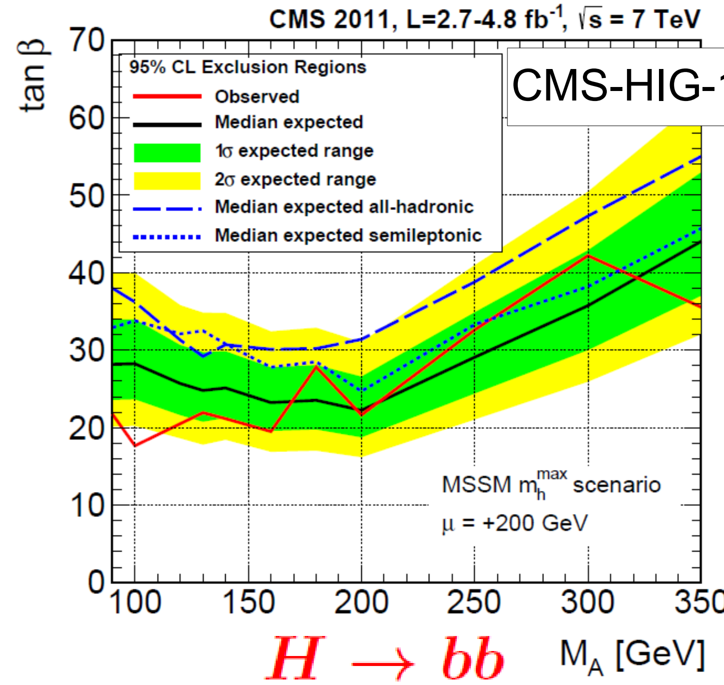
Non-Standard Higgs Searches

Neutral Higgs bosons

ATLAS-HIGG-2013-31



$H \to \tau\tau$

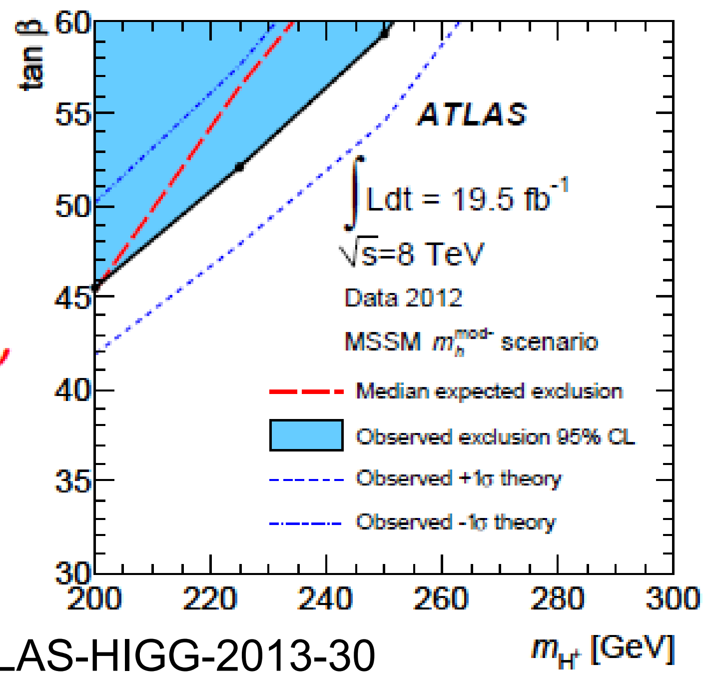


CMS-HIG-12-03

$H \to bb$

Charged Higgs bosons

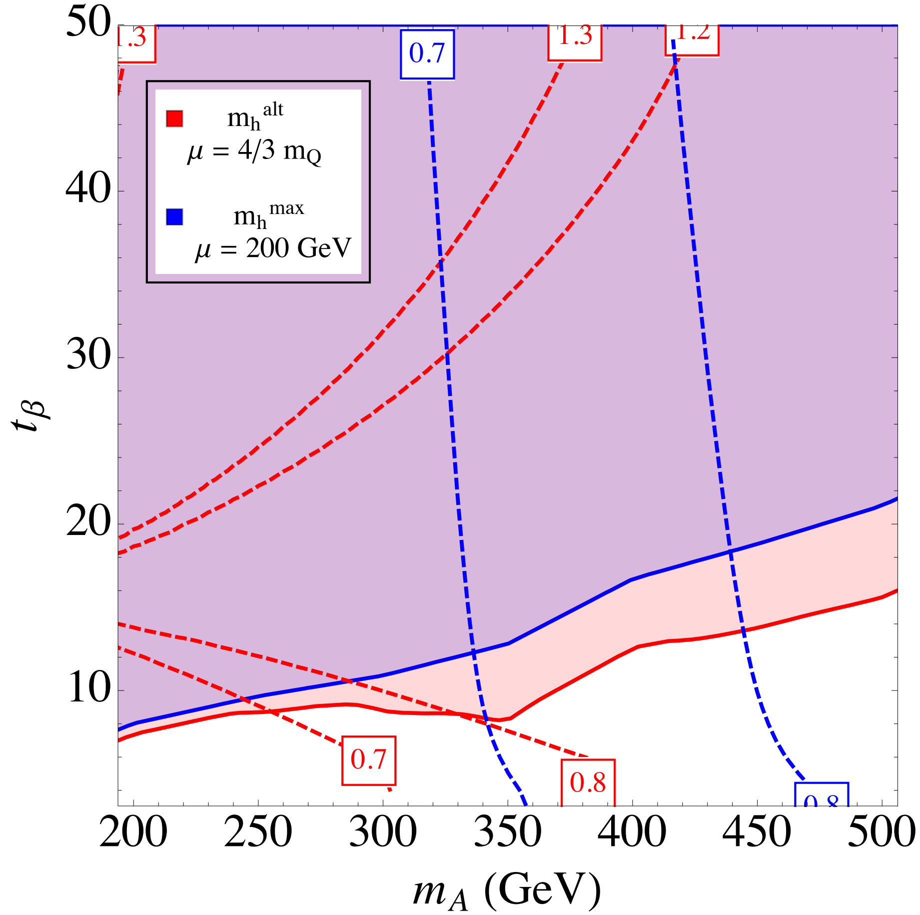
$H^{\pm} \to \tau^{\pm}\nu$



ATLAS-HIGG-2013-30

Complementarity between different search channels

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



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

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

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

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

Alignment in the Higgs Basis

In the Higgs basis,

$$\Phi = \cos\beta H_d + \sin\beta H_u$$
$$H = \sin\beta H_d - \cos\beta H_u$$

The Mass Matrix reads

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} .$$

And the condition of alignment simply relates to the cancellation of the off-diagonal term of this matrix

$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}}$$

$$Z_6 \equiv -\tfrac{1}{2} s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta}\right] + c_\beta c_{3\beta} \lambda_6 + s_\beta s_{3\beta} \lambda_7$$

$$Z_1 = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2\tilde{\lambda}_3 s_\beta^2 c_\beta^2 + 4\lambda_7 s_\beta^3 c_\beta + 4\lambda_6 c_\beta^3 s_\beta$$

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

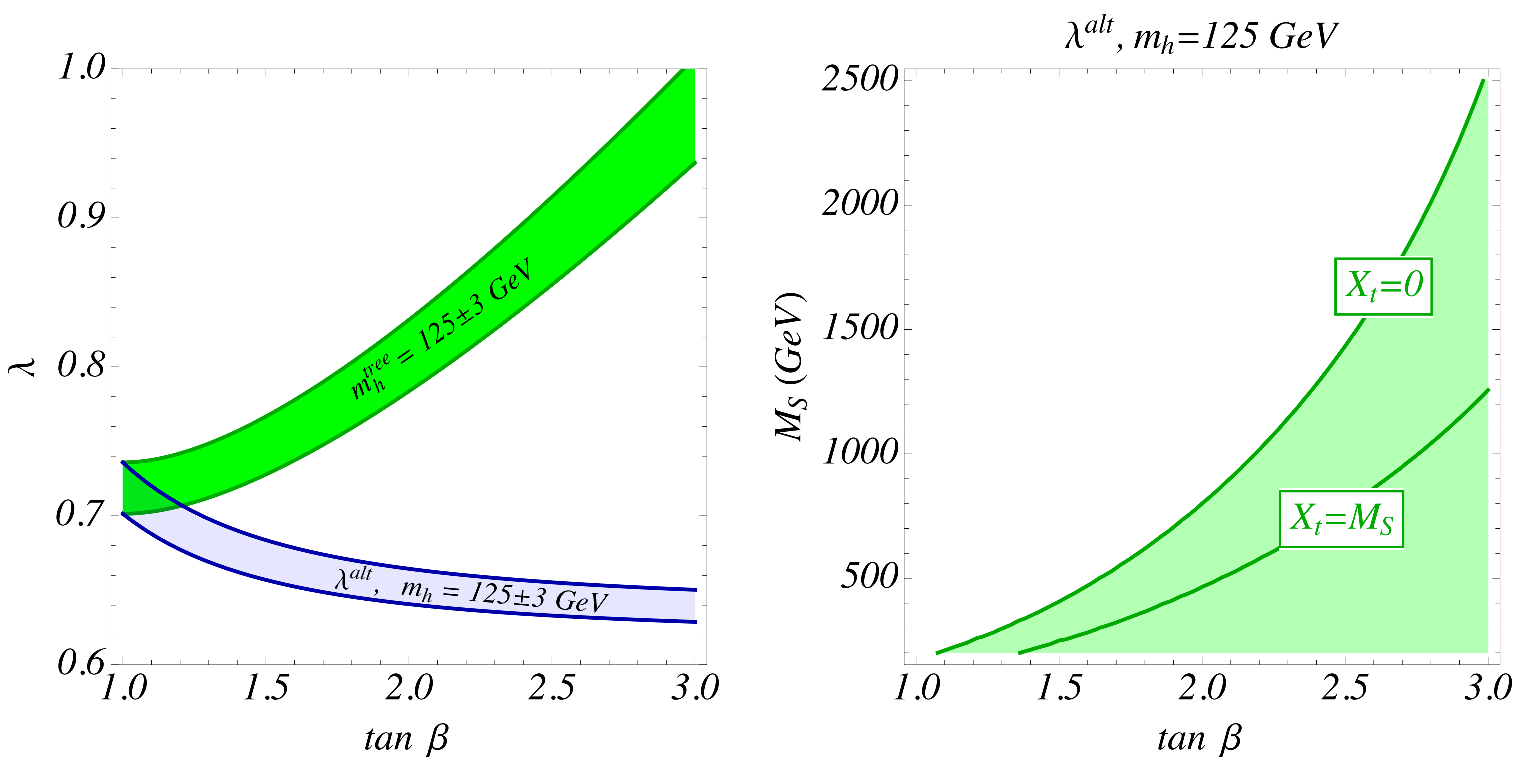
$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Stop Contribution at alignment

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

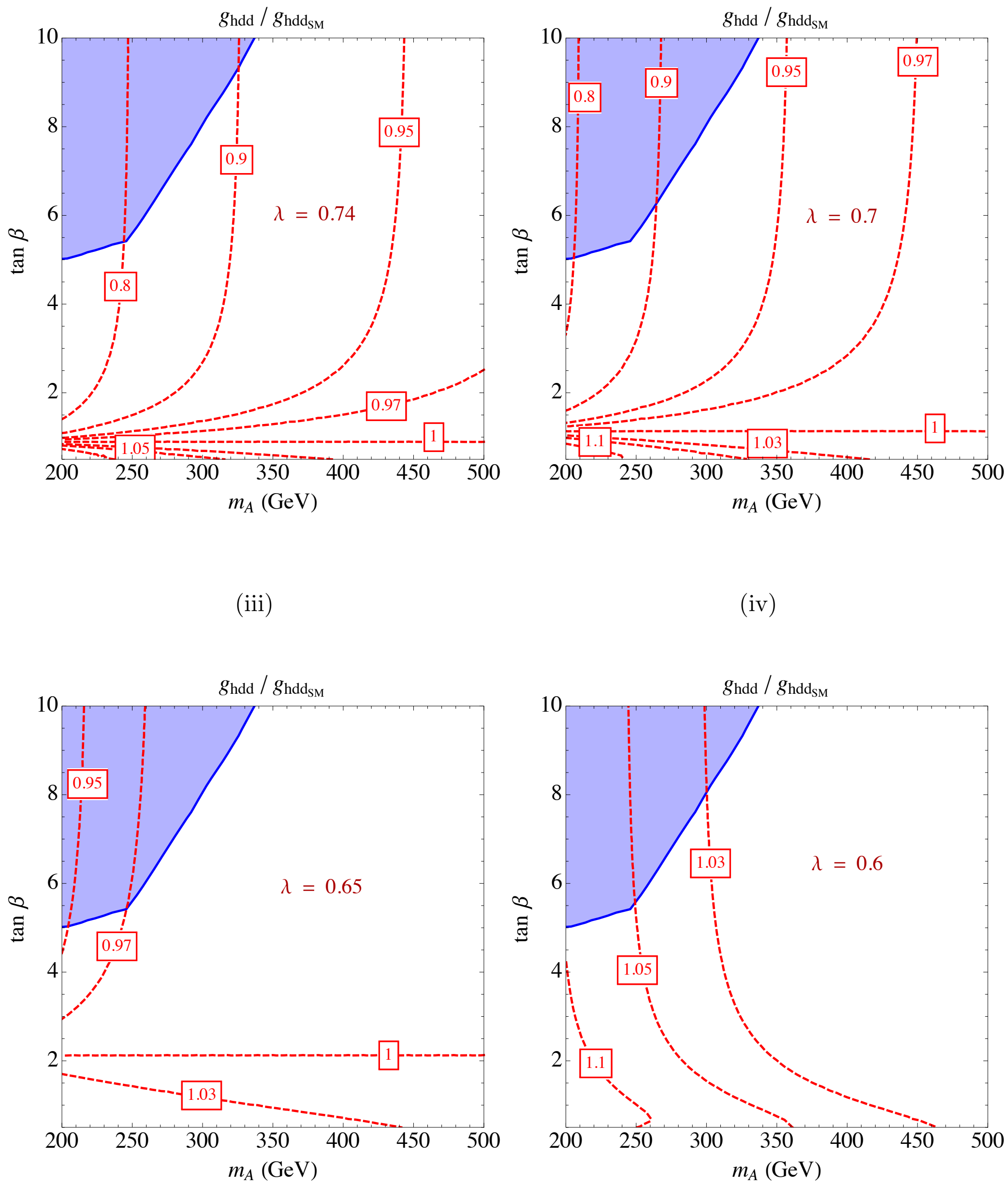
Interesting, after some simple algebra, one can show that

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



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

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

Aligning the CP-even Singlets

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

- The mixing mass matrix element between the singlets and the SM-like Higgs is approximately given by

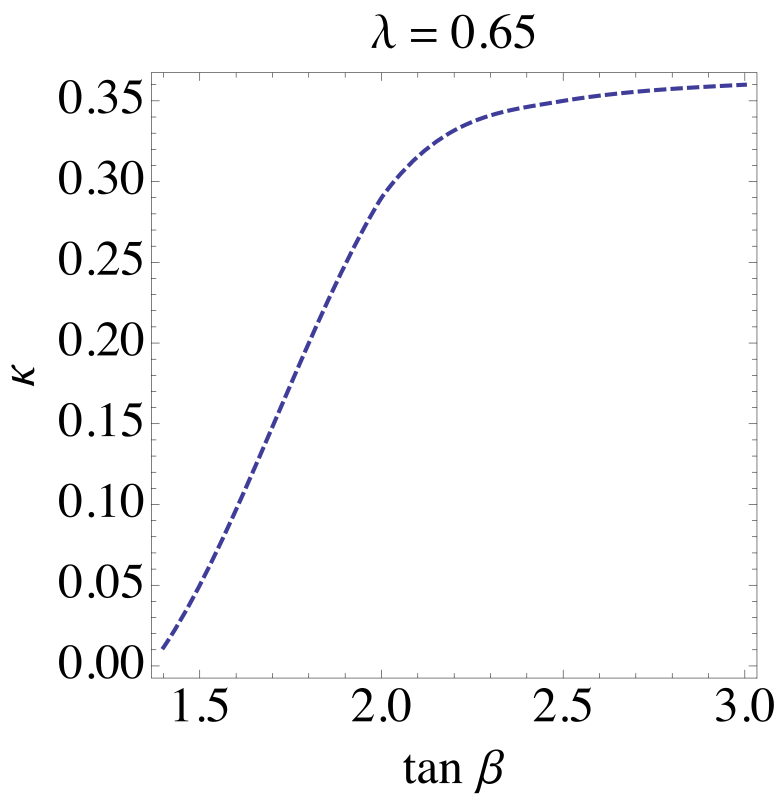
$$M_S^2(1,3) \simeq 2\lambda v\mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime,, the CP-odd Higgs is correlated in mass with the parameter μ

- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM

- Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets (and singlino) become self consistently light

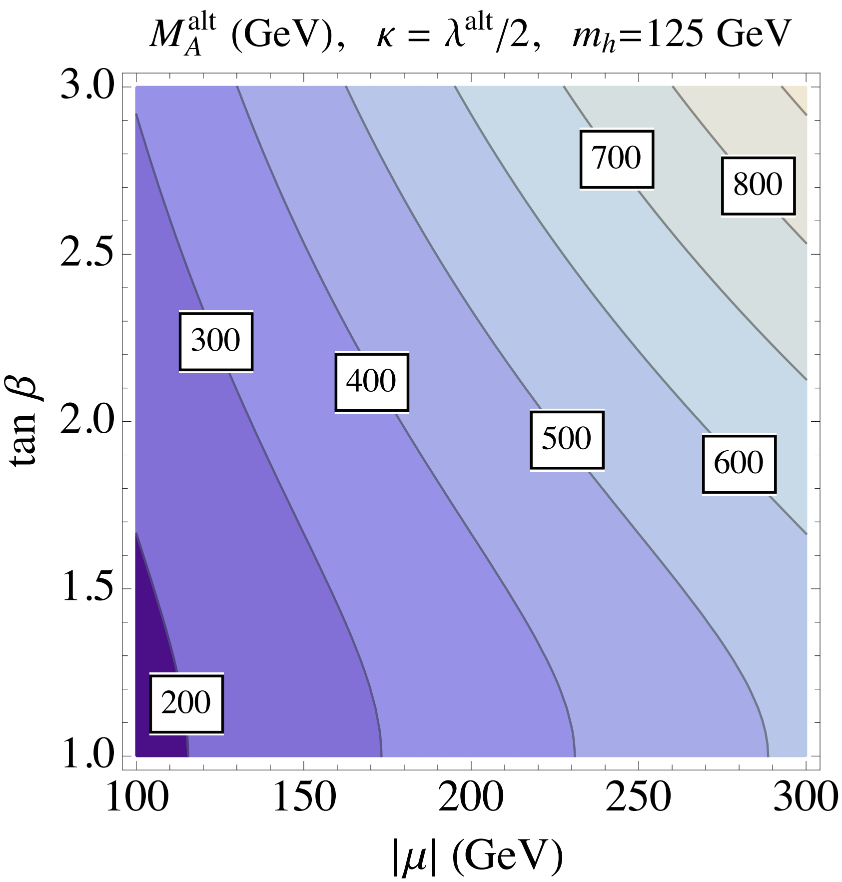
Perturbative Values of kappa

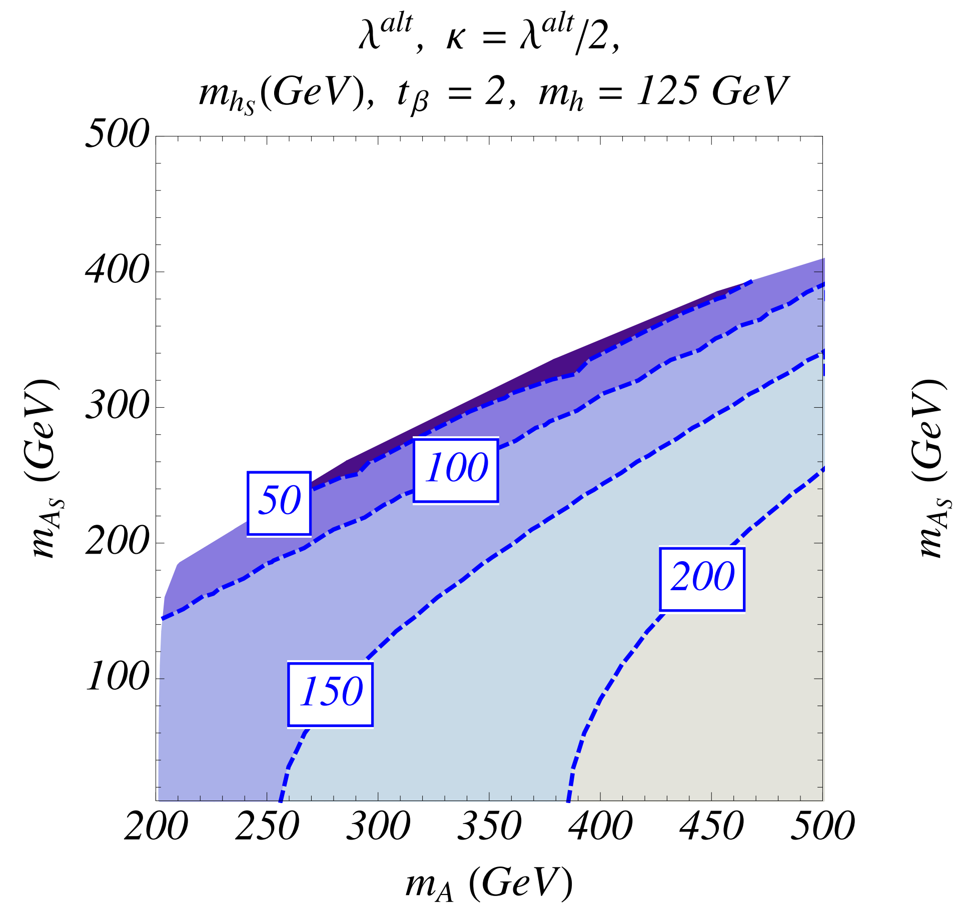


Top Yukawa Coupling becomes stronger for smaller values of $\tan\beta$

Values of the Singlet, Higgsino and Singlino Masses

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





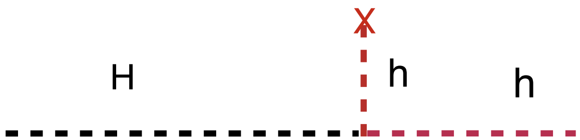
In this limit, the singlino mass is equal to the Higgsino mass.

$$m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}$$

So, the whole Higgs and Higgsino spectrum remains light, as anticipated

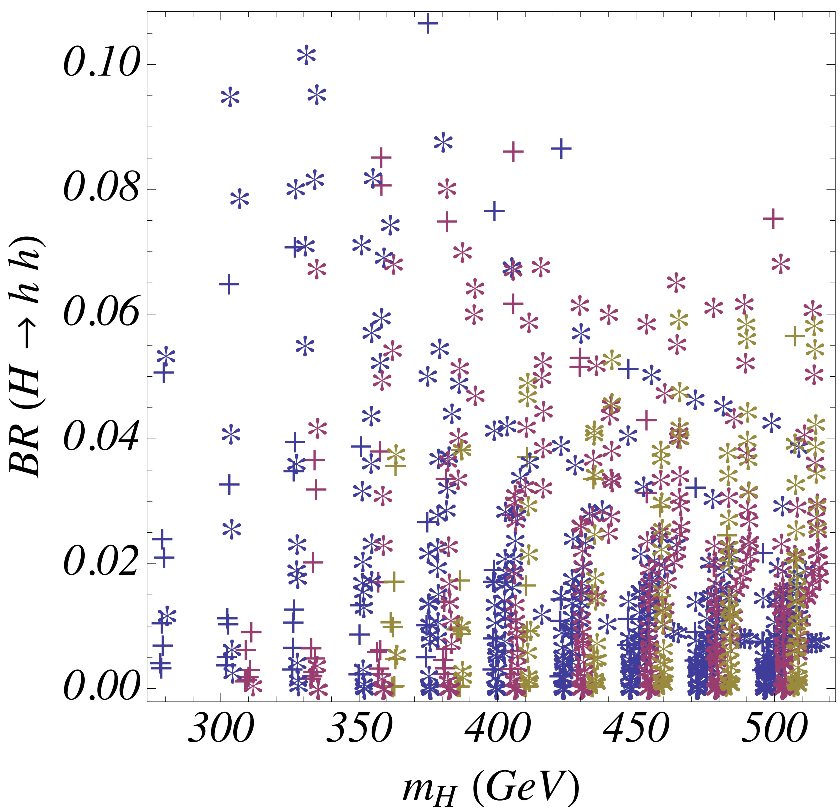
Decays into pairs of SM-like Higgs bosons suppressed by alignment

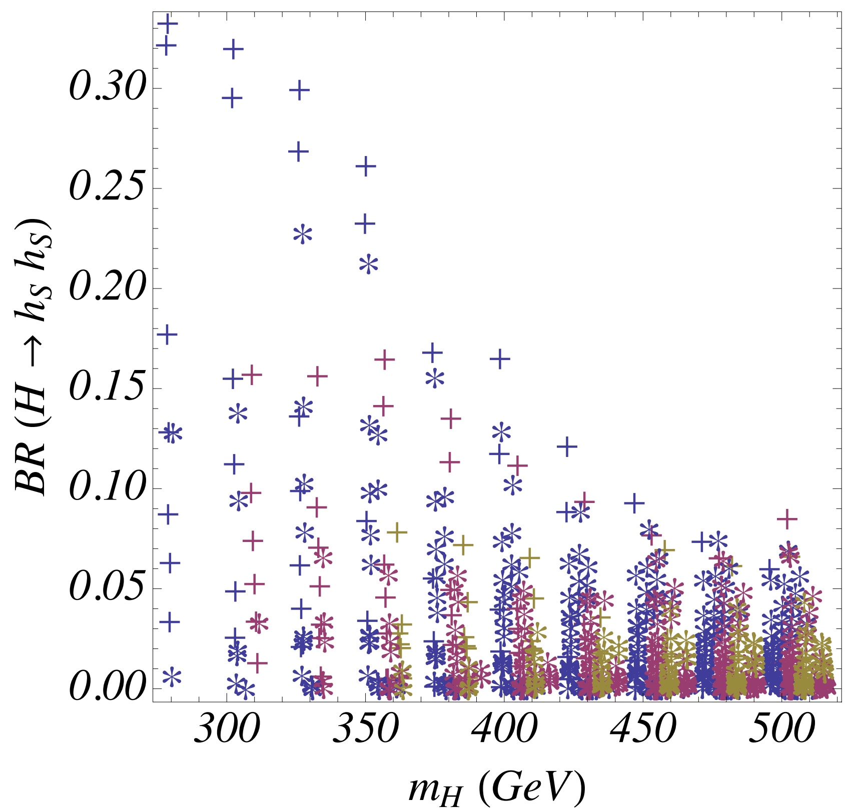
Carena, Haber, Low, Shah, C.W.'15



Crosses : H1 singlet like
Asterix : H2 singlet like

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



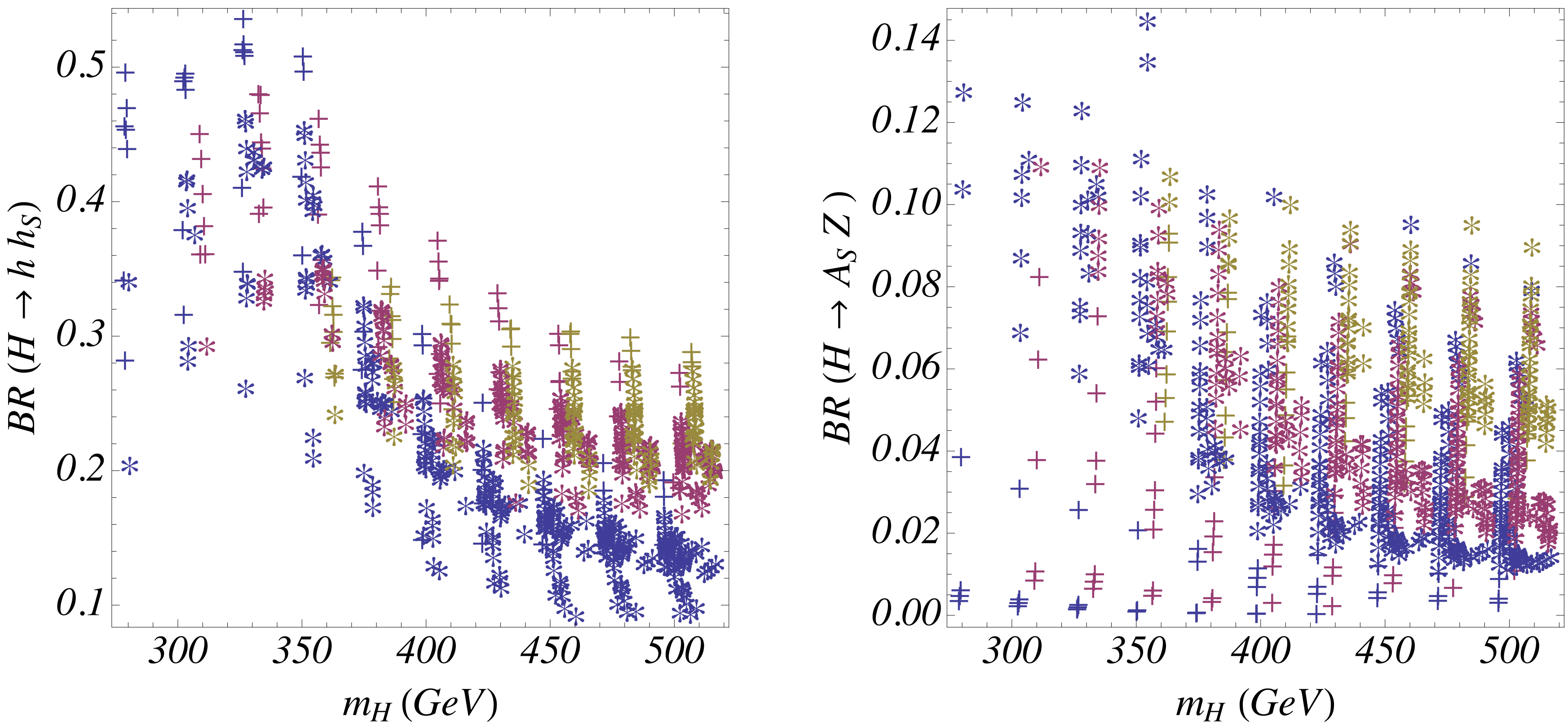


Significant decays of heavier Higgs Bosons into lighter ones and Z's

Crosses : H1 singlet like
Asterix : H2 singlet like

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

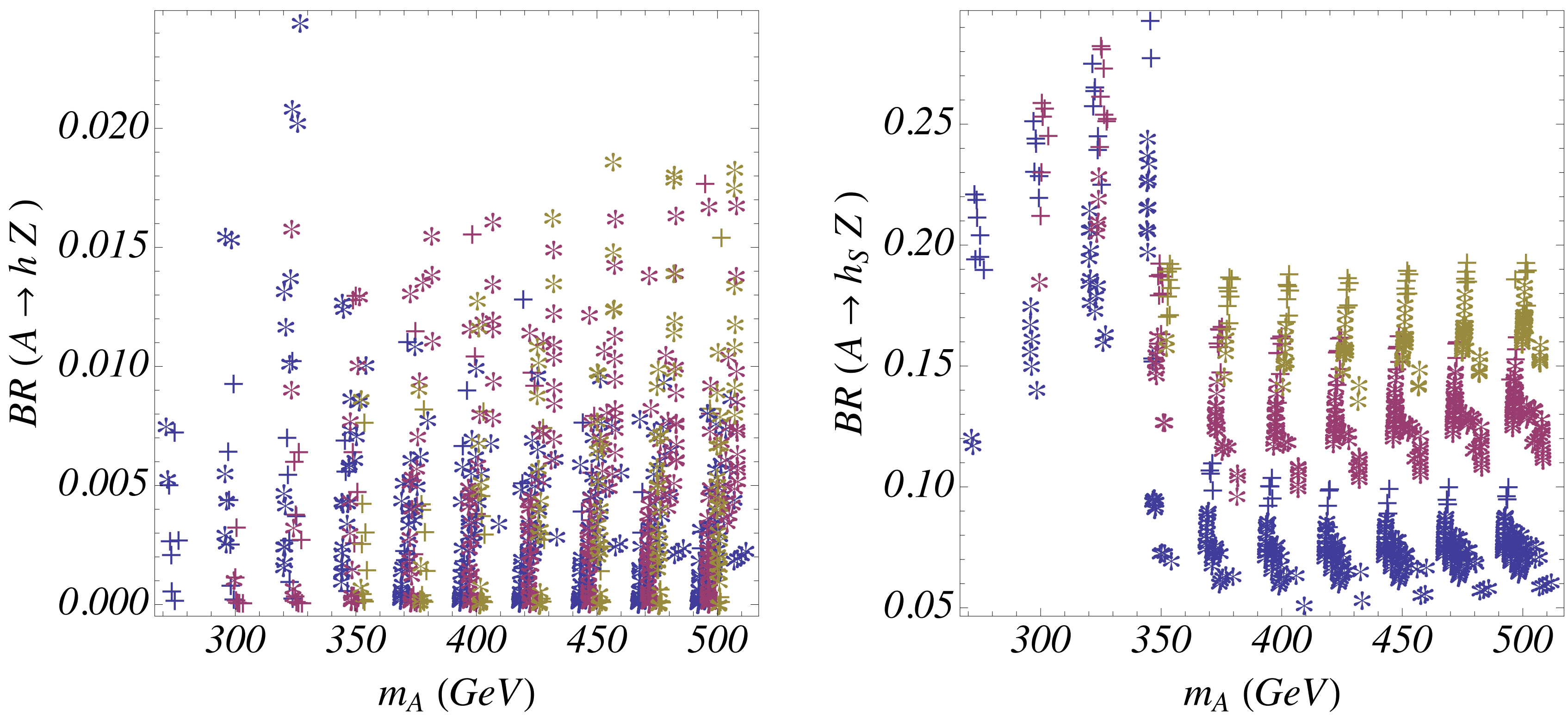
Carena, Haber, Low, Shah, C.W.'15



Heavy CP-odd Higgs Bosons have similar decay modes

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

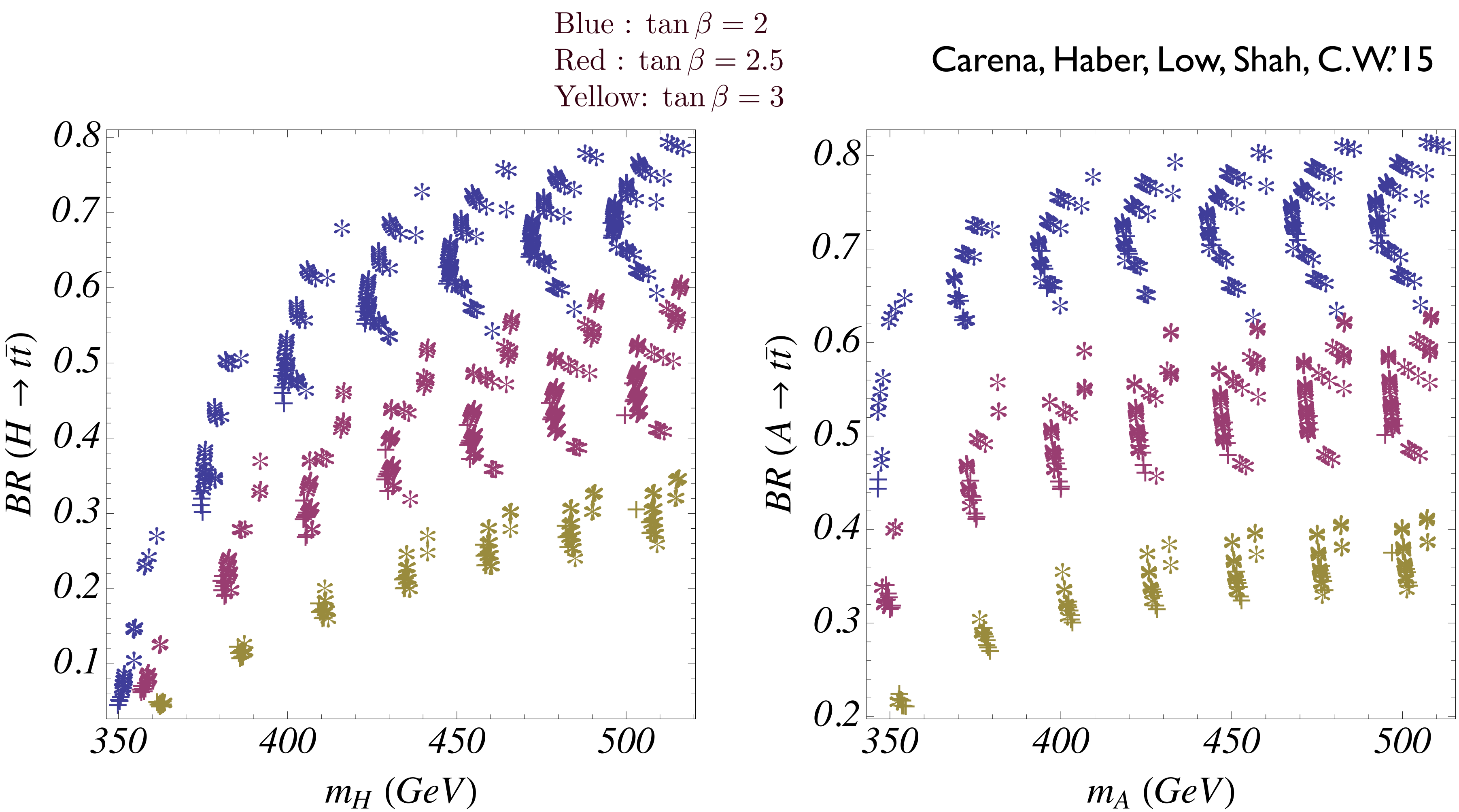
Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$



Significant decay of heavy CP-odd
Higgs bosons into singlet like states plus Z

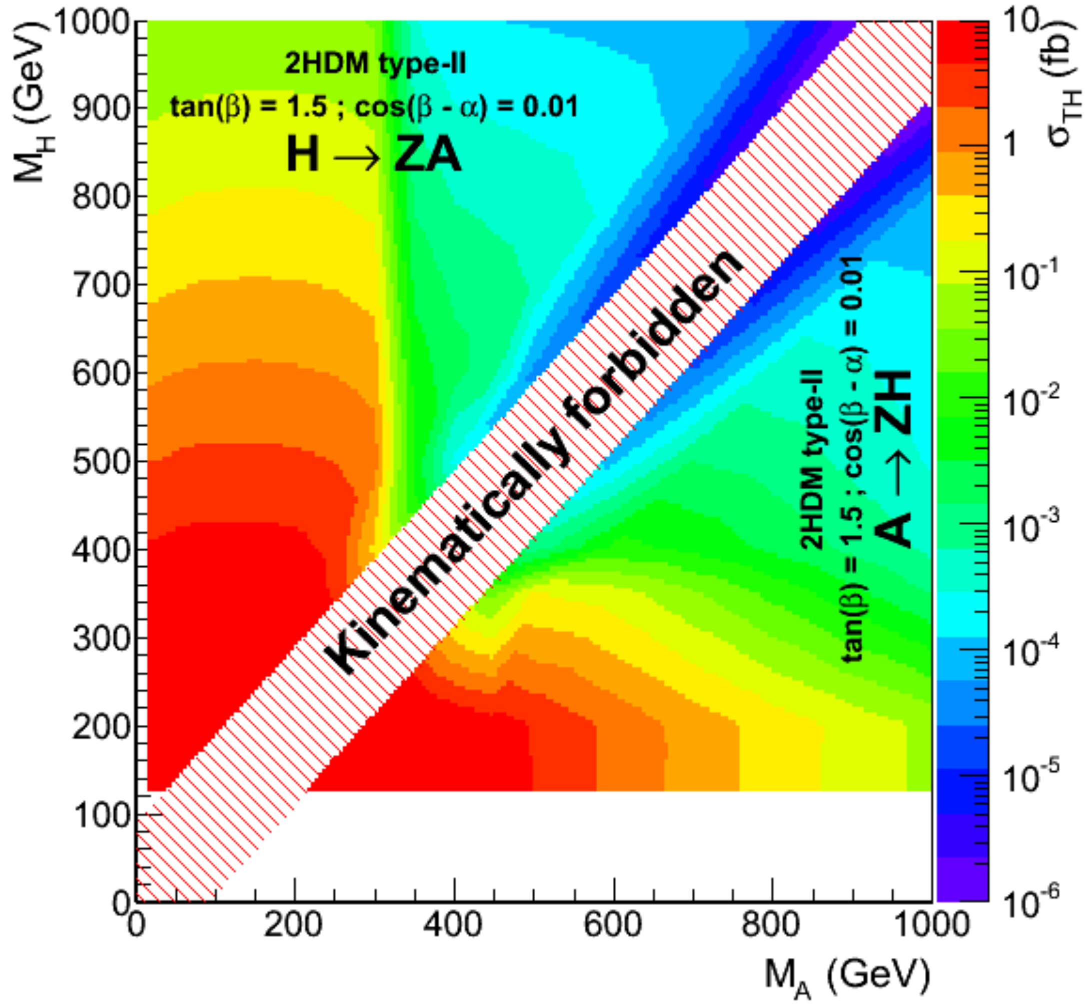
Decays into top significant but may be somewhat suppressed by decays into non-standard particles

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



Search for (psudo-)scalars decaying into lighter ones

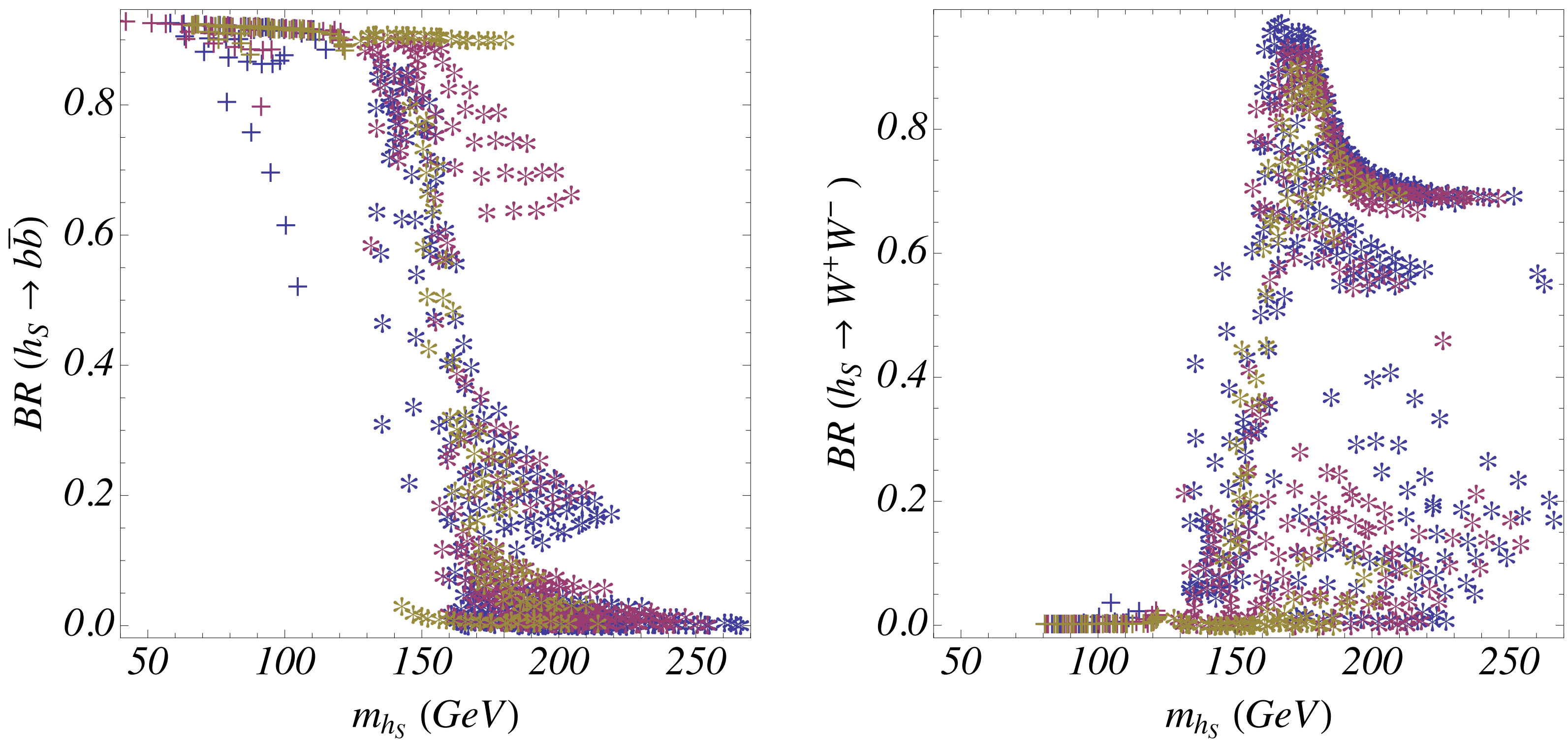
CMS-PAS-HIG-15-001



It is relevant to perform similar analyses replacing the Z by a SM Higgs !

Singlet Decays

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



Decays into Light Singlinos also possible, leading to Mono-Higgs Signatures

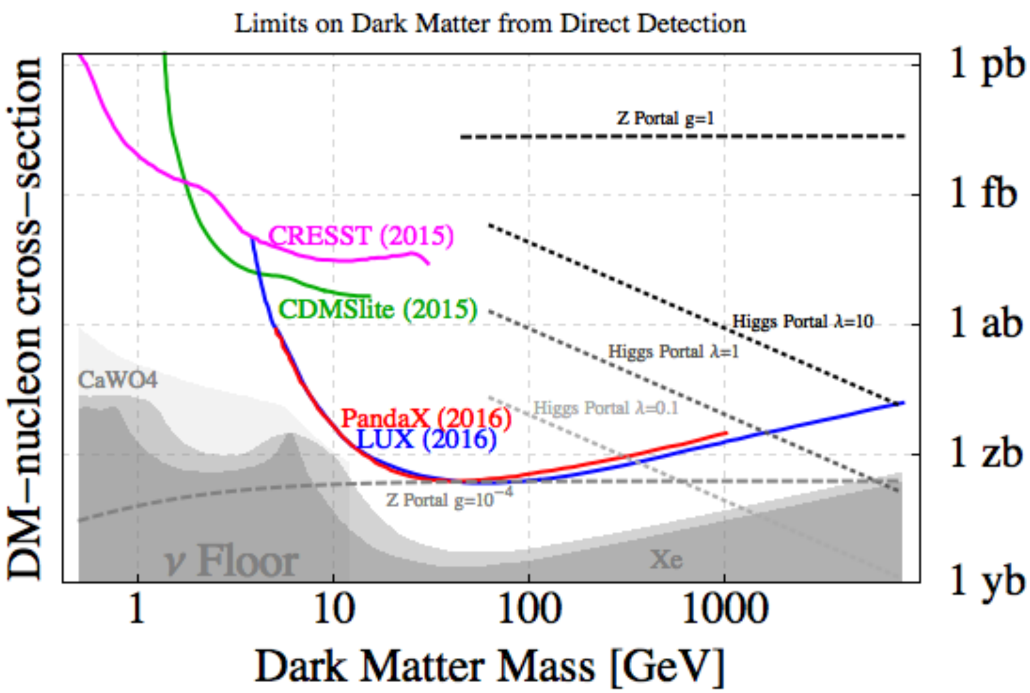
Baum, Freese, Shah, Shakya'17

Dark Matter
Direct Detection

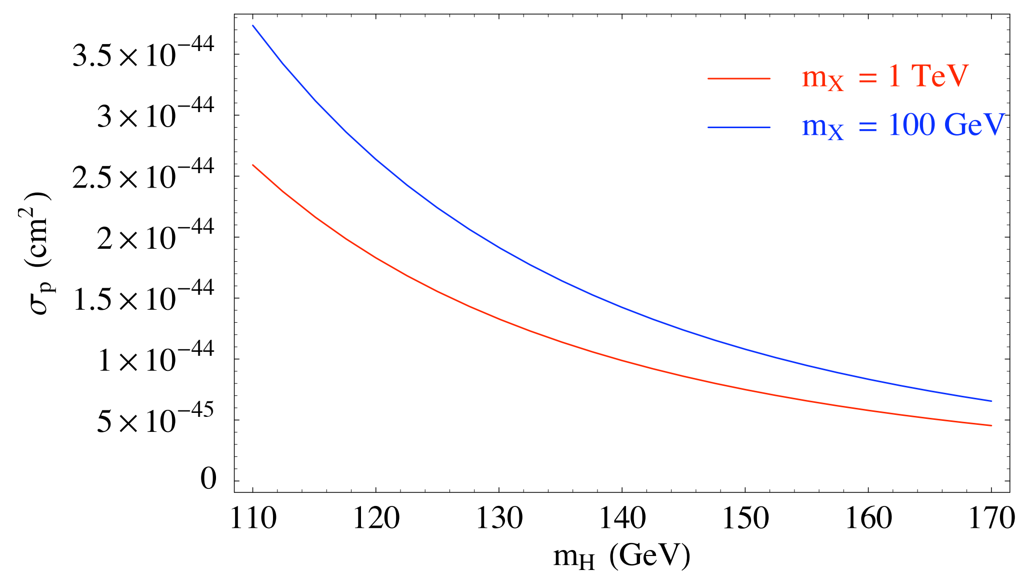
Prospects for direct Dark Matter Detection

Current Limits

$$1\ \text{pb} = 10^{-36}\ \text{cm}^2, \qquad 1\ \text{zb} = 10^{-45}\ \text{cm}^2$$



"Typical" Higgs mediated scenarios constrained by data

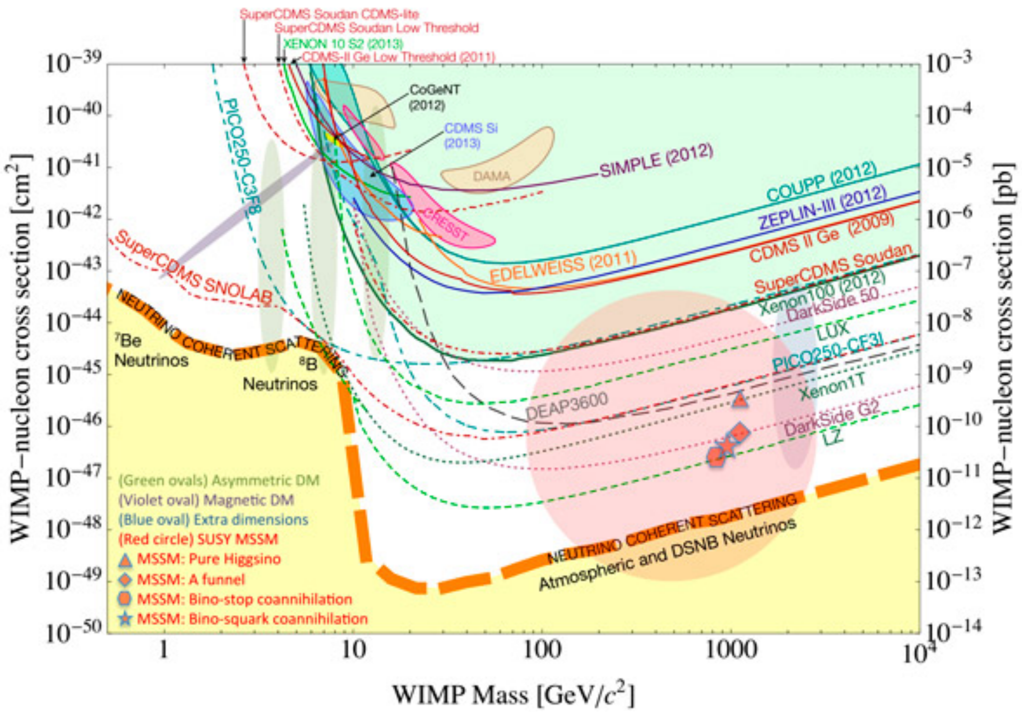


Arkani-Hamed, Dimopoulos, Giudice, Romanino'04

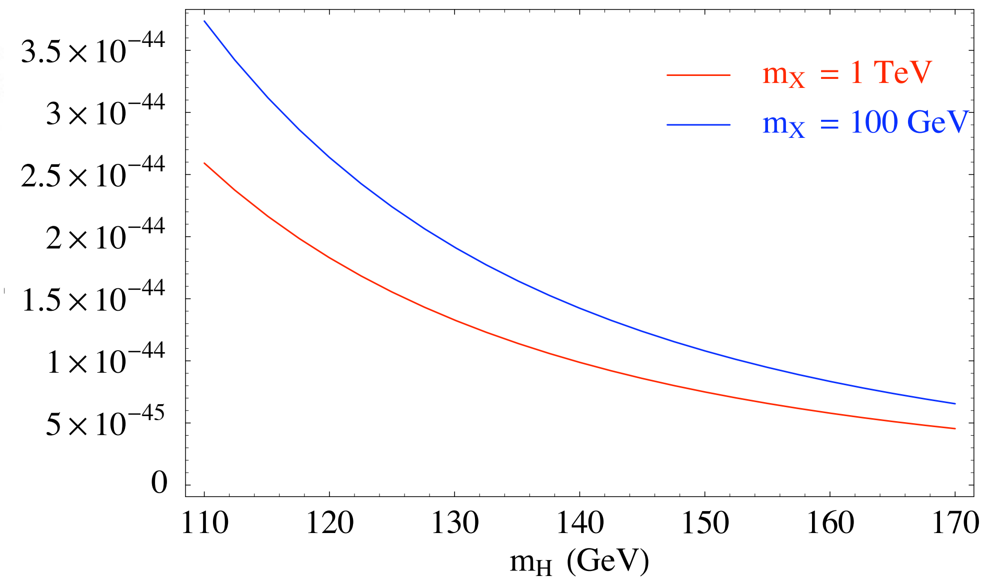
Prospects for direct Dark Matter Detection

Projected Bounds
(with better neutrino floor estimate)

$$1\ \mathrm{pb} = 10^{-36}\ \mathrm{cm}^2, \qquad 1\ \mathrm{zb} = 10^{-45}\ \mathrm{cm}^2$$

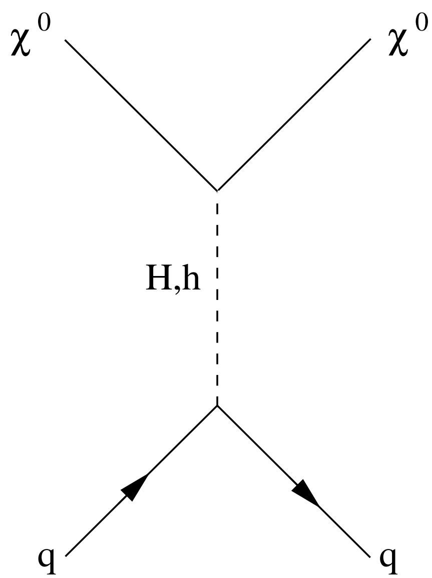


Typical Higgs mediated scenarios constrained by data



Arkani-Hamed, Dimopoulos, Giudice, Romanino'04

Relevant Direct Dark Matter Detection Amplitudes



$$h = \frac{1}{\sqrt{2}}(\cos\alpha \ H_u - \sin\alpha \ H_d)$$
$$H = \frac{1}{\sqrt{2}}(\sin\alpha \ H_d + \cos\alpha \ H_u)$$

$$W = h_u Q U H_u + h_d Q D H_d + \mu H_u H_d \qquad \tan\beta = \frac{v_u}{v_d}$$

For down quarks, for example $\quad m_d = h_d \frac{v}{\sqrt{2}} \cos\beta$

$$a_d \sim \frac{m_d}{\cos\beta}\left(\frac{-\sin\alpha \ g_{\chi\chi h}}{m_h^2} + \frac{\cos\alpha \ g_{\chi\chi H}}{m_H^2}\right)$$

P. Huang, C.W.'15

Direct Dark Matter Detection Cross Section

Putting all together, one gets

$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta(-F_d^{(p)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2}\right]^2$$

with

$$F_u^{(p)} \equiv f_u^{(p)} + 2 \times \tfrac{2}{27} f_{TG}^{(p)} \approx 0.15 \qquad\qquad F_d^{(p)} = f_{Td}^{(p)} + f_{Ts}^{(p)} + \tfrac{2}{27} f_{TG}^{(p)} \approx 0.14$$

One can do a similar calculation for neutrons, and the expression is very similar. Indeed,

$$f_{Tu}^{(n)} = 0.011, \;\; f_{Td}^{(n)} = 0.0273, \; f_{Ts}^{(n)} = 0.0447 \text{ and } f_{TG}^{(n)} = 0.917$$

$$F_u^{(n)} \approx 0.15 \text{ and } F_d^{(n)} \approx 0.14$$

Destructive Interference for negative values of μ and constructive interference for positive values of μ (cos(2β) negative).

P. Huang, C.W.'15

Blind Spots in Direct Dark Matter Detection

The cross section is greatly reduced when the parameters fulfill the approximate relation

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

which at moderate or large values of tanβ reduce to

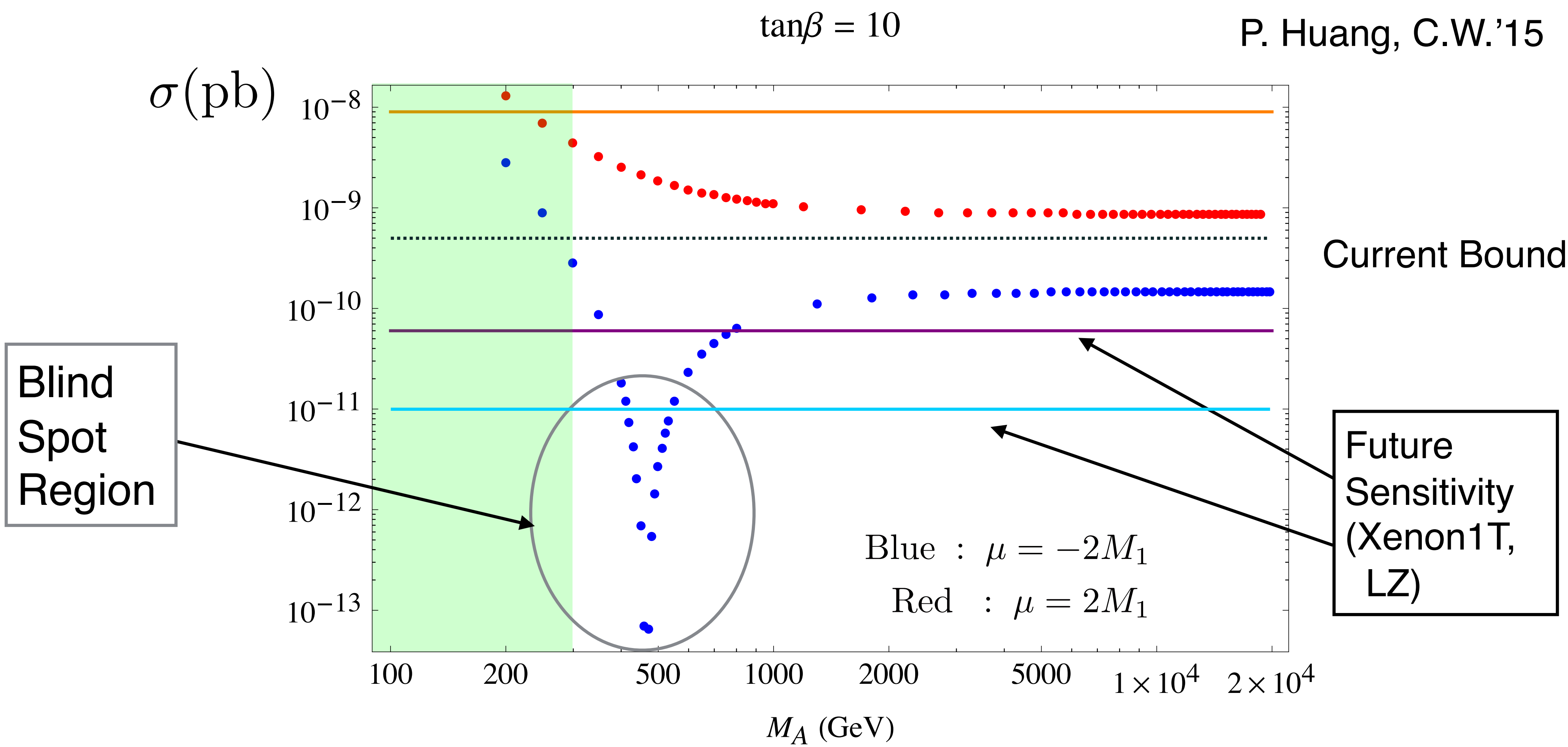
$$\boxed{2\ (m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq -\ \mu \tan\beta \frac{1}{m_H^2}}$$

We shall call this region of parameters the "blind spot region"

Dependence of the cross section on the heavy Higgs mass

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

P. Huang, C.W.'15

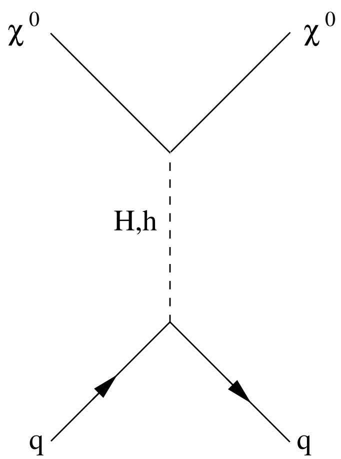


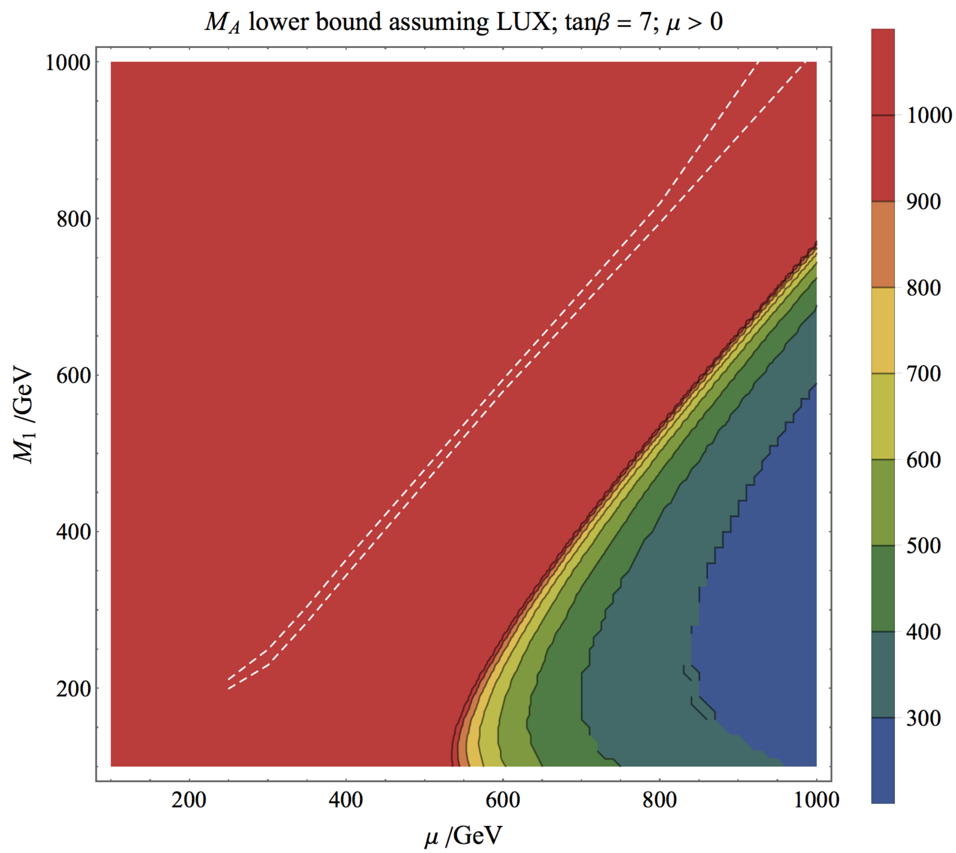
Application of the naive blind spot formula gives MA = 478 GeV

Roglans, Spiegel, Sun, Huang, C.W.'16

Heavy Superpartners

Assuming Neutralino provides the whole Observed Relic Density :
Lower Bound on MA for positive values of μ (constructive interference)

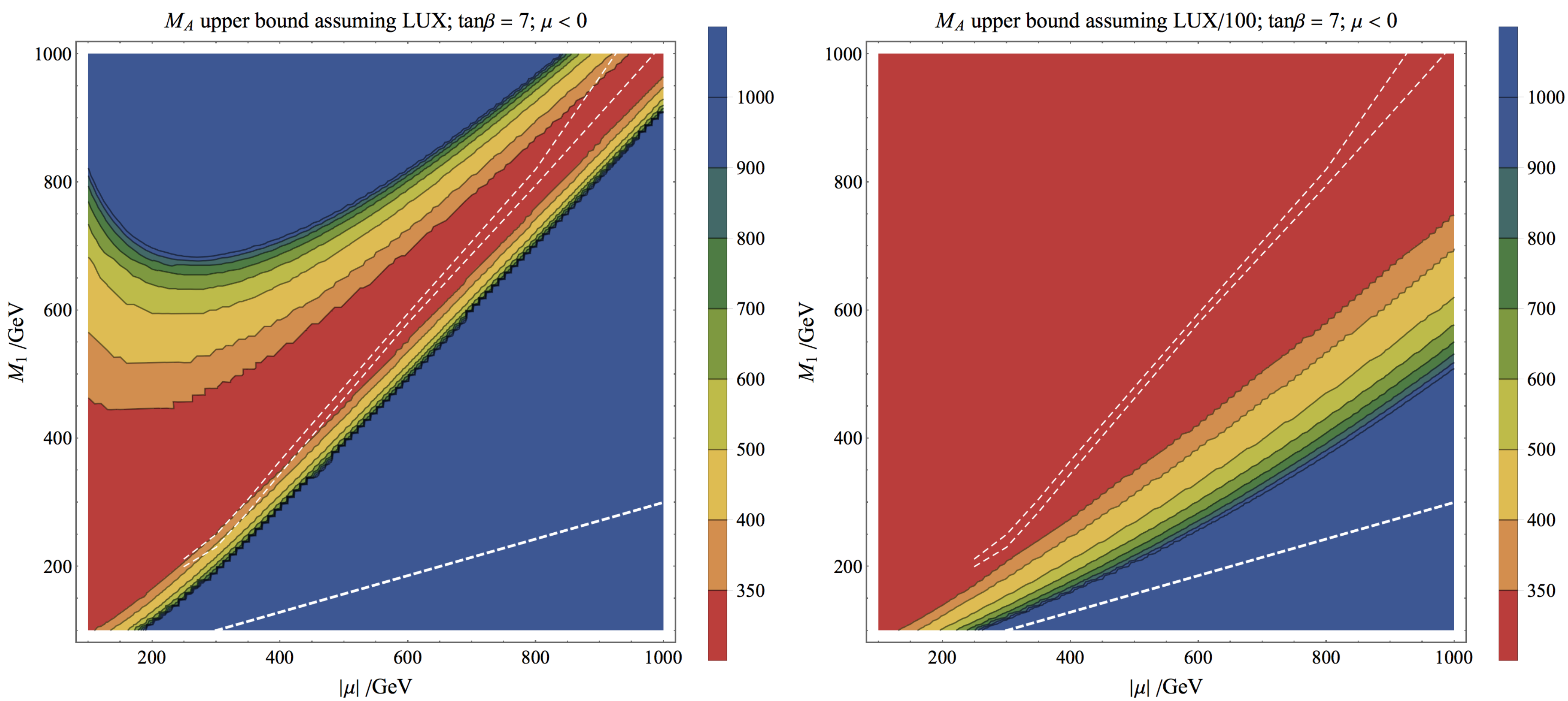




Large Regions of Parameter Space Excluded by Current Measurements

Roglans, Spiegel, Sun, Huang, C.W.'17
See also Badziak, Olechowski, Szczerbiak'17

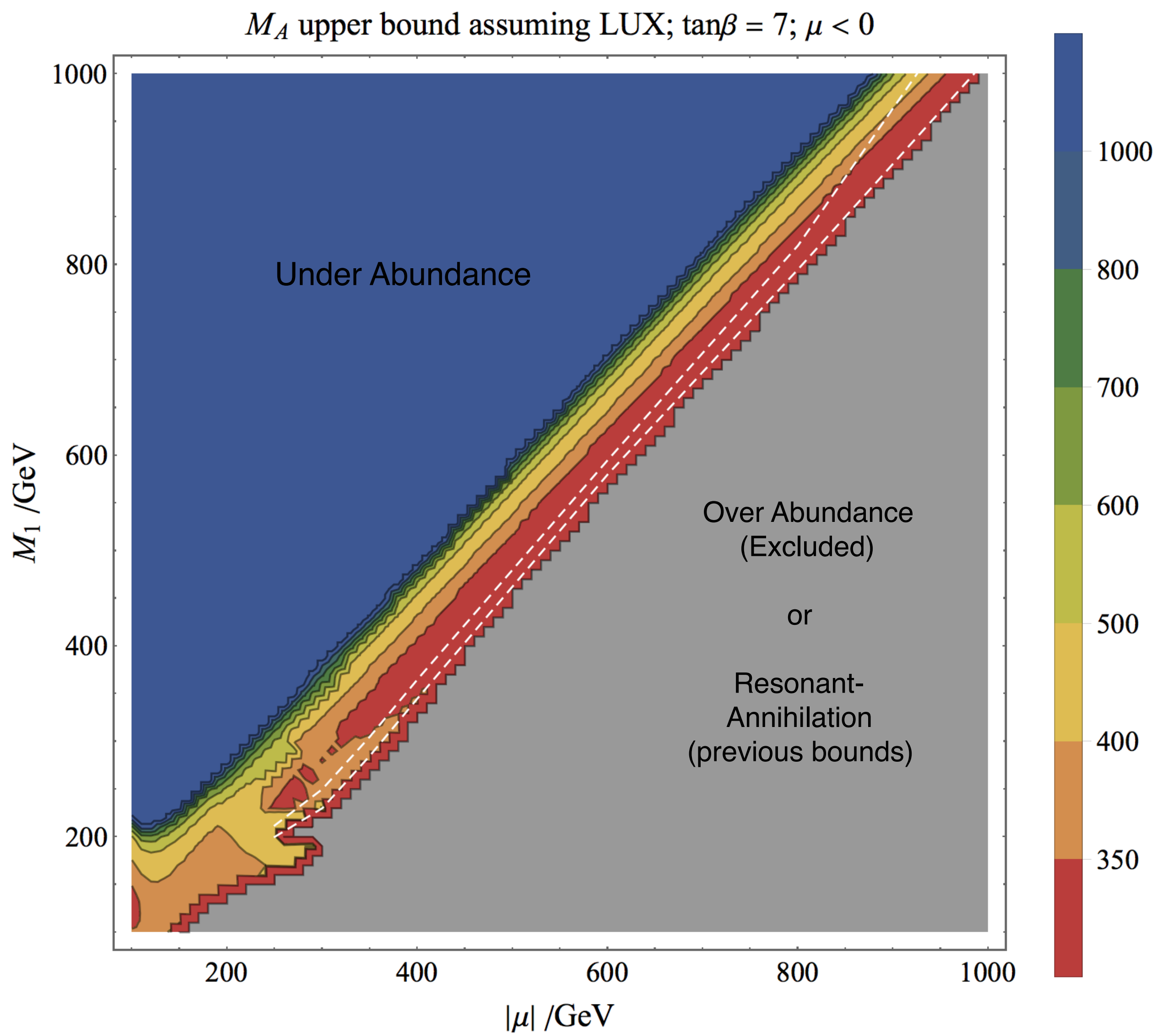
Assuming that the Neutralinos provides the whole Observed Relic Density : Upper Bound on MA for negative values of μ (destructive interference)



Strong Restrictions on the Well Tempered Region (region between dashed white lines)

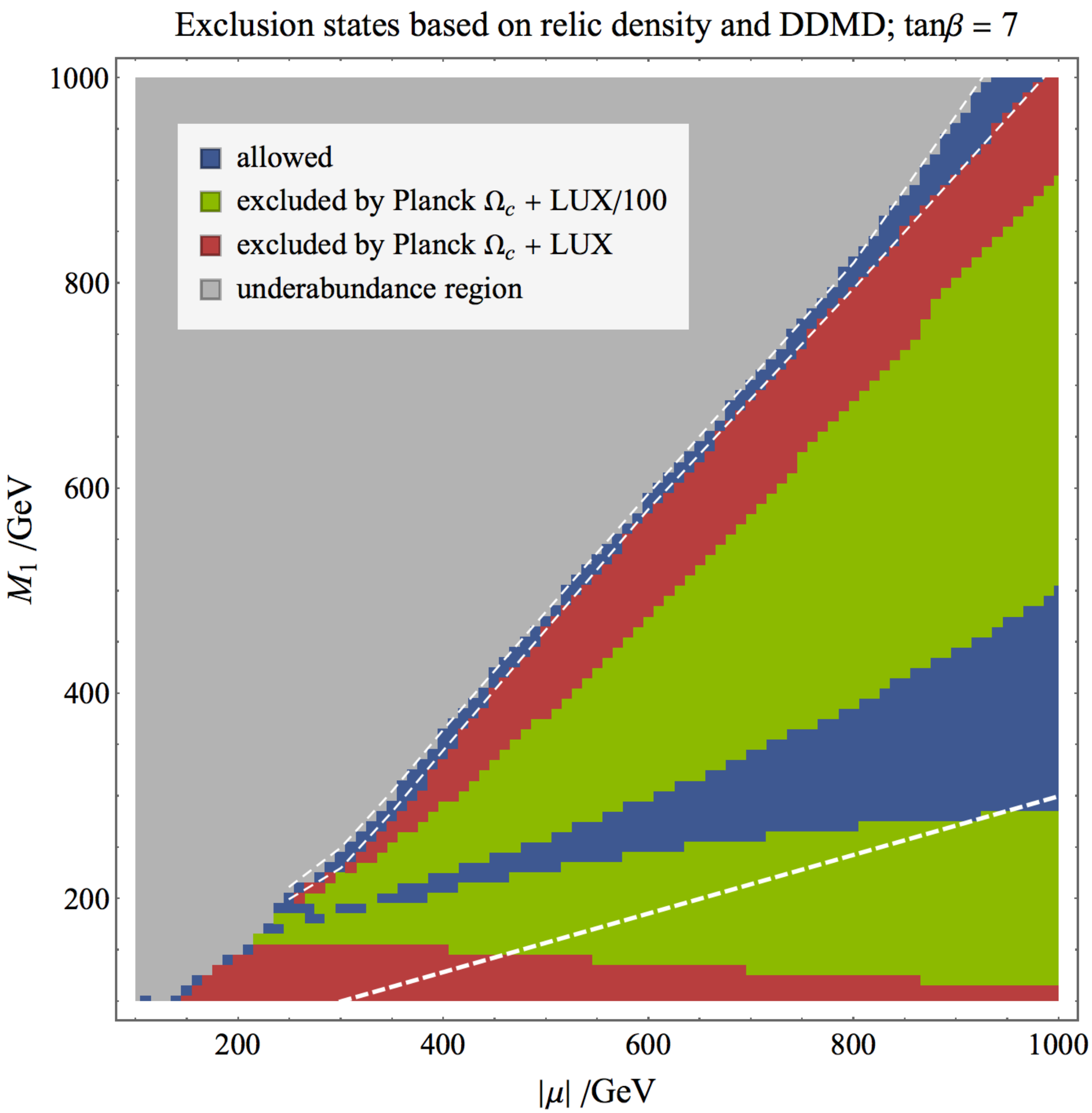
At the edge of the region restricted by precision electroweak measurements.
More easily realized if alignment condition is fulfilled.
Additional contributions to the Higgs sector, like in the NMSSM makes this scenario more realistic, due to constraints on stop sector.

Upper Bound on MA adjusted by assuming the Thermal Relic Density



Putting Constraints Together :

Assuming Thermal Relic Density



Blue : Allowed

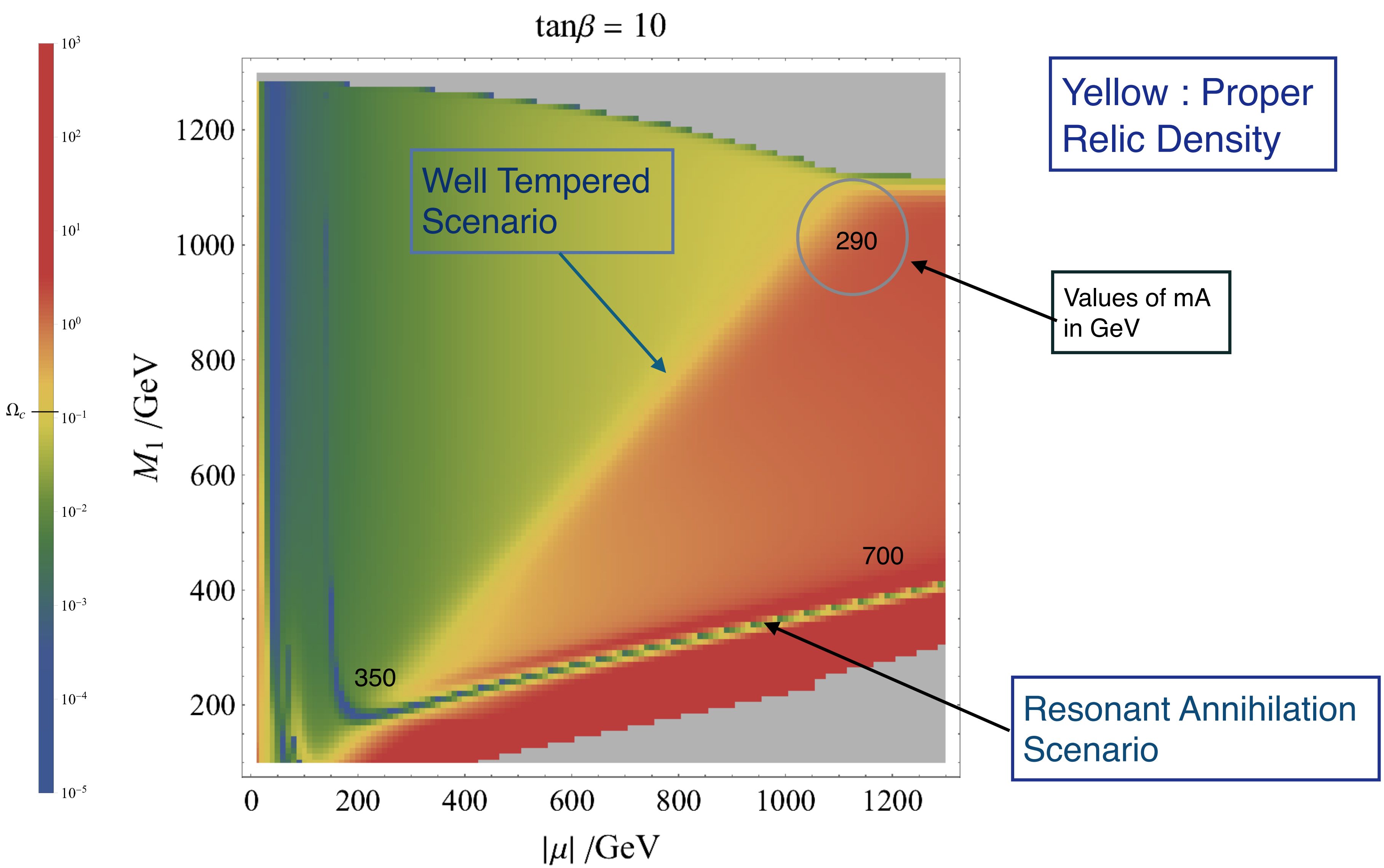
Red : Excluded

Green : To be Probed by LZ

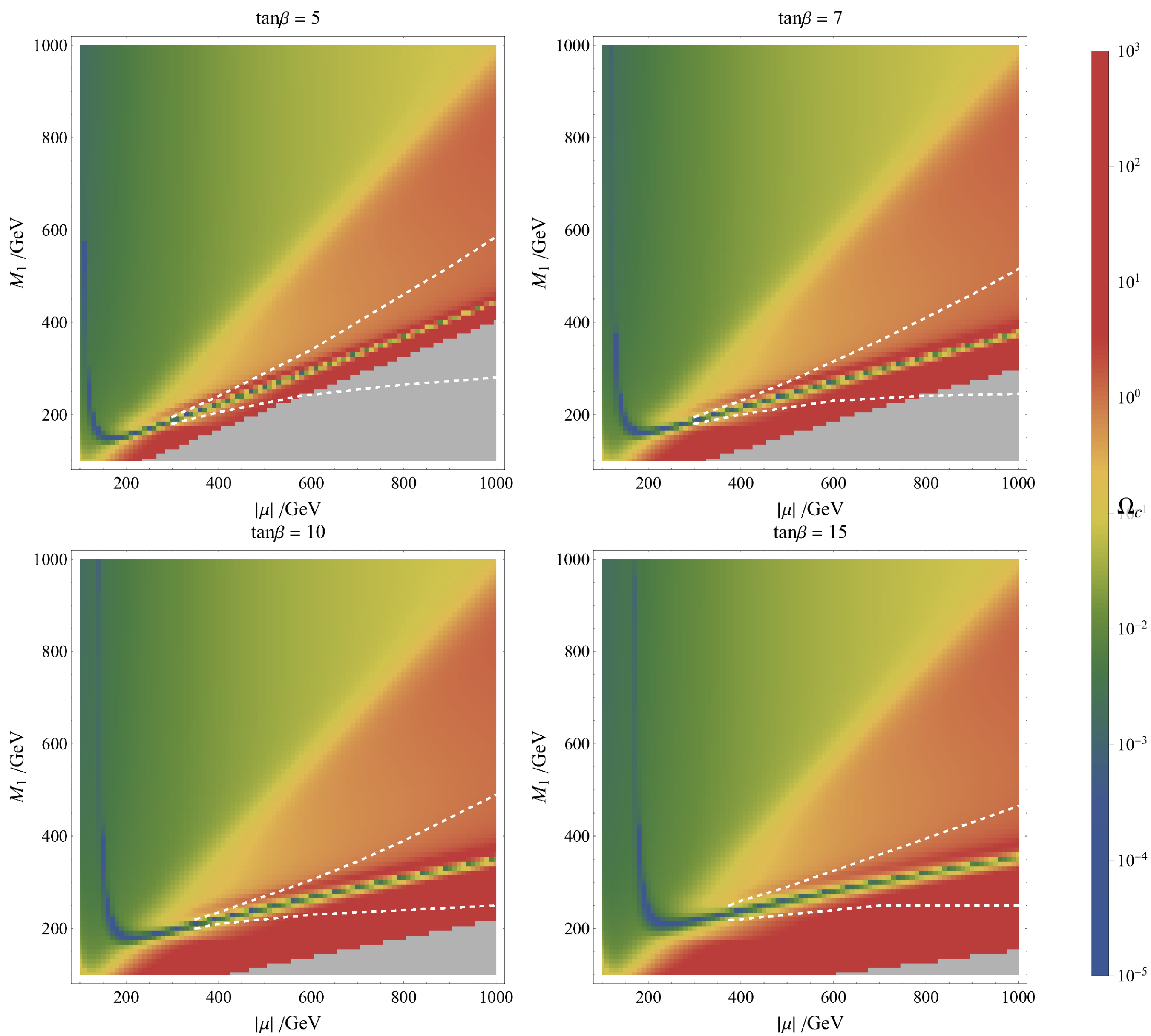
Grey : Underabundance

Roglans, Spiegel, Sun, Huang, C.W.'16

Relic Density and Blind Spot Scenarios II

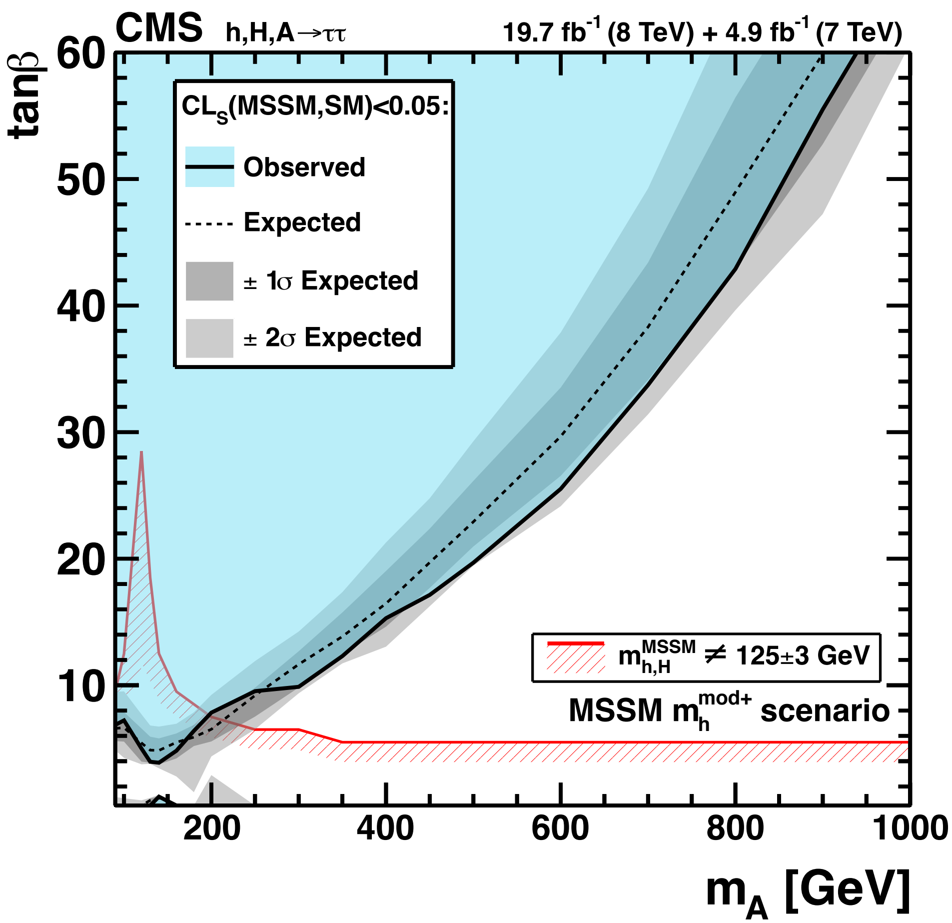


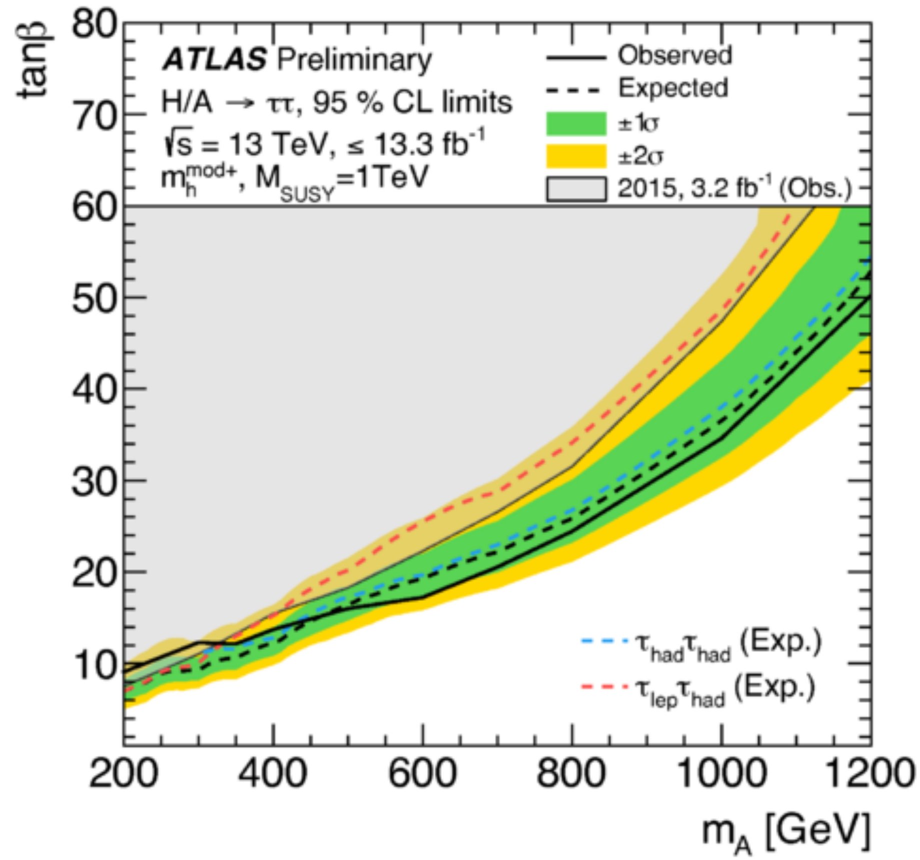
Relic Density Assuming MA is at the Blind Spot Value



Region Between White Line : Could Evade eventual constraints from LZ

Search for new neutral Higgs bosons



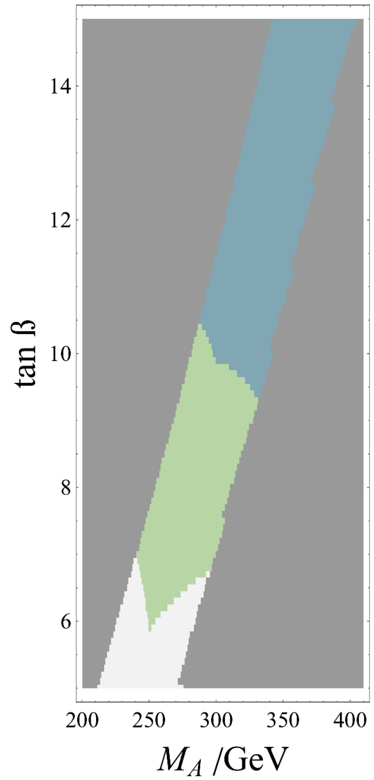


Low values of the new Higgs bosons masses
and large values of tanβ ruled out

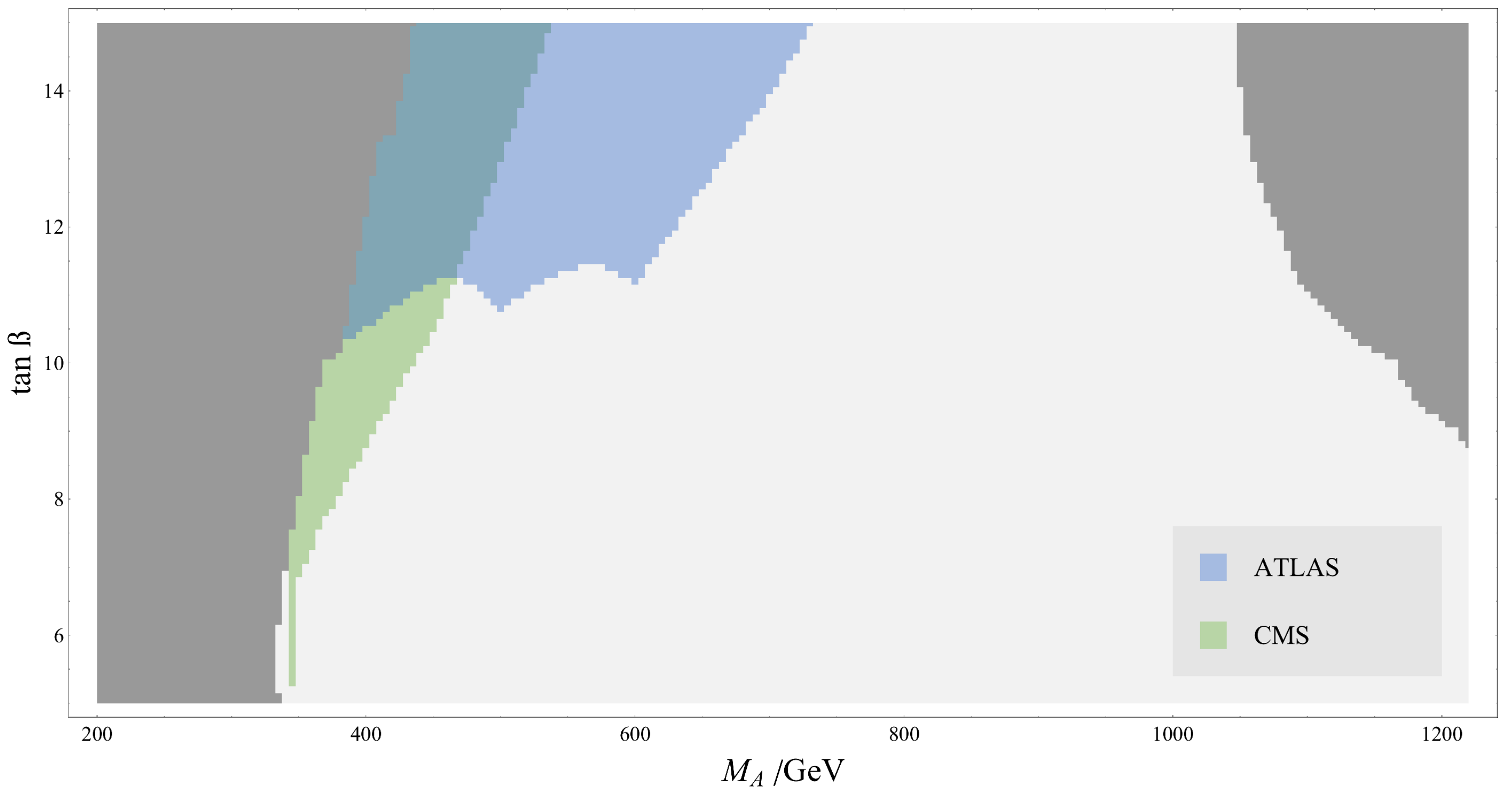
Roglans, Spiegel, Sun, Huang, C.W.'16

Limits from Direct Searches in the two different Blind Spot Regions

Well Tempered Neutralino

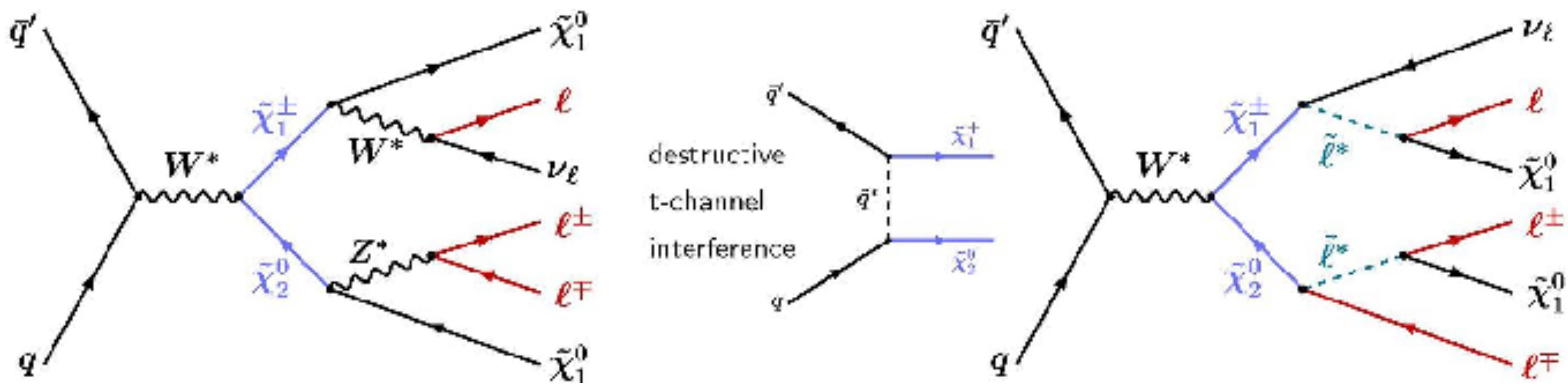


Resonant Annihilation



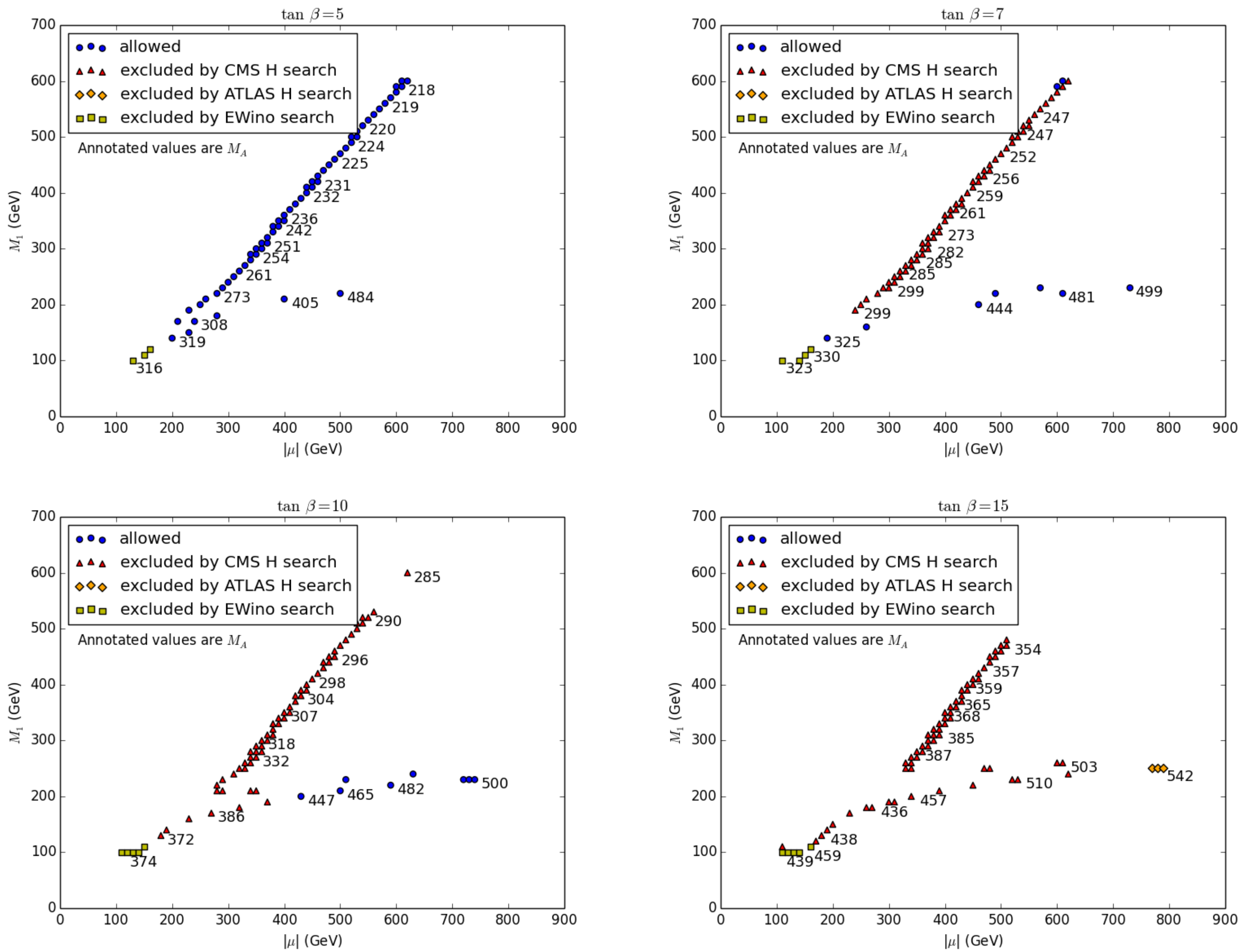
Searches for Charginos and Neutralinos

Trilepton Channel



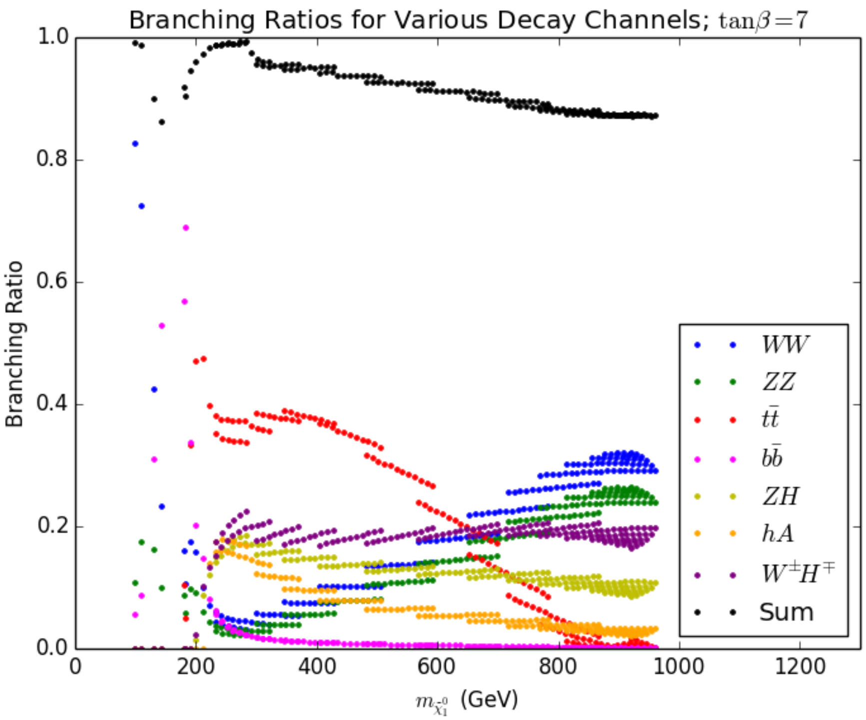
For heavy sleptons, the bounds are weak, due to
Branching Ratio suppression

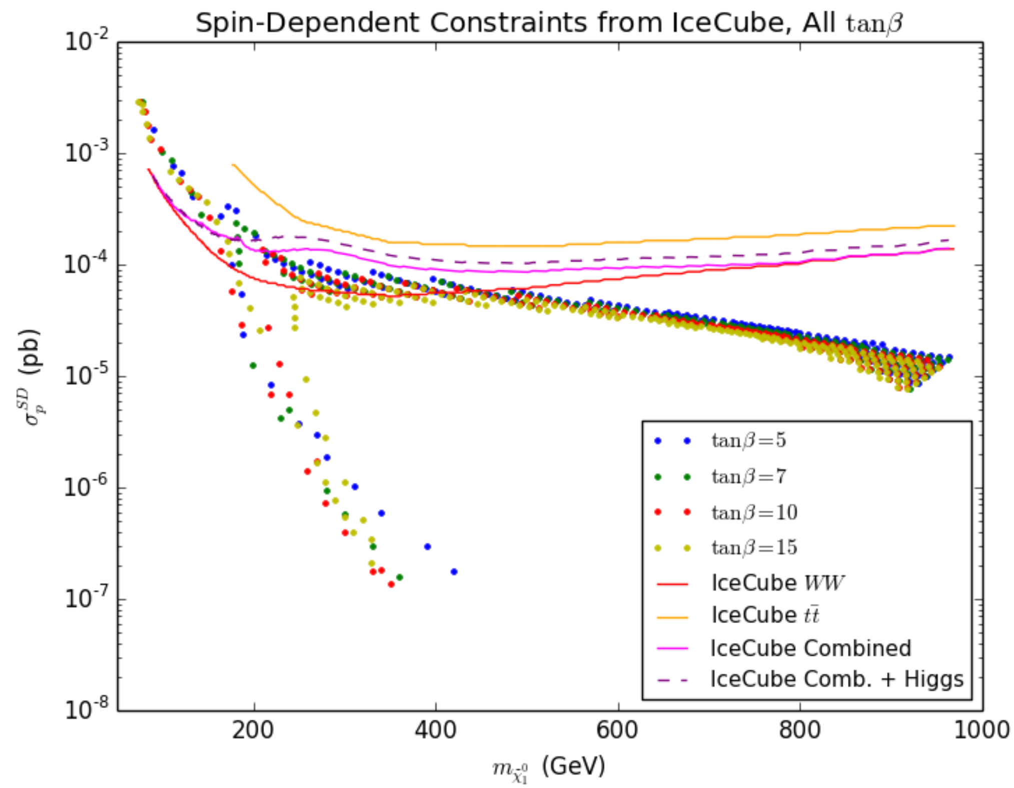
LHC puts very Strong Constraints on Moderate and Large tanβ Scenarios



Spin Independent and Indirect Detection Constraints

Strongest Bounds from IceCube





These Scenarios are Not Strongly Constrained

Conclusions

- Higgs Measurements in good agreement with a Standard Higgs boson (third generation couplings still uncertain)

- A light spectrum in extended Higgs sector demands some alignment between the Higgs and mass eigenstate bases

- Difficult to achieve in the MSSM (large SUSY breaking parameters), but natural in the NMSSM

- Dark Matter at the Well tempered, Bino-Higgsino region, may avoid constraints provided extra Higgs bosons, proceeding from the second doublet, are light. This calls for alignment

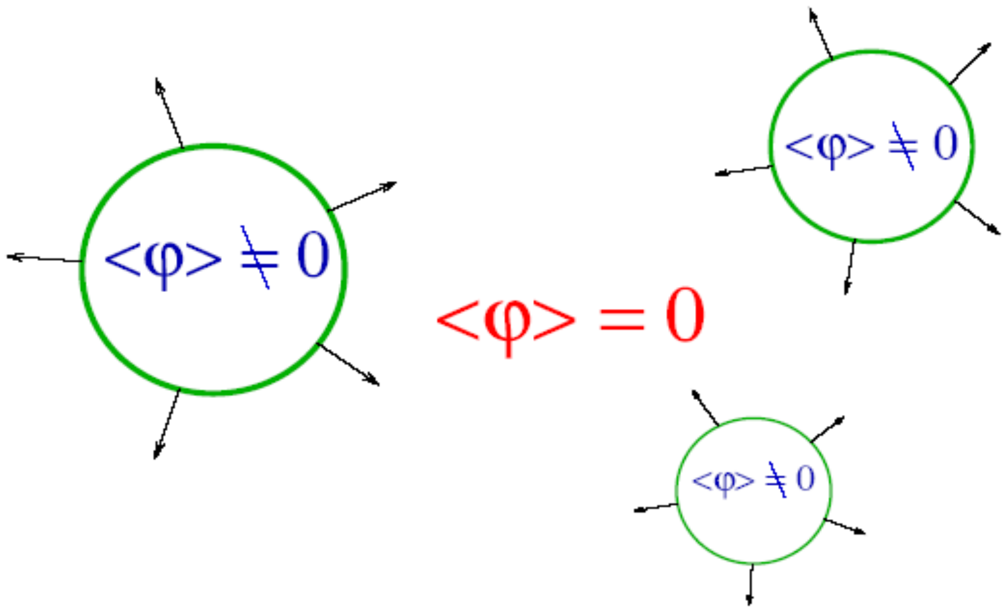
- Present data, and the realization of Dark Matter and electroweak baryogengesis in these theories, call for the search of regions of parameter space, where alignment, blind spots and first order phase transitions may be simultaneously realized.

Weak Scale Origin of the Matter-Antimatter Asymmetry

Electroweak Baryogengesis

Baryon Number Generation

Baryon number is generated by reactions in and around the bubble walls.



Morrissey

Condition for successful baryogengesis :
Suppression of baryon number violating processes inside the bubbles

$$\frac{v(T_c)}{T_c} > 1$$

Generic potential with non-renormallizable operators

$$V_{\text{eff}} = (-m^2 + AT^2)\phi^2 + \lambda\phi^4 + \gamma\phi^6 + \kappa\phi^8 + \eta\phi^{10} + \ldots$$

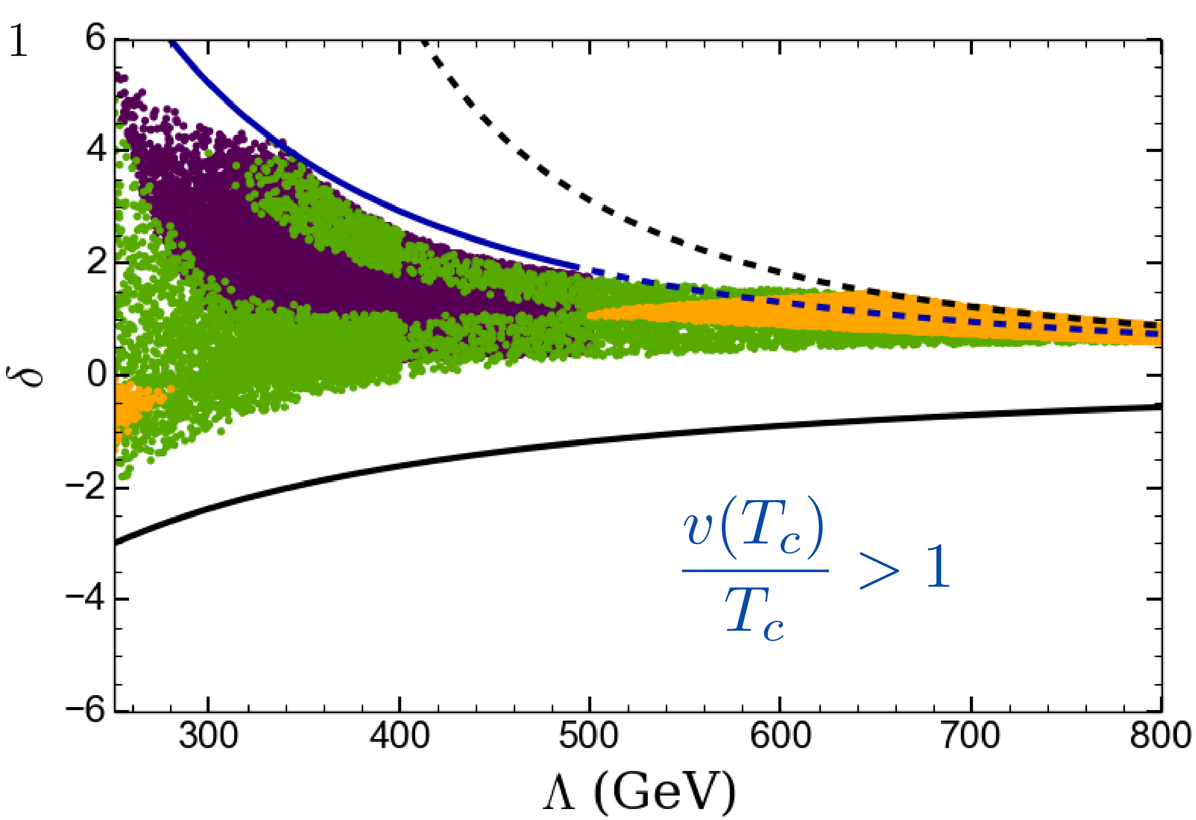
Here, $\gamma \propto 1/\Lambda^2$, $\kappa \propto 1/\Lambda^4$ and $\eta \propto 1/\Lambda^6$.

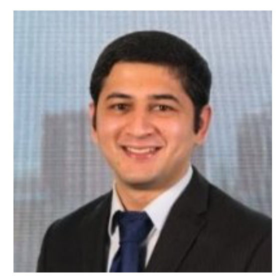
Perelstein, Grojean et al

One of the relevant characteristics of this model is that the self interactions of the Higgs are drastically modified.

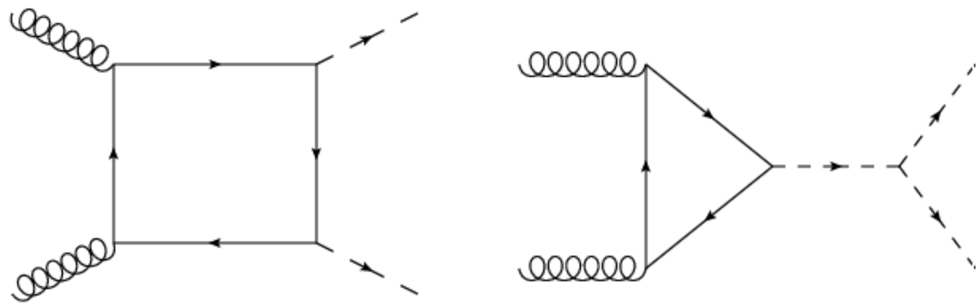
Joglekar, Huang, Li, C.W.'15

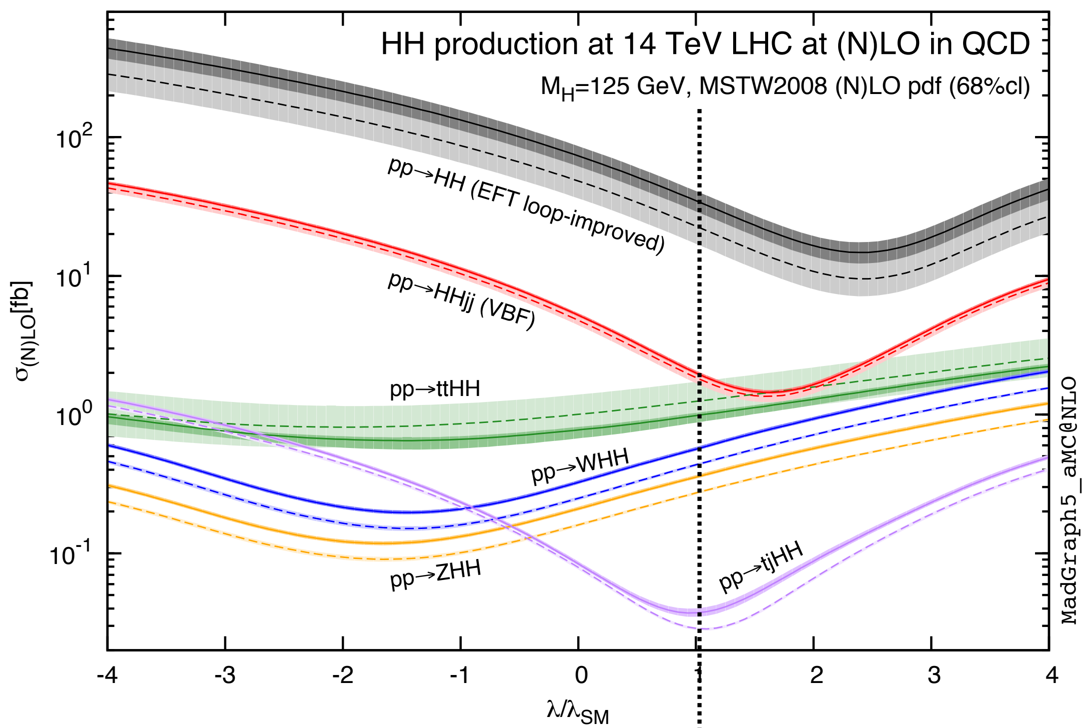
$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1$$





Unfortunately, checking this possibility is hard at the LHC.





Frederix et al'14

Very few events in the SM case after cuts are implemented.

Light Stops or small modifications of the top quark coupling (or both) can strongly enhance the di-Higgs production rate.

Joglekar, Huang, Li, C.W.'17

Baum, Carena, Shah, C.W.'17

Phase Transition in the NMSSM

[Pietroni '92; Davies *et al.* '96; Huber+Schmidt '00; Menon *et al.* '04; ...]

Carena, Shah,C.W'12, Huang et al '14, Shu et al'15, Kozaczuk et al '15…

- The tree-level potential reads

$$\begin{aligned} V(H_u, H_d, S) &= -2\lambda S A_\lambda H_d H_u + \frac{2}{3}\kappa S^3 A_\kappa + \frac{1}{8}\left(g_1^2 + g_2^2\right)\left(H_u^2 - H_d^2\right)^2 + \left(kS^2 - \lambda H_d H_u\right)^2 \\ &+ H_d^2 m_d^2 + \lambda^2 S^2\left(H_d^2 + H_u^2\right) + H_u^2 m_u^2 + m_2^2 S^2 \qquad (2.4) \end{aligned}$$

- The parameter are related to physical parameters by $\lambda < S >= \mu$ and

$$M_A^2 = \frac{2\mu\left(A_\lambda + \kappa\mu/\lambda\right)}{\sin(2\beta)}$$

- Large values of Aλ known to be helpful in inducing a first order phase transition (trilinear coupling)

- It is useful to go to the Higgs basis and decouple the heavy degrees of freedom

$$\begin{aligned} \phi &= H_u \sin\beta + H_d \cos\beta \\ H &= H_d \sin\beta - H_u \cos\beta \end{aligned}$$

Effective Potential for Φ and S

- One arrives to the following potential for the light degrees of freedom

$$V(\phi, S) = m_\phi^2 \phi^2 + \lambda_\phi \phi^4 + m_S^2 S^2 + \frac{2}{3}\kappa A_\kappa S^3 + \kappa^2 S^4 - \lambda \phi^2 S s_{2\beta} \left(A_\lambda + \kappa S\right) + \lambda^2 \phi^2 S^2 + \\ - \frac{\phi^2 c_{2\beta}^2 \left[2\lambda S \left(A_\lambda + \kappa S\right) - s_{2\beta} M_A^2\right]^2}{4\left[M_A^2 + \lambda\left(\lambda + \kappa s_{2\beta}\right)\left(S^2 - \frac{\mu^2}{\lambda^2}\right) + \lambda A_\lambda s_{2\beta}\left(S - \frac{\mu}{\lambda}\right)\right]},$$

- Now, a strongly first order phase transition will occur whenever at finite temperature the would be physical minimum becomes degenerate with the trivial one

- Although this is not necessary, one expect this to happen close to the points in which at zero temperature these minima are not far apart in depth. One can then evaluate the above potential close to the minimum.

- For this, it is useful to include the dominant radiative corrections induce by the stops.

Baum, Carena, Shah, C.W.'17

Potential at the Minimum

- The stop corrections may be absorbed into the mass parameter of the Higgs that couple to up quarks, as well as in the quartic coupling.

- These parameters are related by the minimization condition. The end result of this procedure is that the potential at the minimum is given by

$$V(v,0,\mu/\lambda) \;=\; -\lambda_\phi v^4 - \frac{\kappa}{3}\frac{\mu^3}{\lambda^3}\left(A_\kappa + 3\kappa\frac{\mu}{\lambda}\right) + \frac{\mu v^2 s_{2\beta}}{2}\left(A_\lambda + \frac{2\kappa\mu}{\lambda} - \frac{2\mu}{s_{2\beta}}\right)$$

- Here the parameter λ_ϕ absorbs the dominant radiative corrections to the potential.

- The normalization chosen is such that $v = 174$ GeV, $\lambda \simeq 0.13$ and therefore

$$m_h^2 = 4\,\lambda_\phi v^2$$

- The last term is proportional to the misalignment condition, and vanishes for exact alignment. The other three terms are proportional to the quartic coupling contribution of the singlet and the doublet, and an interesting term in Aκ.

Parameter Constraints

- From here, a constraint on Aκ is obtained, in order to preserve the physical minimum as the global one, namely

$$-\kappa\mu A_\kappa < 3\lambda^3 \frac{v^2}{\mu^2}\left[\lambda_\phi v^2 + \frac{\kappa^2}{\lambda^2}\frac{\mu^2}{v^2}\frac{\mu^2}{\lambda^2} - \frac{\mu s_{2\beta}}{2}\left(A_\lambda + \frac{2\kappa\mu}{\lambda} - \frac{2\mu}{s_{2\beta}}\right)\right]$$

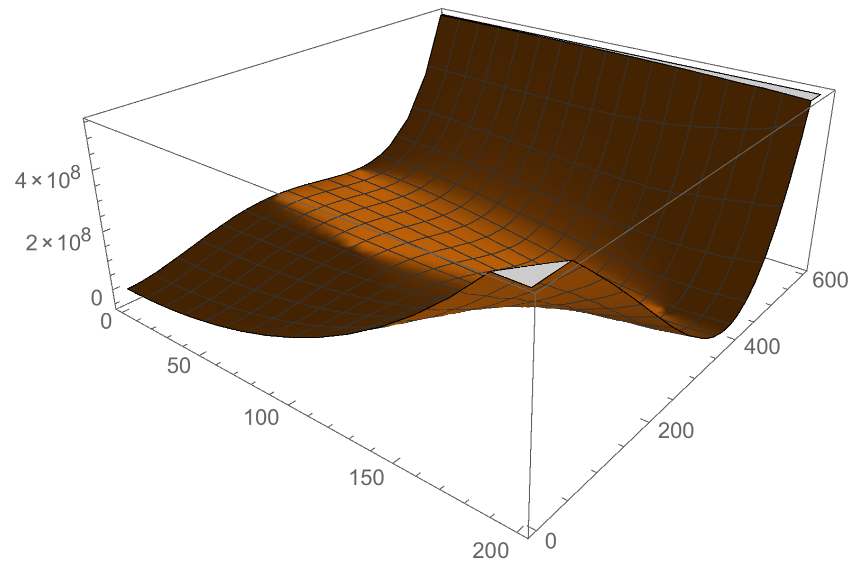
- For values of Aκ saturating this bound the physical minimum is degenerate with the trivial one.

- For values of |Aκ| somewhat smaller than the one given by the bound above, the physical minimum is the global one and temperature effects will induce a first order phase transition.

- The parameter Aκ controls also the CP-even singlet mass, and larger values of (-κμAκ) imply lighter CP-even singlet masses and heavier CP-odd singlet ones.

Baum, Carena, Shah, C.W.'17

Potential close to the Phase Transition



Indeed, a first order phase transition develops for these values of A_κ

Intriguingly enough, for similar values of the parameters, a blind spot in the Higgsino-Singlino region may be obtained

Unfortunately, standard tools, like NMSSMTools have to be corrected in order to make them consistent with this analysis (Bounds on Minima computed at one loop, but with running top masses at the stop scale, but Higgs mass at two loops)

Stay tuned for more news on this subject.

Blind Spots in the Singlino-Higgsino region

- Conditions somewhat different from the Bino-Higgsino case.

- It depends on (Mis)Alignment and on a Light CP-even singlet and it connects to the region where a first order phase transition occurs in an intriguing way.

$$\sigma_{SI} \propto \left\{ \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) \frac{2\, t_\beta}{m_h^2} + \frac{t_\beta}{m_H^2} \right.$$
$$\left. + \frac{1}{m_{h_S}^2} \left(2\, S_{h,s} + \frac{\lambda\, v}{\mu} \right) \left[\frac{\lambda\, v}{\mu^2}\, m_\chi + S_{h,s} \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) + \frac{\kappa\, \mu}{\lambda^2\, v} \right] \right\}^2$$

$$m_{h_S}^2 = \frac{\kappa\mu}{\lambda} \left(A_\kappa + \frac{4\kappa\mu}{\lambda} \right) + \lambda^2 v^2 \left(1 - c_{2\beta}^2\right) - \frac{\kappa^2 v^2}{2} s_{2\beta}^2\, c_{2\beta}^2 - \frac{1}{2} \kappa\lambda v^2 \left(2c_{2\beta}^2 + 1\right) s_{2\beta}$$

- Positive values of μ are now preferred to approach the blind spot scenario.

- Actually, while looking for blind spots in this region, the constraints on the physical vacuum being the global one become relevant

- Looking for compatibility between the obtention of the proper relic density, consistency with direct detection and a first order phase transition is a worthy effort and we are working in that direction.

More on Couplings

M. Badziak and C.W. '1602.06198

NMSSM Implementation : Heavy Singlets

	P1	P2	P3	P4	P5
λ	0.76	0.85	1.1	1.4	1.4
$\tan\beta$	4	2	2	1.5	1.5
m_{Q_3}	700	700	700	700	700
m_{U_3}	500	480	500	480	450
A_t	-1170	-1100	-1030	-780	-1030
μ	300	770	1040	1060	390
M_2	500	500	500	500	-90
μ'	60	45	40	14	-24
M_{P_1}	193	197	277	332	357
M_{P_2}	2000	2500	3000	2400	800
m_h	125.1	125.9	125.0	124.9	125.0
m_H	192	184	262	280	299
$m_{H^\pm}$	167	161	236	257	272
m_A	195	204	293	342	344
$m_{\tilde{\chi}_1^0}$	70	65	66	63	89
$m_{\tilde{\chi}_1^\pm}$	282	504	516	514	109
$m_{\tilde{t}_1}$	236	232	241	231	222
$m_{\tilde{t}_2}$	726	752	766	757	730
$R_{VV}^{\rm tth}$	1.79	1.84	1.96	1.92	1.87
$R_{\gamma\gamma}^{\rm tth}$	1.97	2.12	2.22	2.19	1.96
$R_{VV}^{\rm gg}$	1.16	1.00	1.12	1.18	1.23
$R_{\gamma\gamma}^{\rm gg}$	1.29	1.15	1.27	1.34	1.29
$R_{VV}^{\rm VBF/VH}$	1.70	1.57	1.65	1.48	1.43
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.89	1.80	1.87	1.69	1.50
$R_{\tau\tau}^{\rm VBF/VH}$	0.70	0.71	0.67	0.71	0.65
$\mathrm{BR}(H\to\tilde{\chi}_1^0\tilde{\chi}_1^0)$	0.71	0.49	0.24	0.14	0.19
$\mathrm{BR}(H\to\tilde{\chi}_1^0\tilde{\chi}_2^0)$	0	0	0	0	0.17
$\mathrm{BR}(H\to hh)$	0	0	0.47	0.71	0.54
$\mathrm{BR}(A\to\tilde{\chi}_1^0\tilde{\chi}_1^0)$	0.85	0.89	0.78	0.75	0.88
$\mathrm{BR}(A\to H^\pm W^\mp)$	0	0	0	0.05	0

- One can implement the previous idea within the NMSSM
- However, the NMSSM is more than just adding a stop to the 2HDM, because as shown before the matrix elements depend on the parameters of the theory, and for certain parameters alignment is obtained
- Departure of alignment here demands larger values of lambda and values of $\tan\beta \simeq 1$ are difficult to achieve
- Constraints on the production of heavy Higgs bosons can be easily arranged by a small amount of decay into neutralinos, that is natural in this theory.
- Most constraining observable : Diphoton production in vector boson fusion.

Badziak, C.W. , to appear

Alternative : Light Singlets

- The previous reasoning was adequate when one considered an effective 2x2 CP-even Higgs matrix, resulting from the decoupling of singlets.
- However, in the case of light singlets, a component of the SM-like CP-even Higgs on the doublet states may be induced by mixing with light singlets.
- This may be achieved, with values of the coupling λ that are smaller than 0.7 and therefore in the region of consistency with perturbative behavior up to the GUT scale.

Badziak, C.W. , to appear

NMSSM Scenarios with light singlets

	P1	P2	P3	P4
λ	0.5	0.53	0.5	0.55
$\tan\beta$	1.6	1.6	2	2
m_{Q_3}	800	800	800	800
m_{U_3}	320	310	280	270
A_t	-1500	-1400	-1500	-1400
μ	600	800	600	800
μ'	330	500	330	310
M_A	300	300	300	400
M_P	246	382	347	382
A_λ	905	1125	1055	1610
m_s	98	98	79	85
m_h	124.5	125.8	124.7	125.1
m_H	317	390	393	465
$m_{H^\pm}$	236	200	225	325
m_a	101	136	130	89
m_A	329	412	395	496
$m_{\tilde{\chi}_1^0}$	243	245	243	245
$m_{\tilde{t}_1}$	282	282	276	275
$m_{\tilde{t}_2}$	954	960	952	954

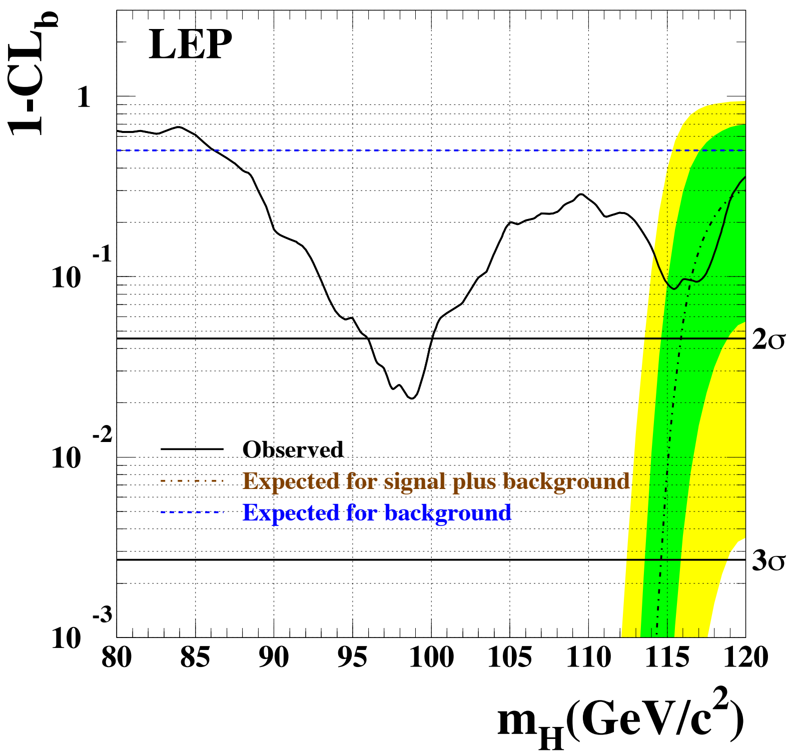
	P1	P2	P3	P4
$R_{VV}^{\rm tth}$	1.60	1.61	1.62	1.61
$R_{\gamma\gamma}^{\rm tth}$	1.82	1.82	1.81	1.79
$R_{VV}^{\rm gg}$	1.02	1.01	1.04	1.04
$R_{\gamma\gamma}^{\rm gg}$	1.16	1.15	1.16	1.16
$R_{VV}^{\rm VBF/VH}$	1.32	1.34	1.43	1.42
$R_{\gamma\gamma}^{\rm VBF/VH}$	1.51	1.53	1.60	1.57
$R_{\tau\tau}^{\rm VBF/VH}$	0.73	0.78	0.78	0.77
$\xi_{b\bar{b}}^{\rm LEP}$	0.10	0.04	0.04	0.04
$\bar{g}_s$	0.31	0.20	0.18	0.20
$\mathrm{BR}(H \to t\bar{t})$	0	0.024	0.036	0.071
$\mathrm{BR}(H \to ss)$	0.37	0.04	0.002	0.15
$\mathrm{BR}(H \to aa)$	0.23	0.63	0.42	0.24
$\mathrm{BR}(H \to aZ)$	0.23	0.11	0.26	0.39
$\mathrm{BR}(H \to hs)$	0.15	0.03	0.019	0.017
$\mathrm{BR}(H \to H^\pm W^\mp)$	0	0.15	0.25	0.13
$\mathrm{BR}(A \to t\bar{t})$	0	0.13	0.12	0.12
$\mathrm{BR}(A \to as)$	0.64	0.26	0.26	0.31
$\mathrm{BR}(A \to Zs)$	0.22	0.24	0.32	0.34
$\mathrm{BR}(A \to ah)$	0.10	0.036	0.021	0.002
$\mathrm{BR}(A \to H^\pm W^\mp)$	0.02	0.33	0.27	0.22
$\mathrm{BR}(H^+ \to t\bar{b})$	0.52	0.63	0.36	0.24
$\mathrm{BR}(H^+ \to W^+ a)$	0.26	0	0.08	0.40
$\mathrm{BR}(H^+ \to W^+ s)$	0.22	0.37	0.56	0.35

Large decay Branching ratio of MSSM Higgs into singlet states

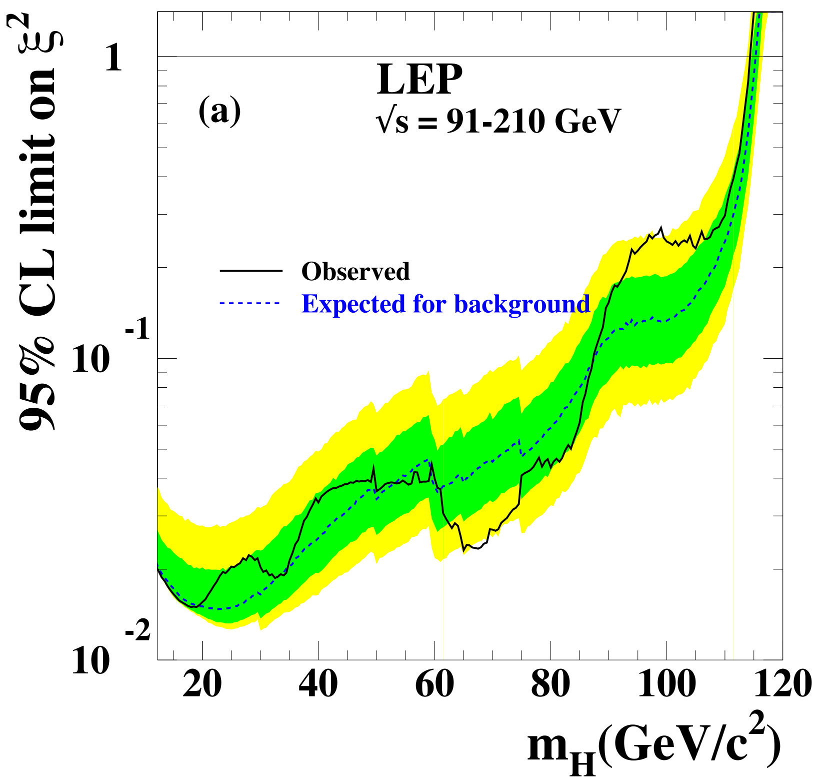
Consistent with the LEP2 Excess (not a necessary ingredient)

LEP2 Excess

LHWG-2003-011

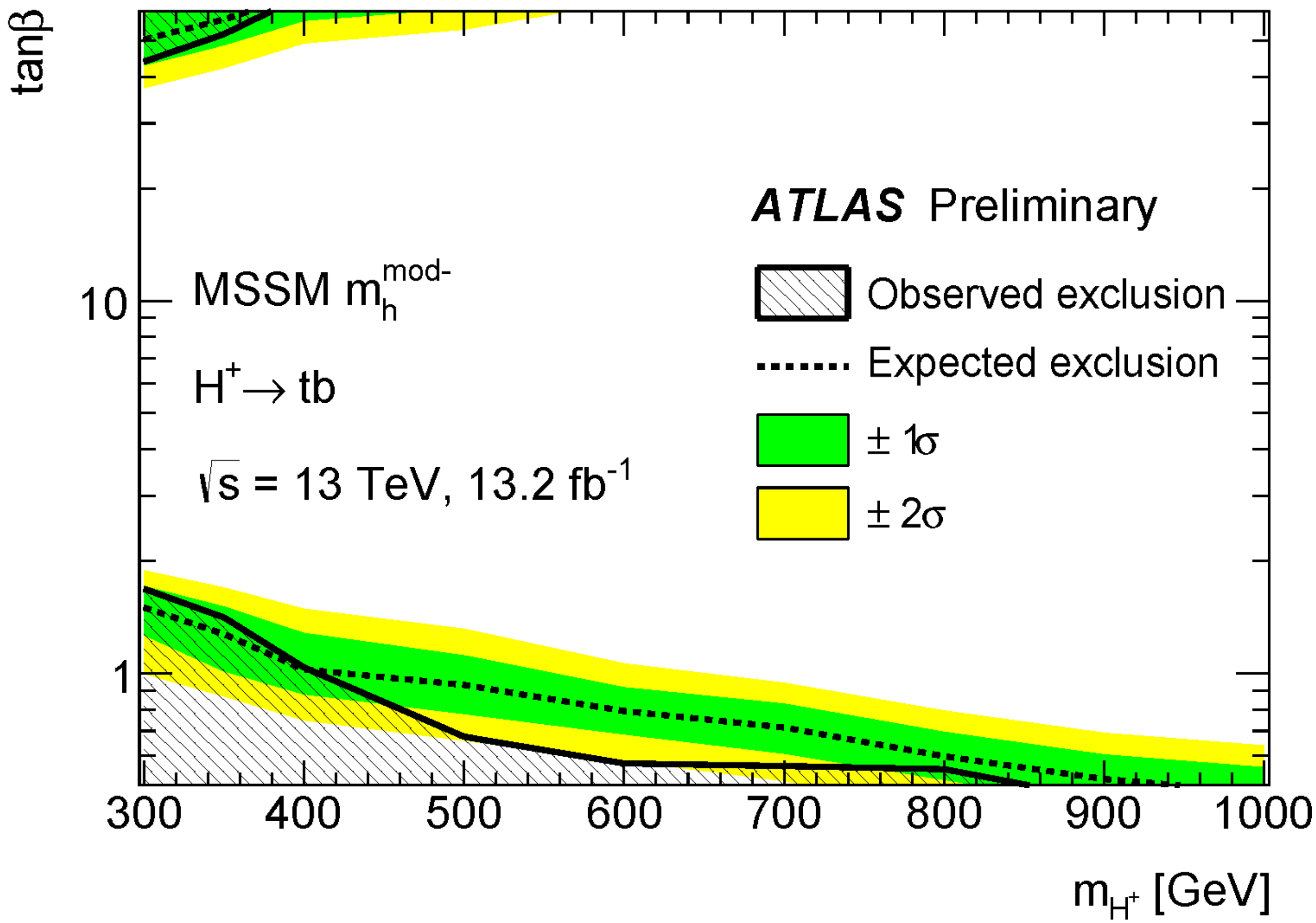


$$\xi^2 = g^2_{ZZh}/g^2_{ZZh_{SM}} \times \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})}$$



Some additional relevant channels

Charged Higgs searches in top bottom final states



Already putting relevant constraints on these scenarios.

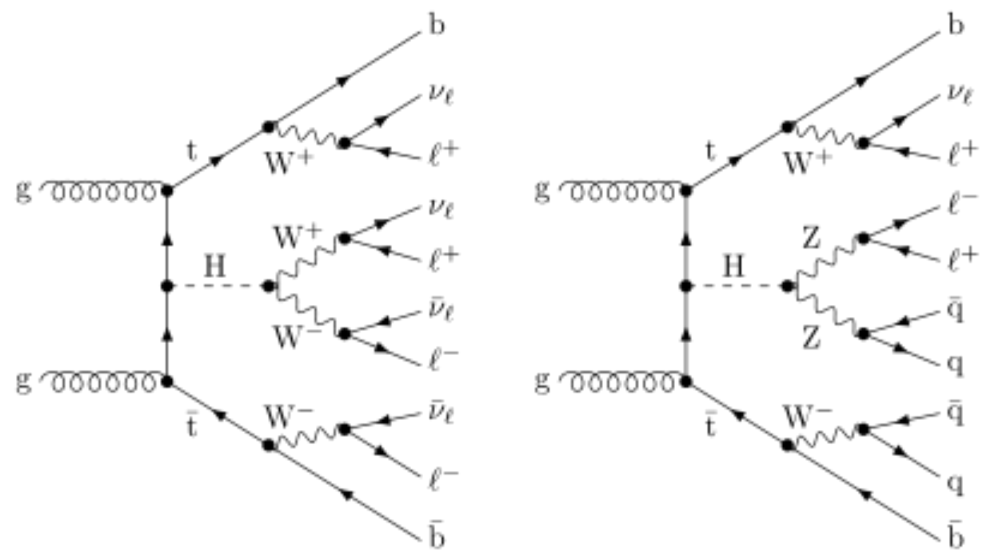
Extrapolation to lower masses ?

Alternative Interpretation of tth excess ?

Take a closer look at the main signature

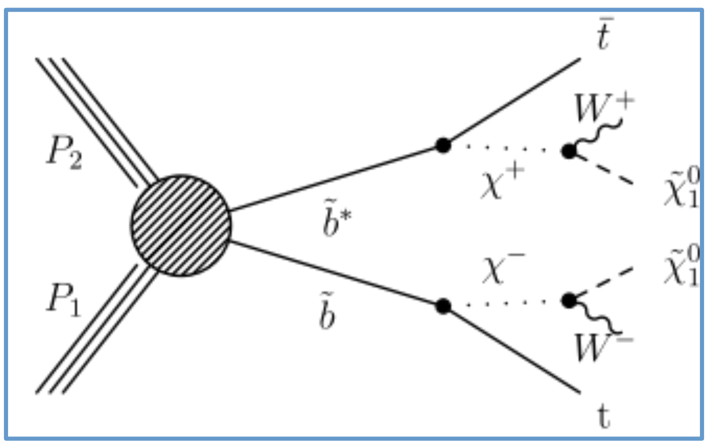
What are we seeing exactly?
tth, h->W^+W^-
It is really a search for 2t + 2W, or equivalently 2b+4W

Final states
2b + 4W gives rise to the multi-lepton + multi-(b)jets + MET signatures
tth, h->W+W- is really not about tth, but about new physics!

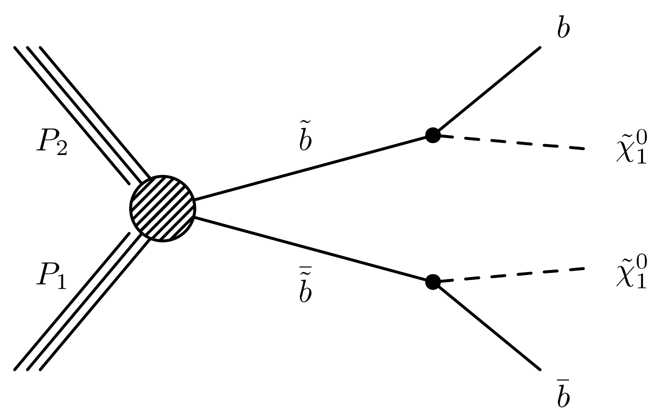


Excesses in multi-lepton + b-jets + MET

2t + 2W final states, exactly what you would do when you search for sbottoms



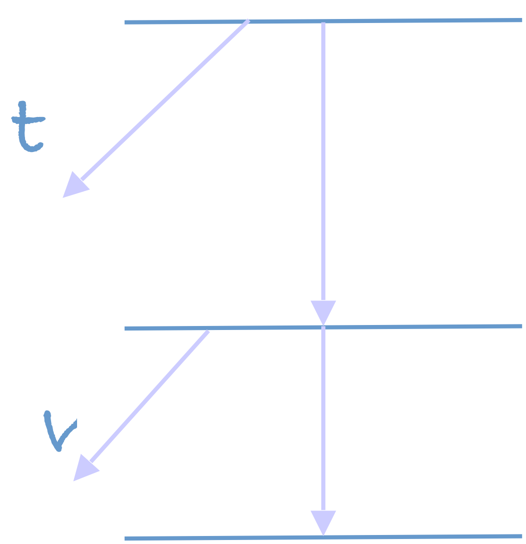
Caveat in the simplified model: can not have 100% Branching ratio, some BR goes to



CMS-SUS-13-008

Just an example, a right-handed stop

Stops are pair produced, 2t + 2W



$\tilde{t}_1 = \tilde{t}_R$;

$\tilde{\chi}_2^0 = \tilde{B}$;

$\tilde{\chi}_1^\pm = \tilde{W}^\pm$; $\chi_1^0 = \tilde{W}^0$;

A pure right-handed stop does not couple to winos, 100% BR

The neutralino mass difference is smaller than the Higgs mass, 100% BR

P. Huang, A. Ismail, I. Low, C. Wagner, 1507.01601