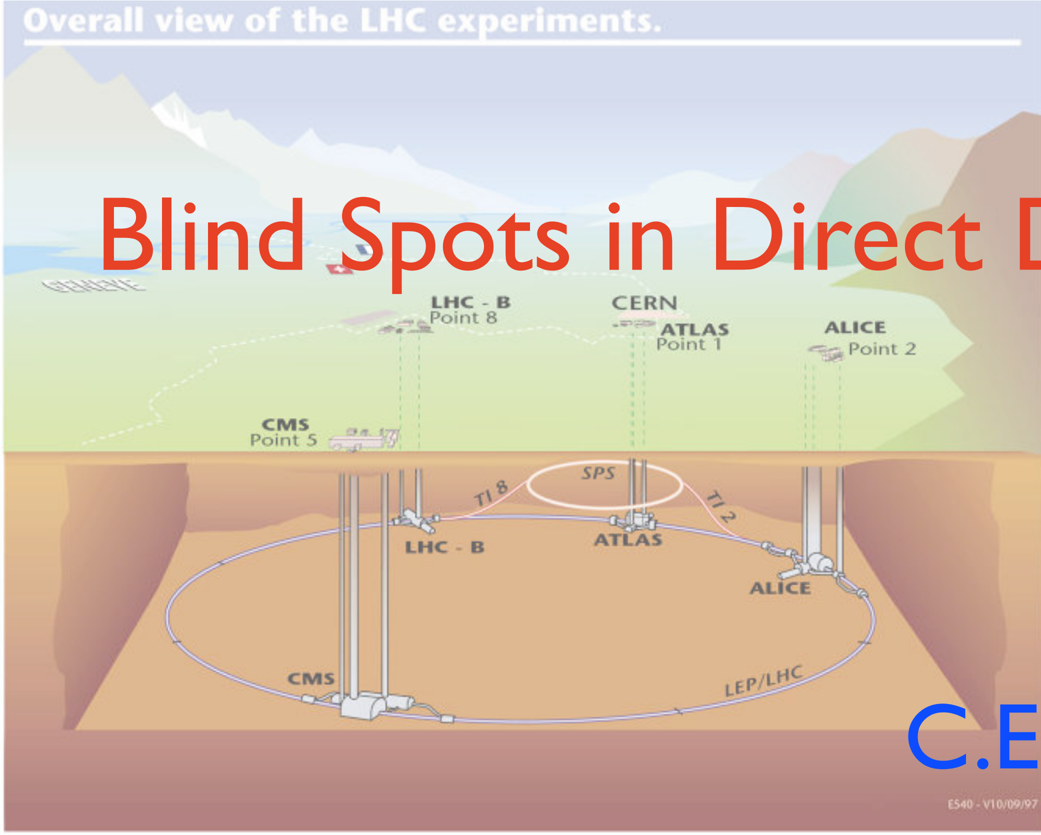
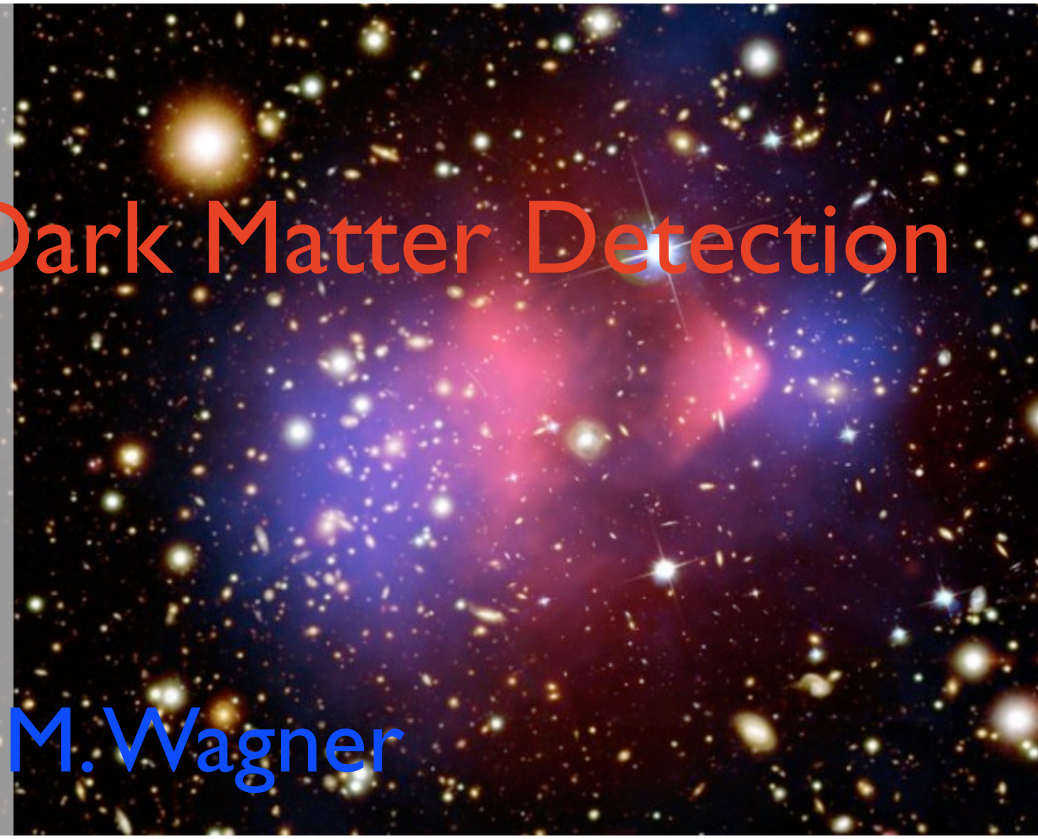
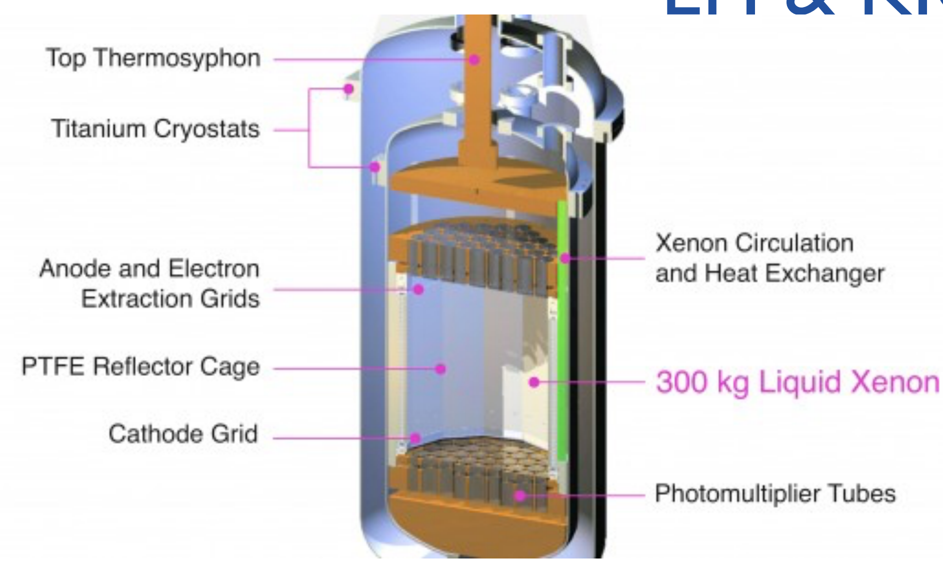
Blind Spots in Direct Dark Matter Detection

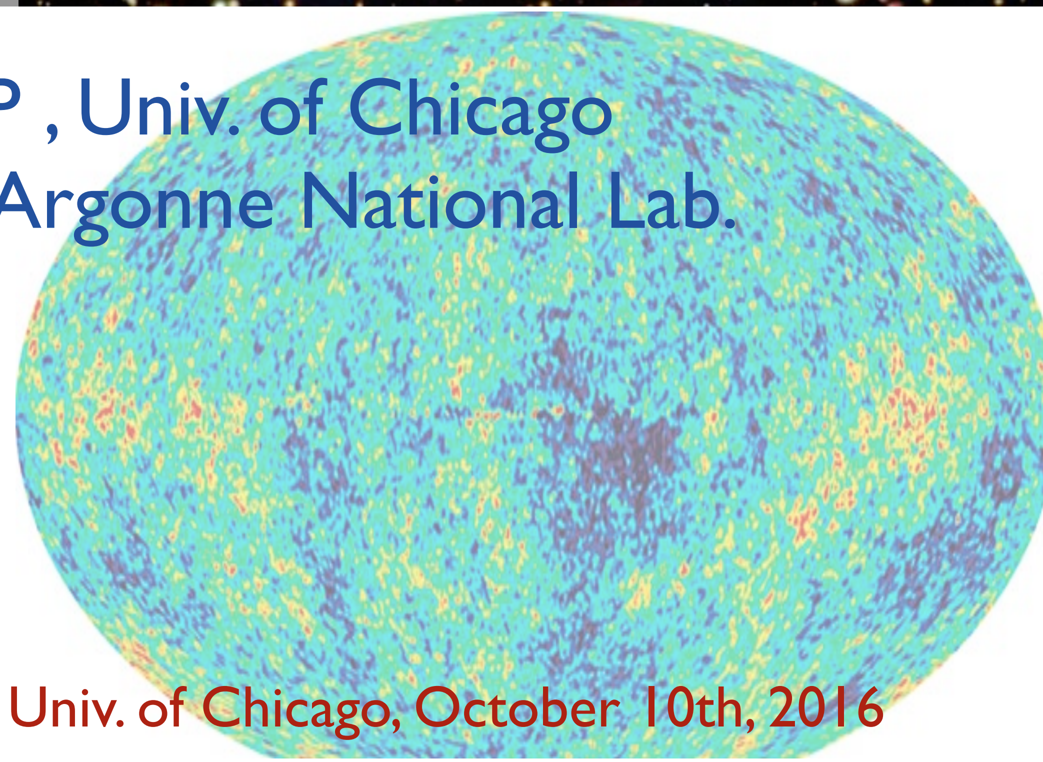




C.E.M. Wagner

EFI & KICP , Univ. of Chicago
, Argonne National Lab.

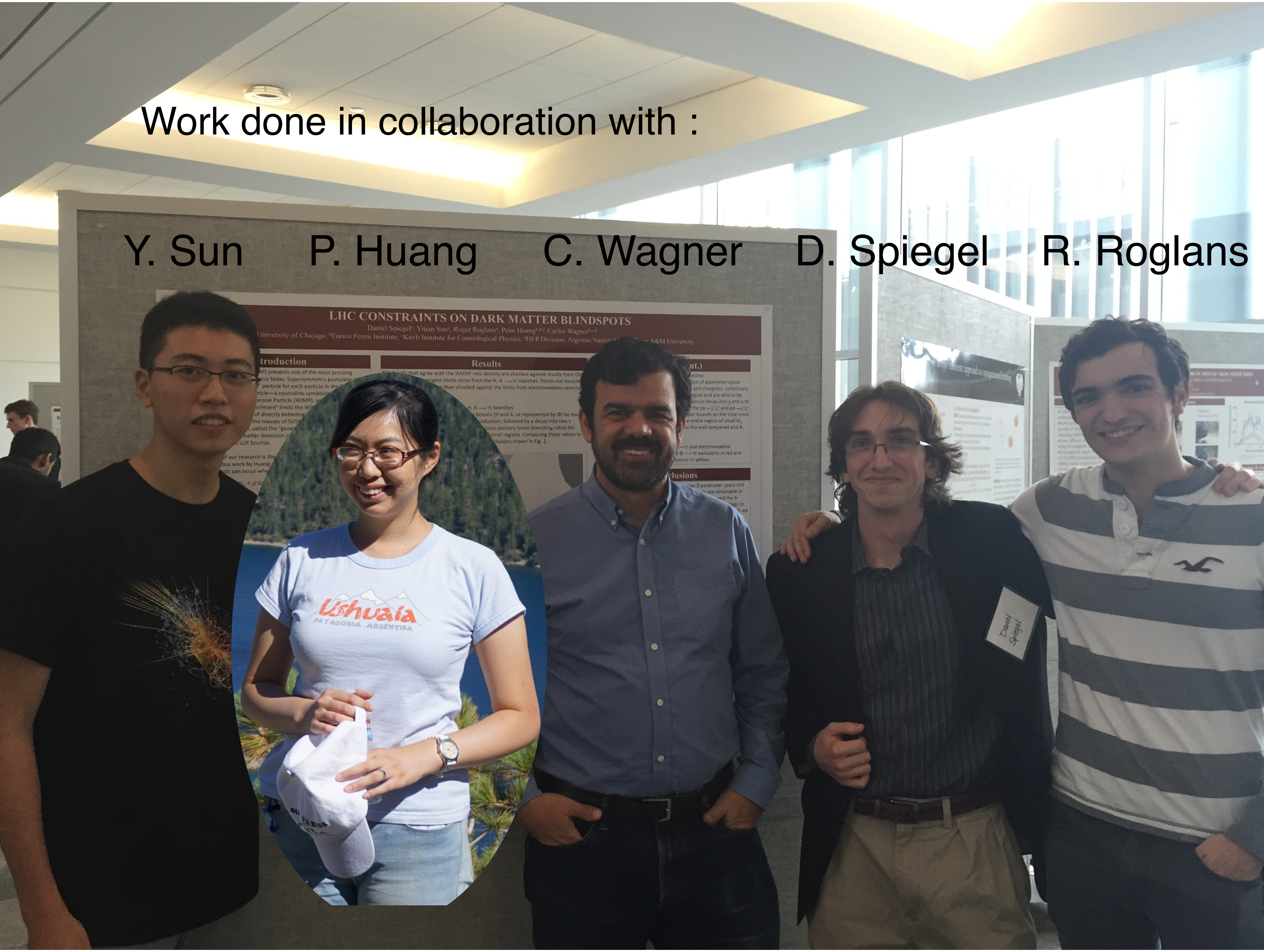




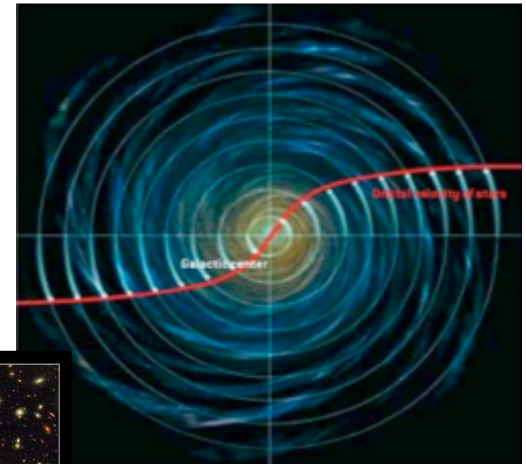
KICP workshop, Univ. of Chicago, October 10th, 2016

Work done in collaboration with :

Y. Sun P. Huang C. Wagner D. Spiegel R. Roglans



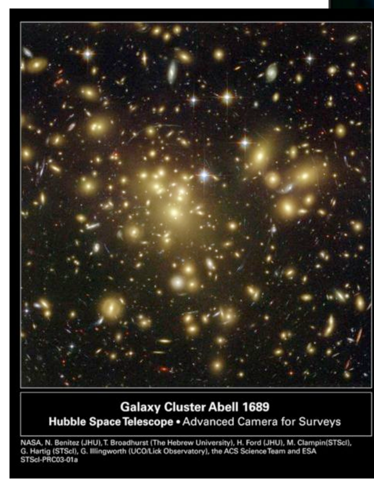
The Mystery of Dark Matter



- Rotation curves from Galaxies.

  Luminous disk → not enough mass to explain rotational velocities of galaxies → Dark Matter halo around the galaxies

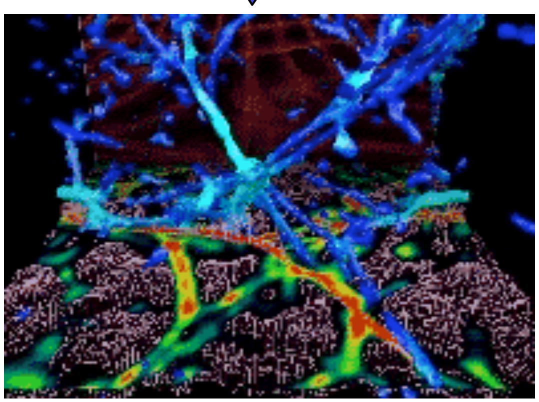
- Gravitational lensing effects

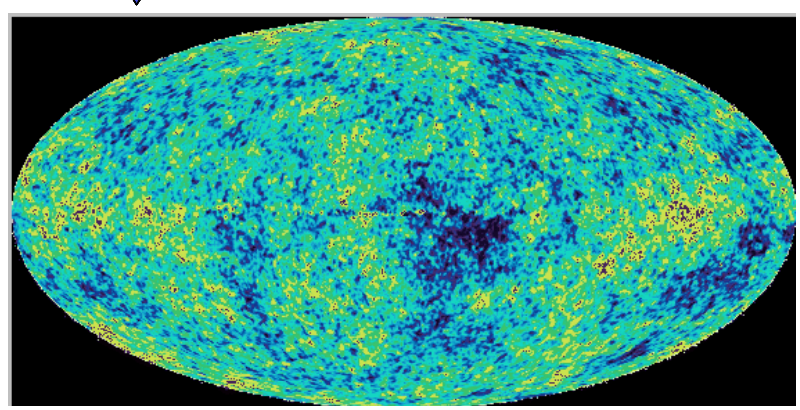


Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies

- Structure formation:

Large scale structure and CMB Anisotropies





The manner in which structure grows depends on the amount and type of dark matter present. All viable models are dominated by cold dark matter.

Dark Matter Annihilation Rate

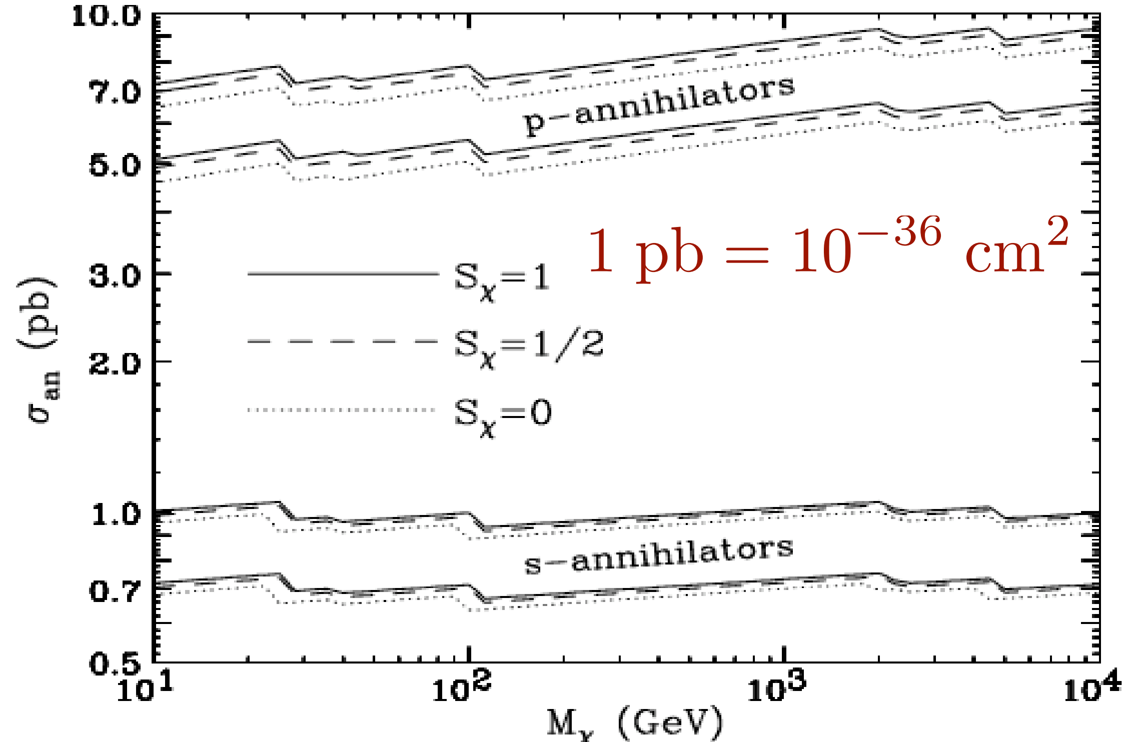
- The main reason why we think there is a chance of observing dark matter is that, when we compute the annihilation rate necessary for a thermal relic density, we get a cross section

$$\sigma_{\text{ann.}}(\text{DM DM} \to \text{SM SM}) \simeq 1 \text{ pb}$$

- This is approximately

$$\sigma_{\text{ann.}} \simeq \frac{\alpha_W^2}{\text{TeV}^2}$$

This suggests that it is probably mediated by weakly interacting particles with weak scale masses

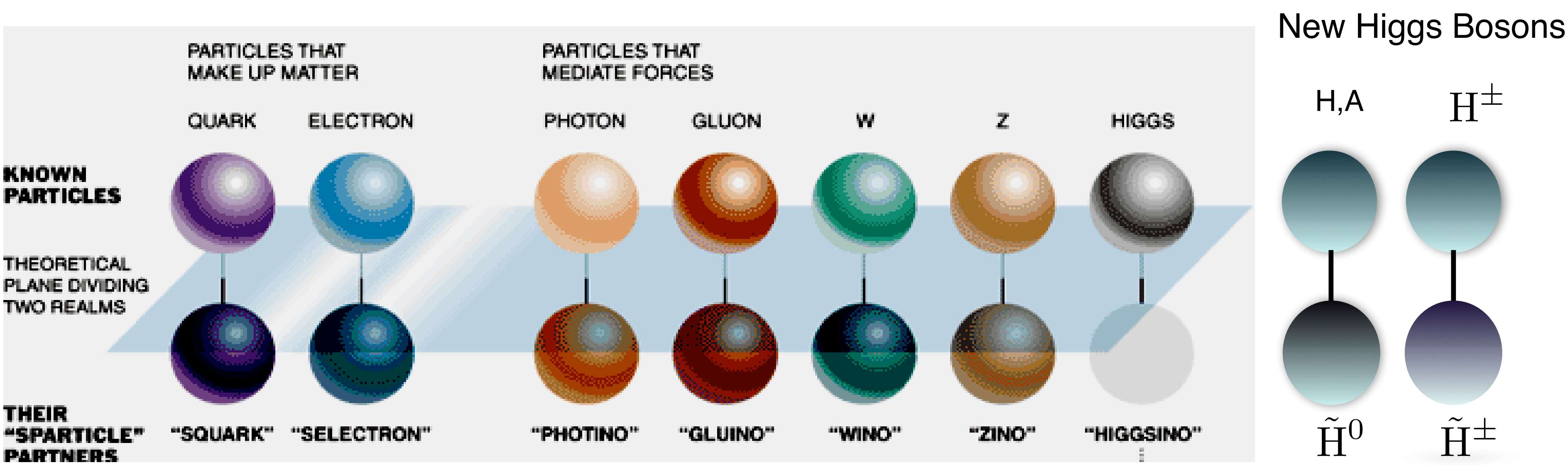


(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

- Connection of Thermal Dark Matter to the weak scale and to the mechanism of electroweak symmetry breaking

Supersymmetry

fermions   bosons



Additional Higgsinos

Photino, Zino and Neutral Higgsino: Neutralinos

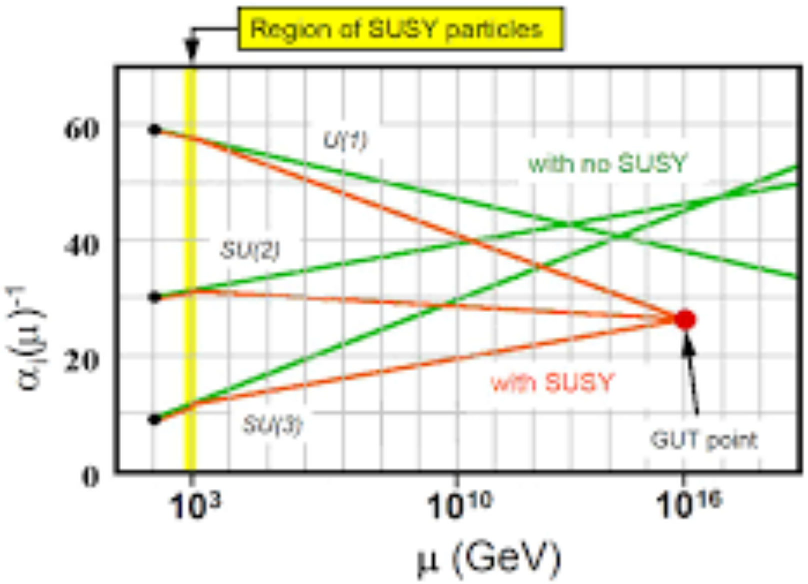
Charged Wino, charged Higgsino: Charginos

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)

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

Consequences of SUSY

Unification

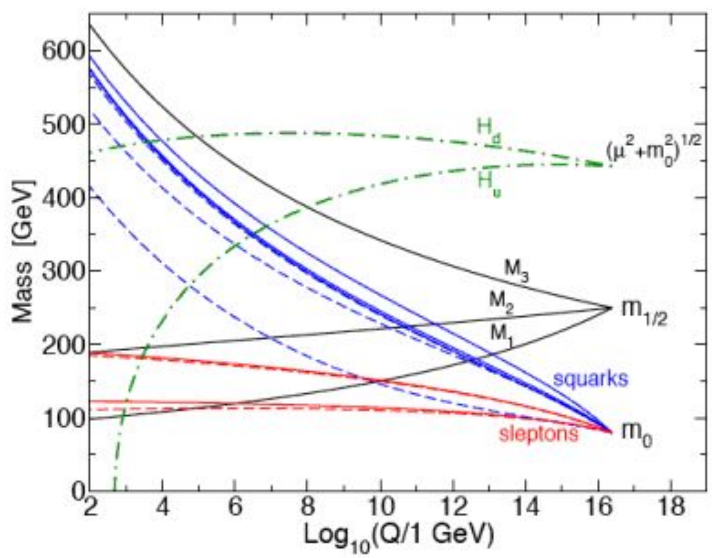


SUSY Algebra

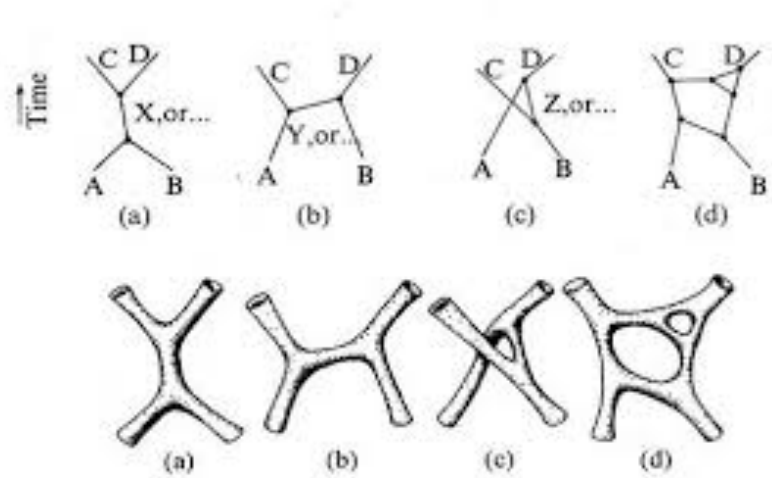
$$\left\{Q_\alpha, \overline{Q}_{\dot{\alpha}}\right\} = 2\sigma^\mu{}_{\alpha\dot{\alpha}} P_\mu$$

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

Electroweak Symmetry Breaking

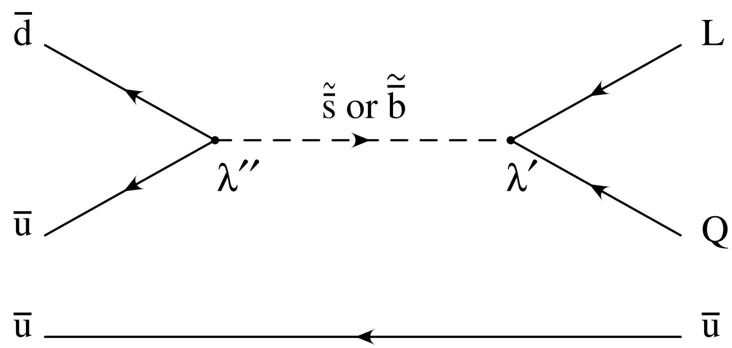


Quantum Gravity ?



Proton Decay Problem :

$$\mathrm{L} = \begin{pmatrix} \nu \\ l^- \end{pmatrix} \qquad \mathrm{Q} = \begin{pmatrix} u \\ d \end{pmatrix}$$



If all the couplings allowed by supersymmetry and gauge invariance are present, and take values of order one, the proton would present a very fast decay rate.

- Both lepton and baryon number violating couplings involved.
- Proton: Lightest baryon. Lighter fermions: Leptons

R-Parity

- A solution to the proton decay problem is to introduce a discrete symmetry, called R-Parity. In the language of component fields,

$$R_P = (-1)^{3B+2S+L}$$

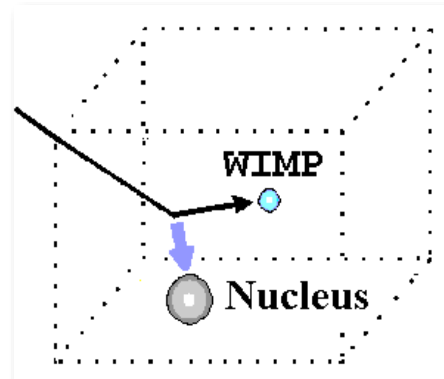
- All Standard Model particles have $R_P = 1$.
- All supersymmetric partners have $R_P = -1$.
- All interactions with odd number of supersymmetric particles, like the Yukawa couplings inducing proton decay are forbidden.
- Supersymmetric particles should be produced in pairs.
- The lightest supersymmetric particle is stable.
- Good dark matter candidate. Missing energy at colliders.

Direct Detection Dark Matter Experiments

- **Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP**

- Direct Detection Experiments can establish the existence of Dark Matter particles

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

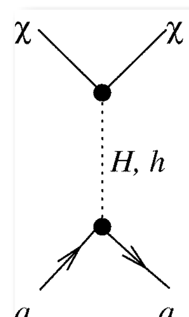


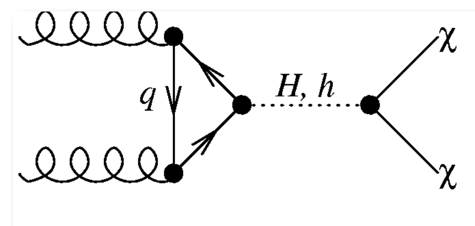
$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$

Direct DM experiments:
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\,pb$)

==> dominated by virtual exchange of H and h

- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops





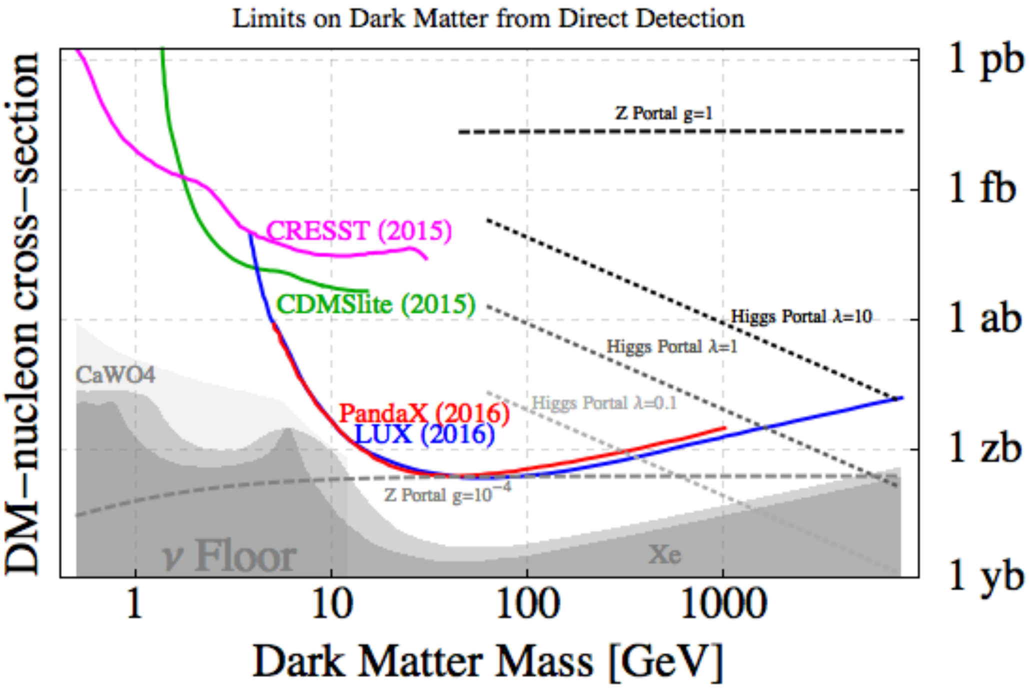
$$\frac{\sigma_{SI}}{A^4} \approx \frac{0.1 g_1^2 g_2^2 N_{11}^2 N_{13}^2 m_p^4 \tan^2\beta}{4\pi m_W^2 M_A^4}$$

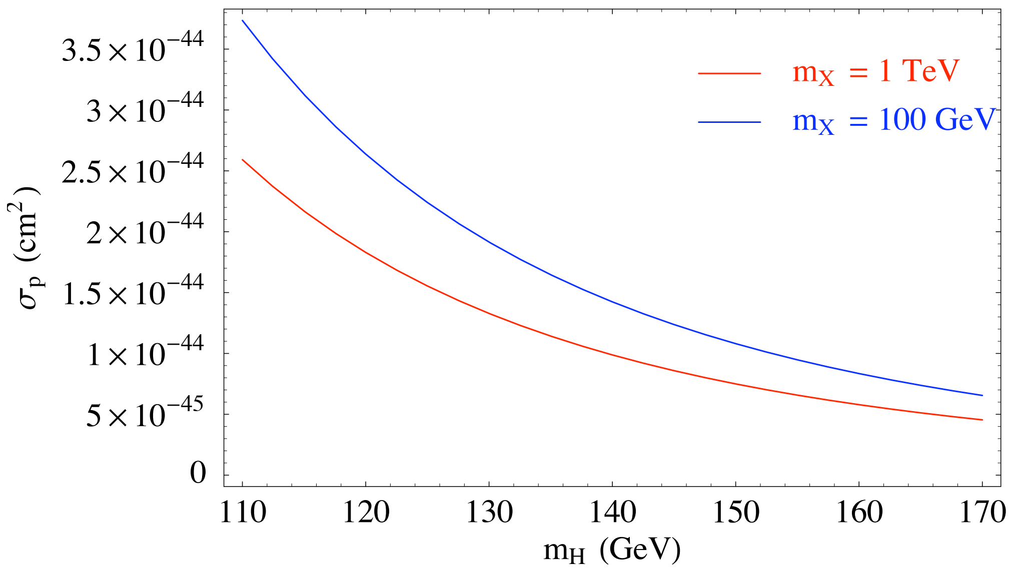
Prospects for direct Dark Matter Detection

Current Limits

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

"Typical" scenarios constrained by data





$$\sigma_p = \frac{8}{\pi}\left[\frac{G_F M_W m_p \mu_\chi}{9 m_H^2}\left(2 + 7\sum_{q=u,d,s} f_q^{(p)}\right)\gamma\right]^2 = \left(\frac{115\ \text{GeV}}{m_H}\right)^4 \gamma^2\ 5.4\times 10^{-43}\,\text{cm}^2$$

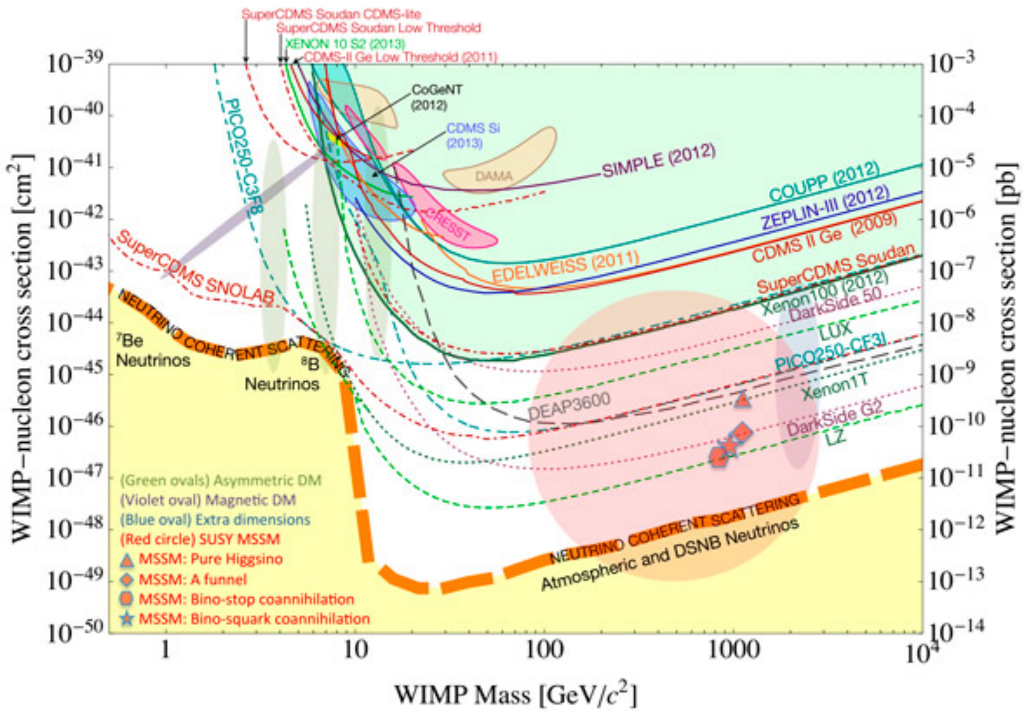
$$\gamma = \frac{1}{g}\left(\tilde{g}_u N_{\chi 2} N_{\chi 4} - \tilde{g}_d N_{\chi 2} N_{\chi 3} - \tilde{g}'_u N_{\chi 1} N_{\chi 4} + \tilde{g}'_d N_{\chi 1} N_{\chi 3}\right)\ .$$

Arkani-Hamed, Dimopoulos, Giudice, Romanino'04

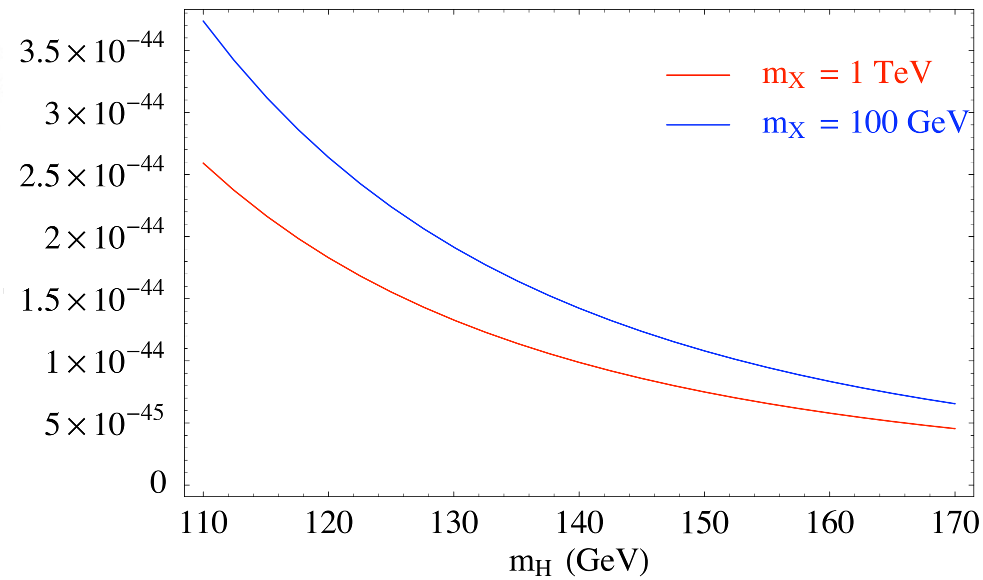
Prospects for direct Dark Matter Detection

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 scenarios
constrained by data



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$$\gamma = \frac{1}{g}\left(\tilde{g}_u N_{\chi 2} N_{\chi 4} - \tilde{g}_d N_{\chi 2} N_{\chi 3} - \tilde{g}'_u N_{\chi 1} N_{\chi 4} + \tilde{g}'_d N_{\chi 1} N_{\chi 3}\right)\ .$$

Arkani-Hamed, Dimopoulos, Giudice, Romanino'04

Neutralino Mixing in the MSSM

In the basis of fermion super partners of the gauge and Higgs fields

$$\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$$

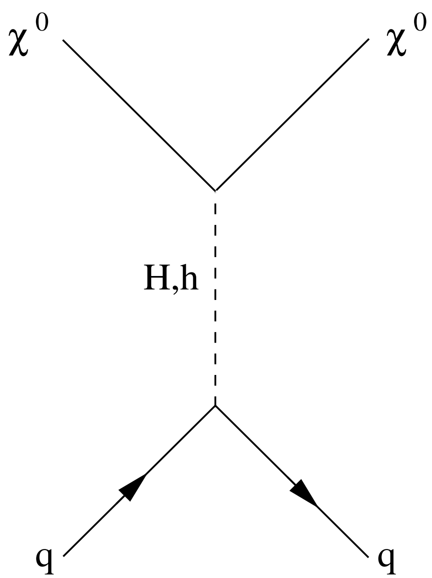
One can write a neutralino mass matrix that mix these states

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.}$$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

$$\widetilde{N}_i = \mathbf{N}_{ij} \psi_j^0$$

Relevant Direct Dark Matter Detection Amplitudes



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

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

For down quarks, for example

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

Higgs couplings to Neutralinos

$$L \supset -\sqrt{2} g' Y_{H_u} \tilde{B} \tilde{H}_u H_u^* - \sqrt{2} g \tilde{W}^a \tilde{H}_u t^a H_u^* + (u \leftrightarrow d)$$

It is a product of the gaugino component and the Higgsino components, times the gauge couplings

$$g_{\chi\chi h} \sim (g_1 N_{i1} - g_2 N_{i2})(-\cos\alpha \; N_{i4} - \sin\alpha \; N_{i3})$$

$$g_{\chi\chi H} \sim (g_1 N_{i1} - g_2 N_{i2})(-\sin\alpha \; N_{i4} + \cos\alpha \; N_{i3})$$

Combining all the previous information, we get

$$a_d \sim \frac{m_d (g_1 N_{i1} - g_2 N_{i2})}{\cos\beta} \left[N_{i4} \sin\alpha \cos\alpha \left(\frac{1}{m_h^2} - \frac{1}{m_H^2} \right) + N_{i3} \left(\frac{\sin^2\alpha}{m_h^2} + \frac{\cos^2\alpha}{m_H^2} \right) \right]$$

From the structure of the neutralino mass matrix, one obtains that

Pierce, Shah'15

$$N_{i3} \sim (m_\chi \cos\beta + \mu \sin\beta)$$

$$N_{i4} \sim (m_\chi \sin\beta + \mu \cos\beta)$$

Proper SM-like Higgs properties : $\cos\alpha \simeq \sin\beta, \quad \sin\alpha \simeq -\cos\beta$

For moderate values of tanβ and close to the decoupling limit, one obtains

$$a_d \sim \frac{m_d}{\cos\beta}\left[\cos\beta(m_\chi + \mu\sin 2\beta)\,\frac{1}{m_h^2} - \mu\sin\beta\cos 2\beta\,\frac{1}{m_H^2}\right]$$

Similarly,

$$a_u \sim \frac{m_u}{\sin\beta}\left[\sin\beta(m_\chi + \mu\sin 2\beta)\,\frac{1}{m_h^2} + \mu\cos\beta\cos 2\beta\,\frac{1}{m_H^2}\right]$$

The quark couplings allow us to obtain the expression for the proton and neutron couplings

$$a_p = \left(\sum_{q=u,d,s} f_{Tq}^{(p)}\frac{a_q}{m_q} + \frac{2}{27}f_{TG}^{(p)}\sum_{q=c,b,t}\frac{a_q}{m_q}\right)m_p$$

$$f_{Tu}^{(p)} = 0.017 \pm 0.008,\ f_{Td}^{(p)} = 0.028 \pm 0.014,\ f_{Ts}^{(p)} = 0.040 \pm 0.020 \text{ and } f_{TG}^{(p)} \approx 0.91$$

$$< p|m_q q\bar{q}|p >\equiv m_p f_{Tq}^{(p)}, \qquad f_{TG}^{(p)} = 1 - \sum f_{Tq}^{(p)}.$$

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

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

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

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

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

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

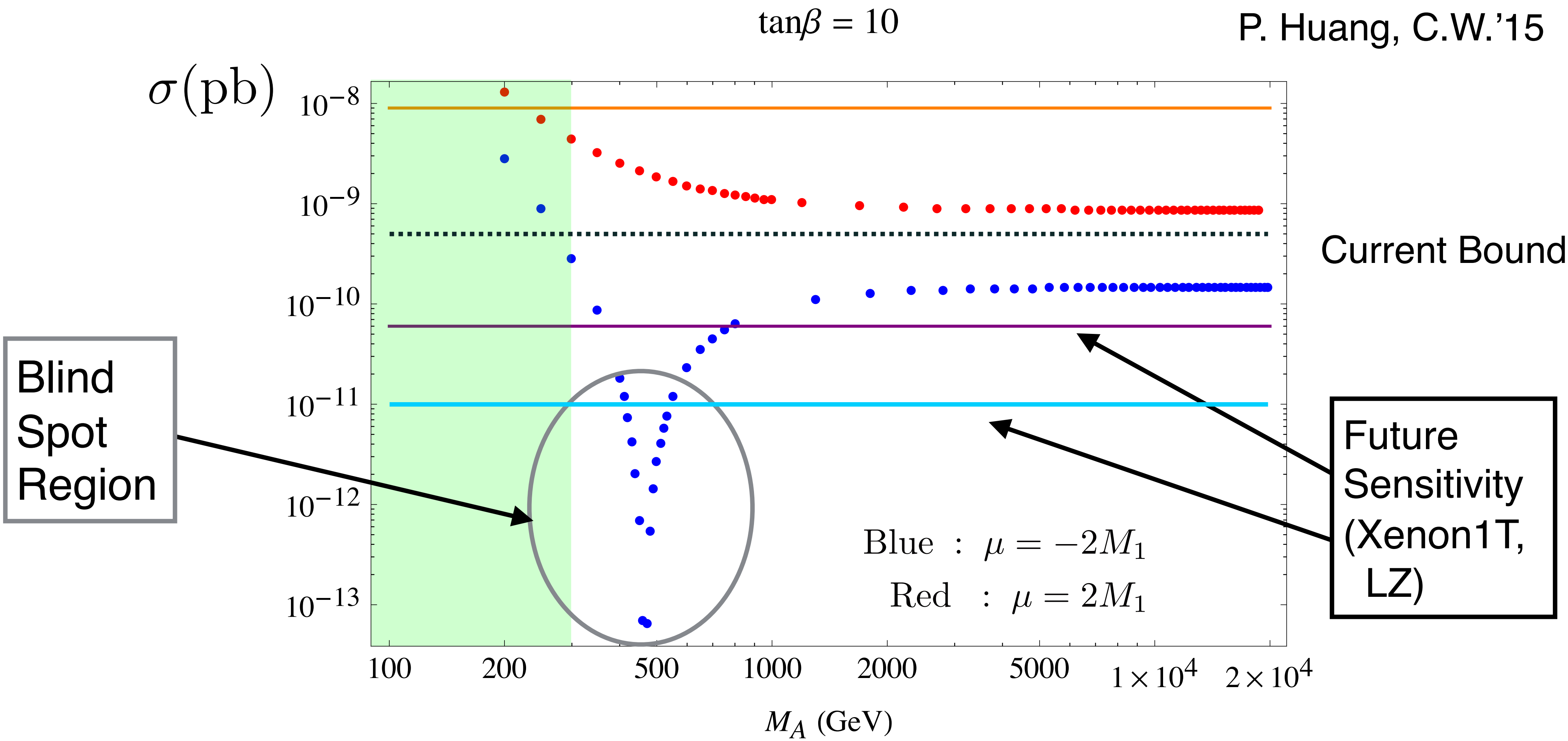
$$\boxed{2 \; (m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq - \; \mu \tan\beta \frac{1}{m_H^2}}$$

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

Dependence of the cross section on the heavy Higgs mass

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

P. Huang, C.W.'15

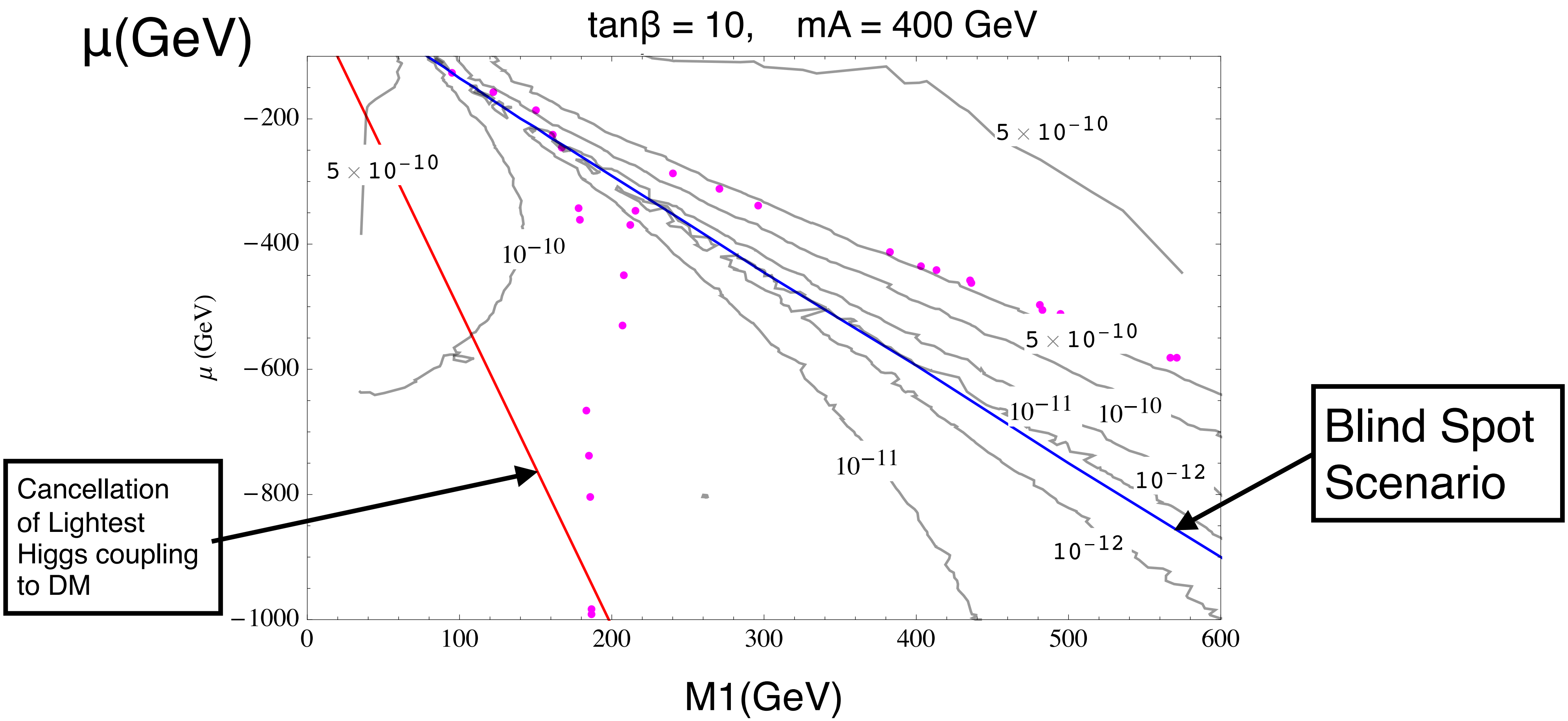


Application of the naive blind spot formula gives MA = 478 GeV

P. Huang, C.W.'15

Blind Spot Scenarios and Relic Density

Depends strongly on MA. All other s-particles assumed to be heavy



Well tempered scenario consistent with the proper relic density

$$|\mu| \simeq M_1$$

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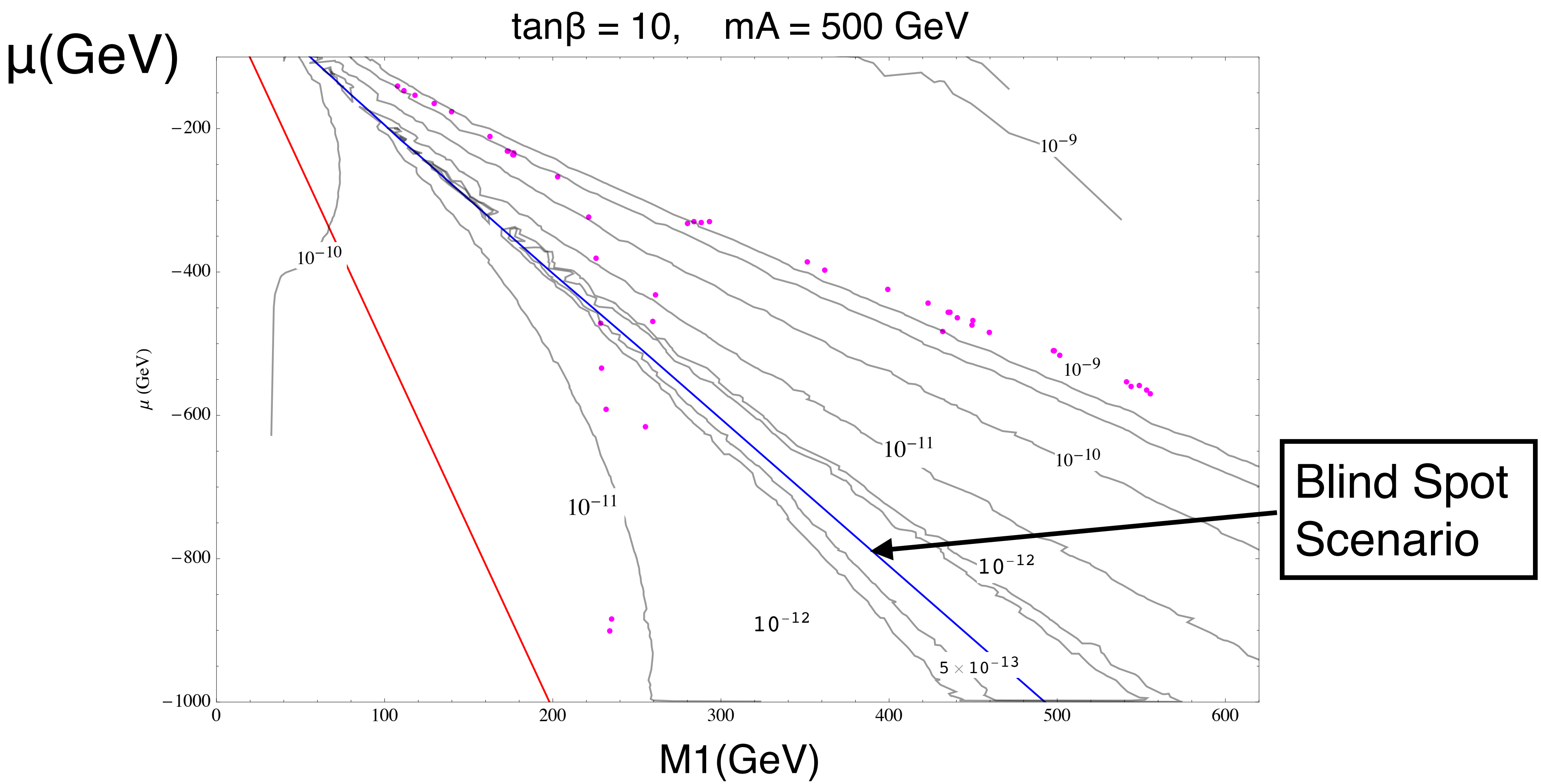
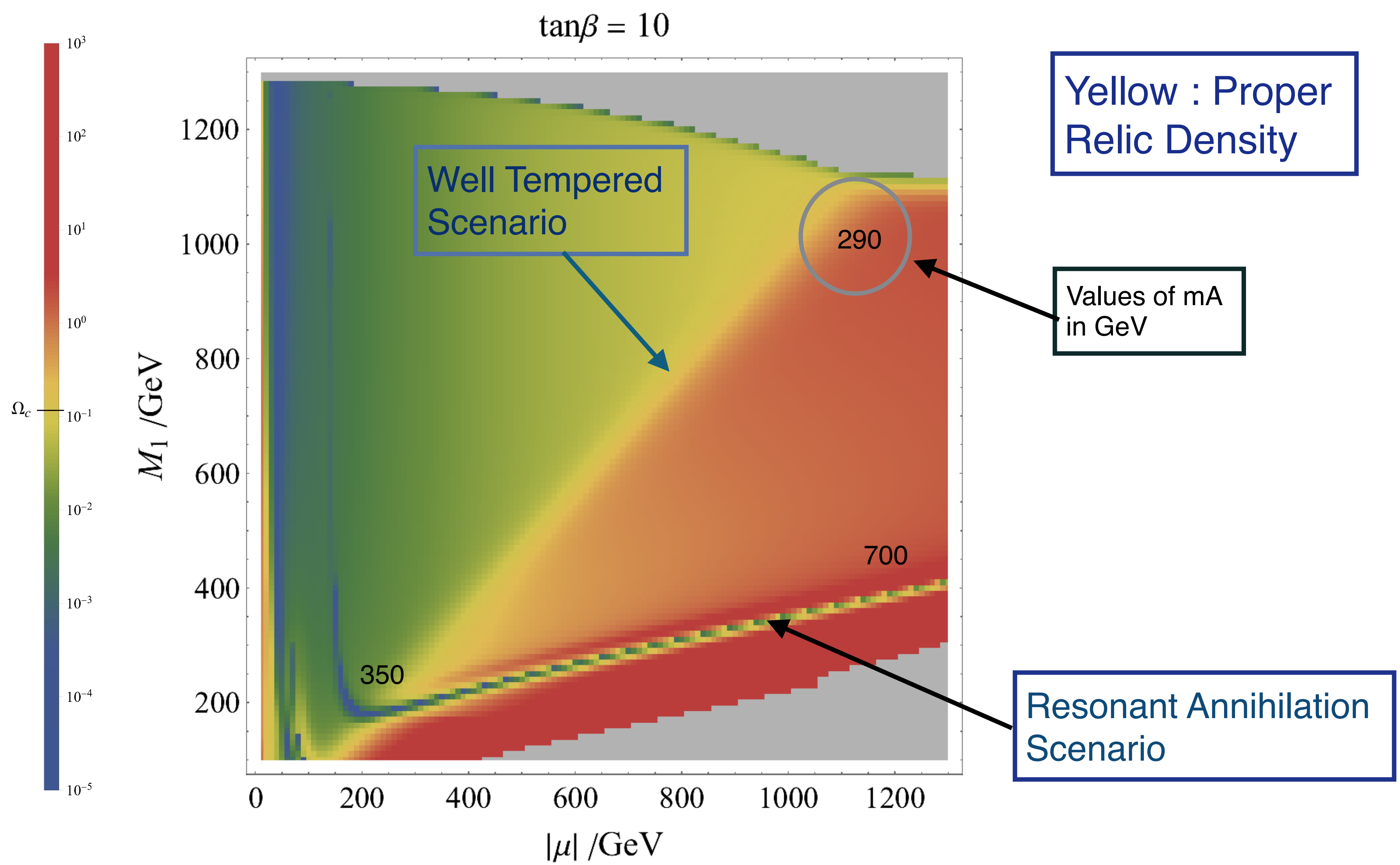
Blind Spot Scenarios and Relic Density



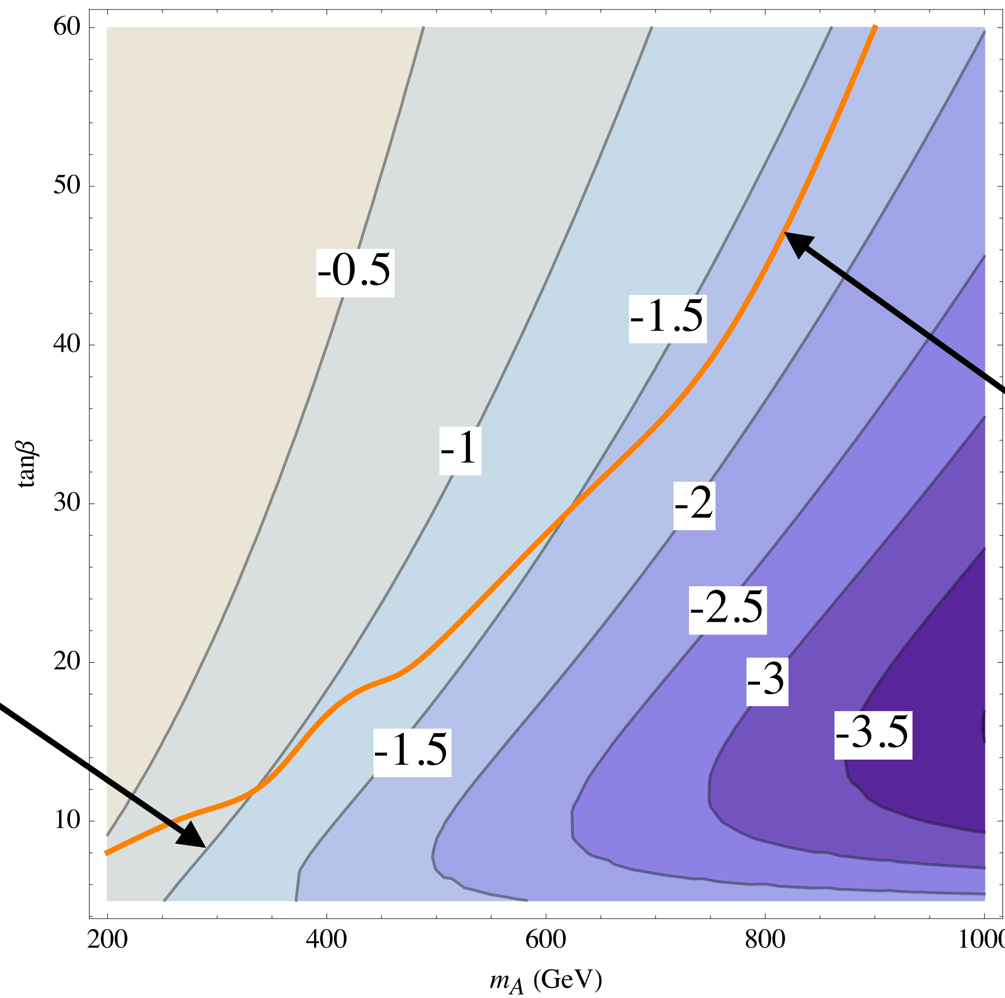
Resonant Annihilation of Dark Matter through MA interchange
This scenario is consistent with the proper relic density

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

Relic Density and Blind Spot Scenarios II



Blind Spot Regions



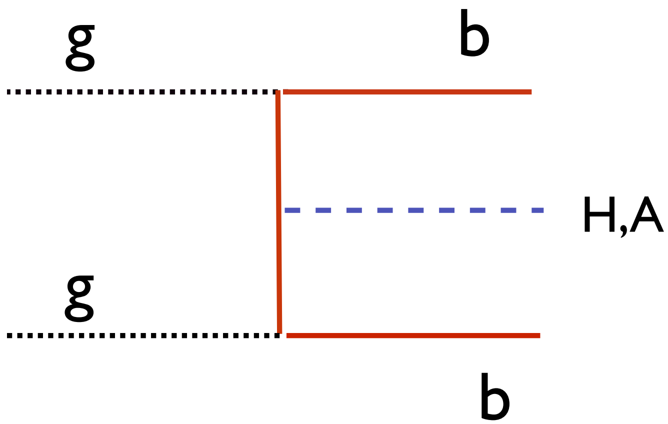
Well Tempered Region Implies low values of MA, restricted by direct searches

Direct Searches

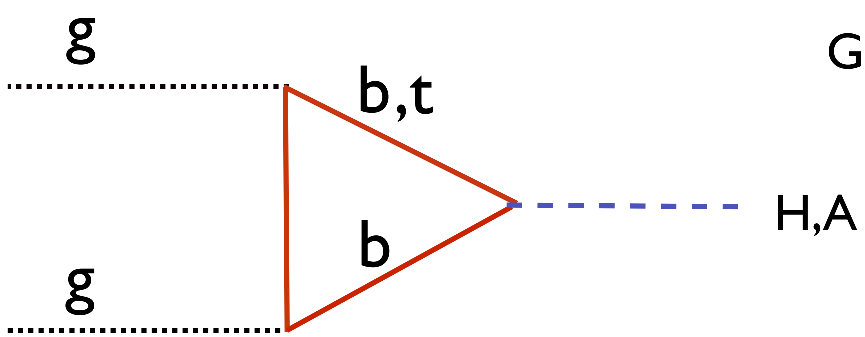
Ratio of μ and m_χ at the blind spot

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/06031



Associated Production



Gluon Fusion

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

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

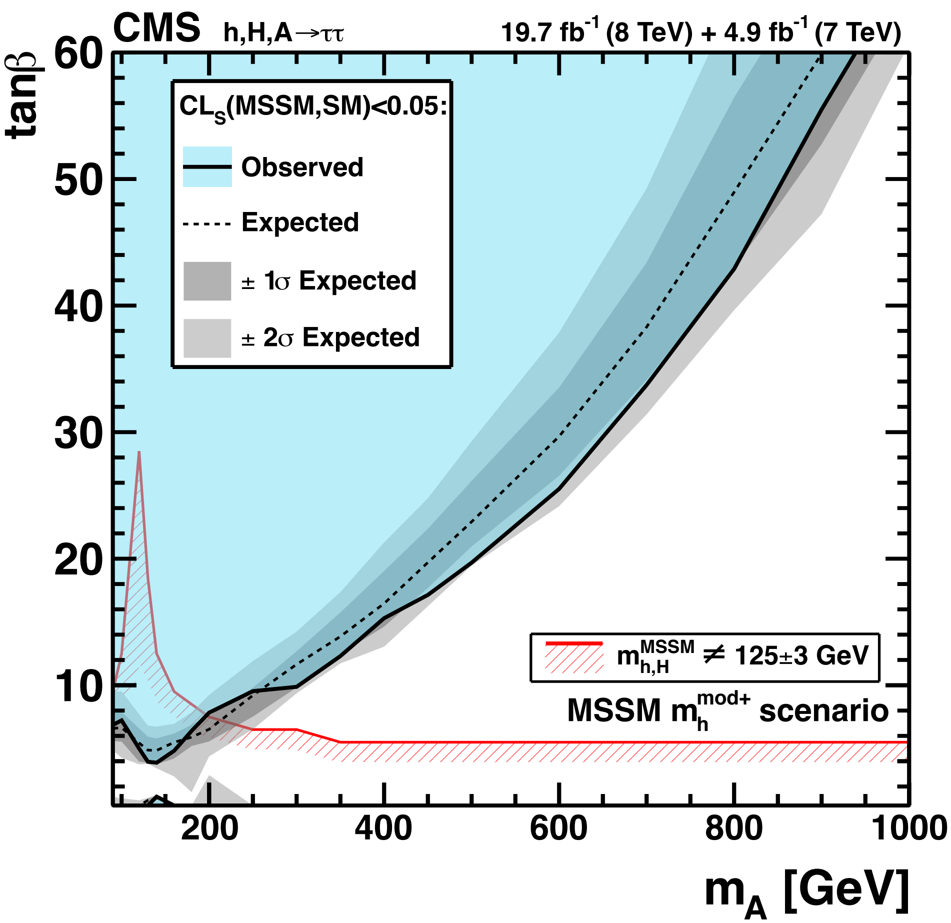
$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

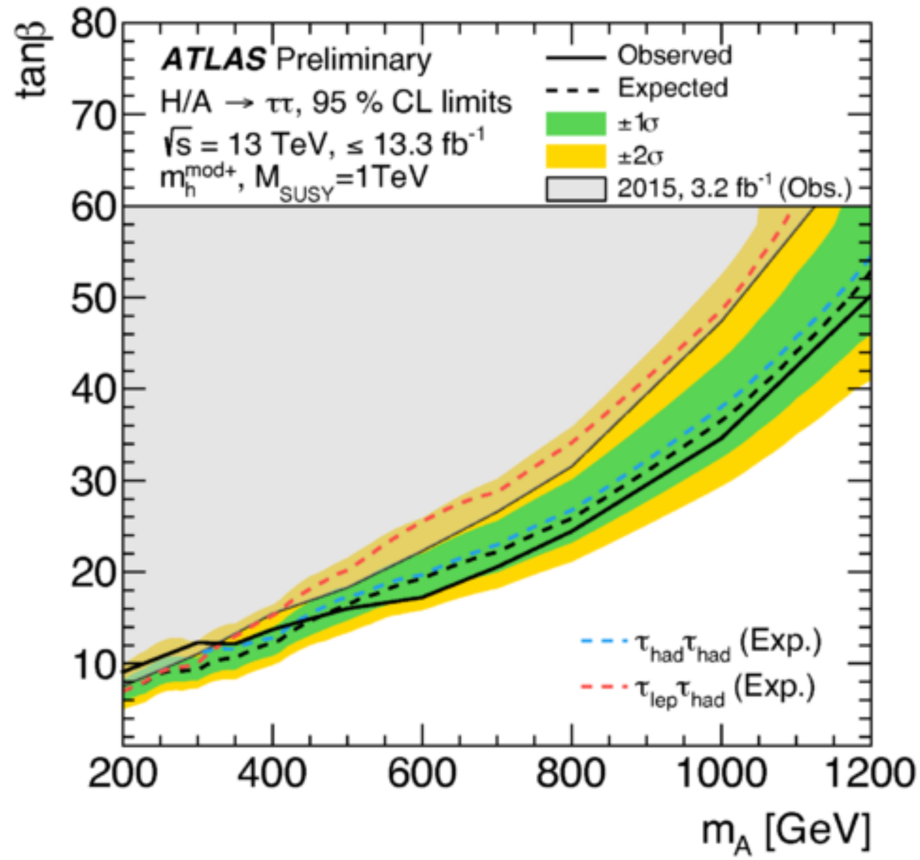
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

- If charginos are light, they contribute to the total with, suppressing the BR.

$$\sigma(pp \to H, A \to \tau\tau) \propto \frac{\tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{(M_W^2+M_Z^2)(1+\Delta_b)^2}{m_\tau^2\tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\right]}$$

Search for new neutral Higgs bosons



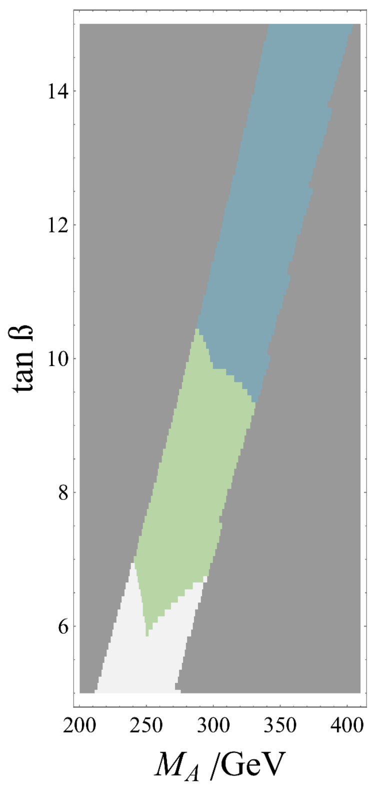


Low values of the new Higgs bosons masses
and large values of tanβ ruled out

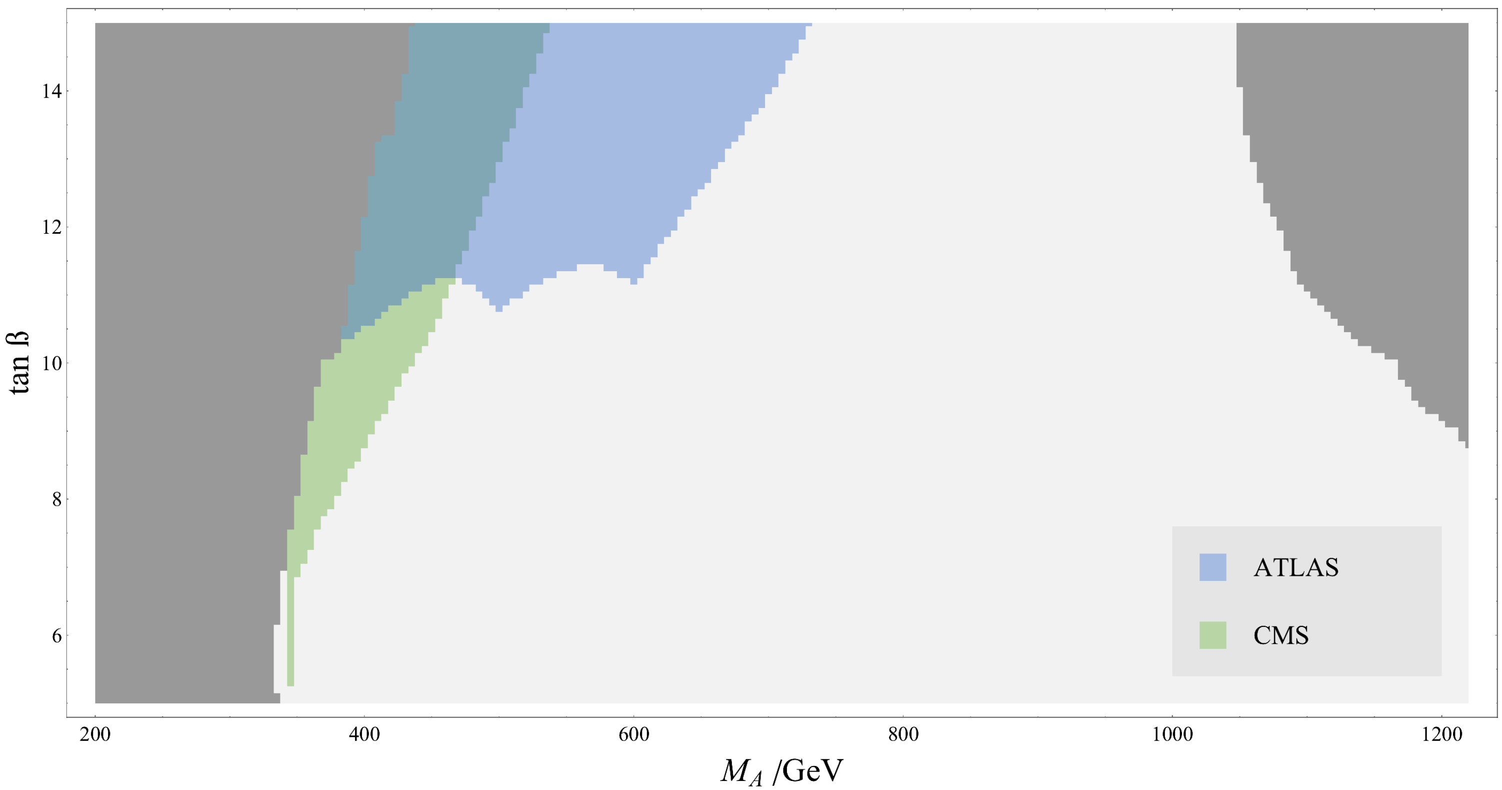
Roglans, Spiegel, Sun, Huang, C.W.'16

Limits from Direct Searches in the two different Blind Spot Regions

Well Tempered Neutralino



Resonant Annihilation



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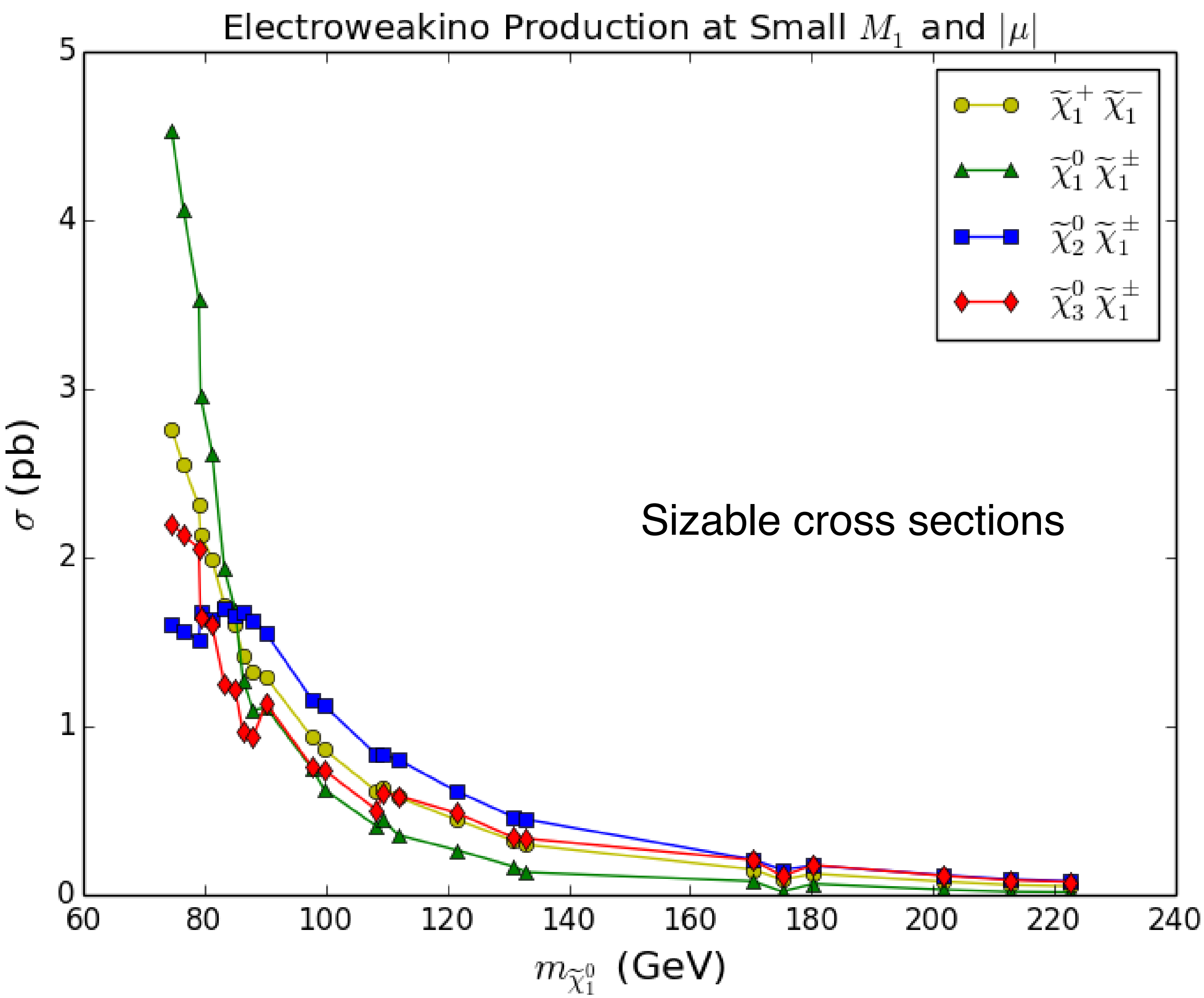
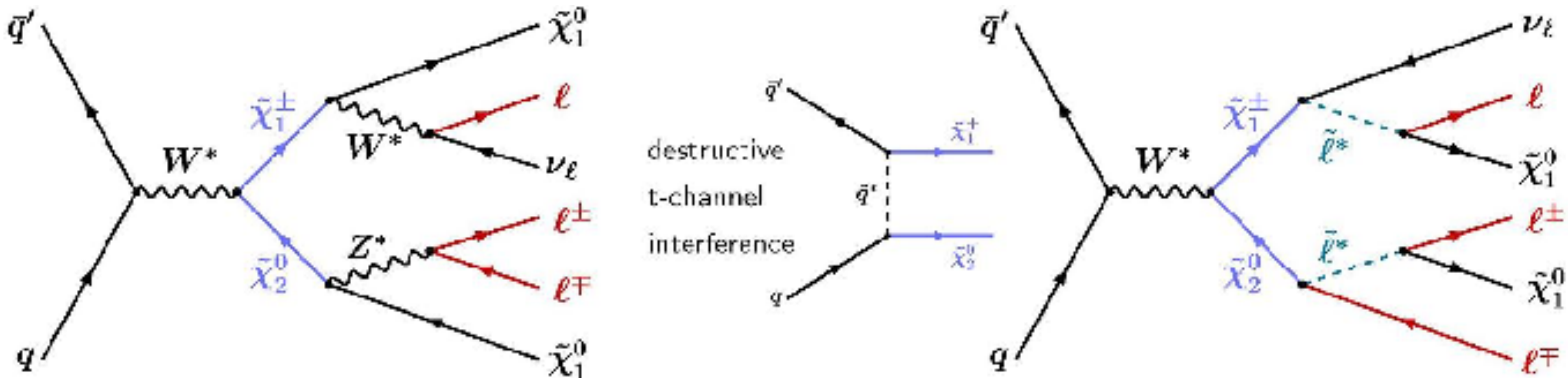
Production of Charginos and Neutralinos at the 13 TeV Collider



Searches for Charginos and Neutralinos

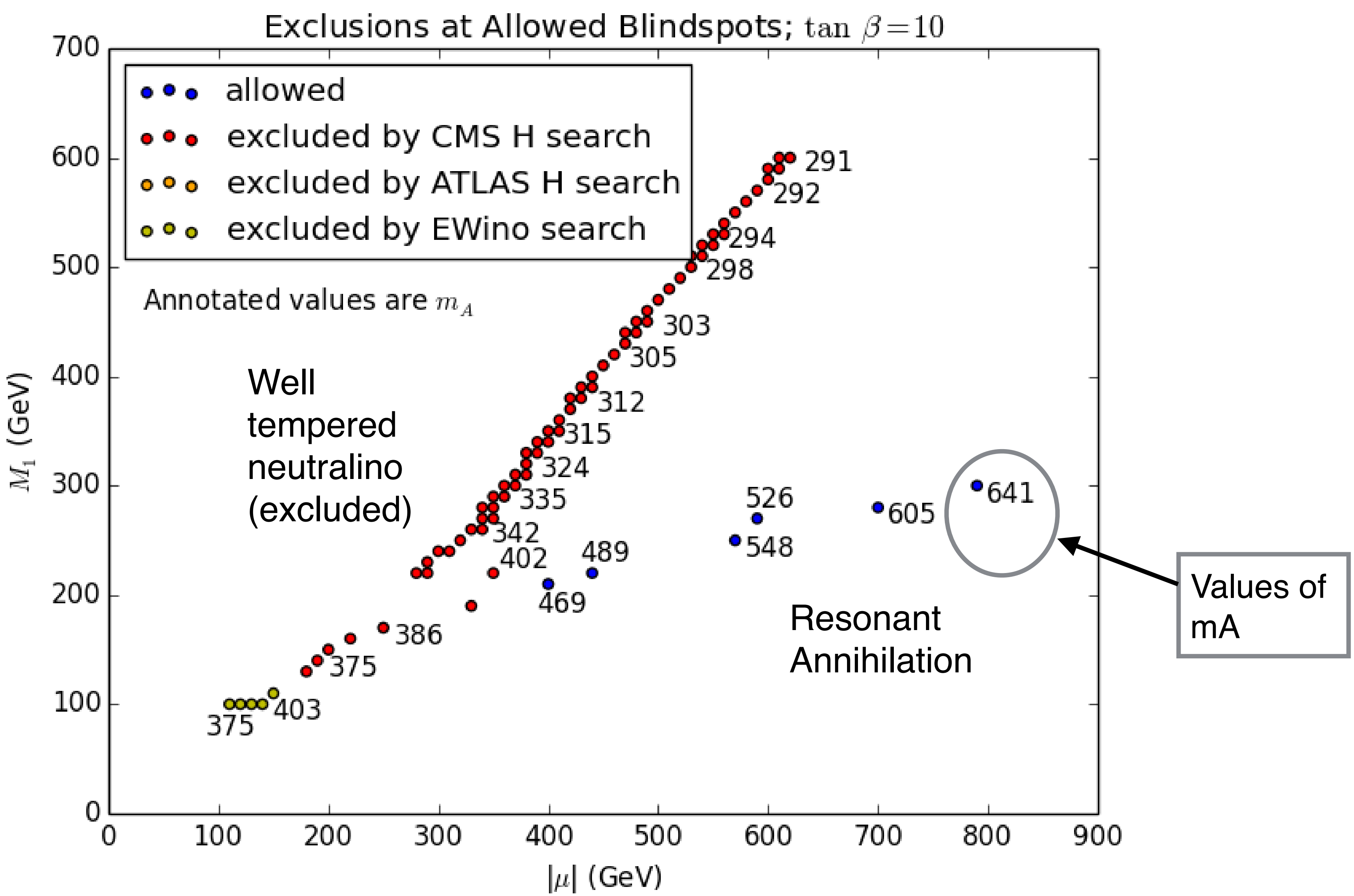
Trilepton Channel



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

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

Bounds on the Blind Spot Scenarios coming from Direct Searches for Higgs and Electroweakinos



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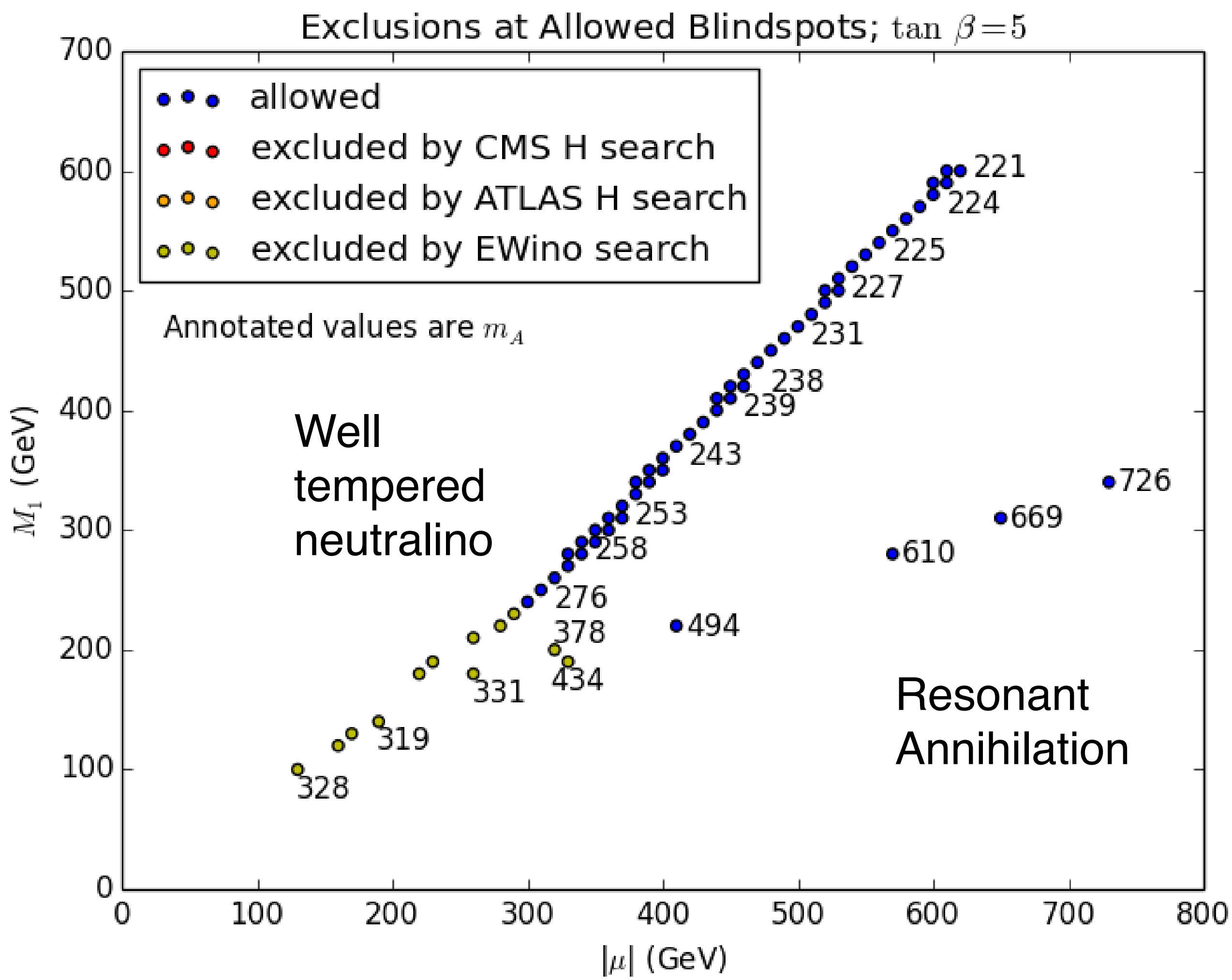
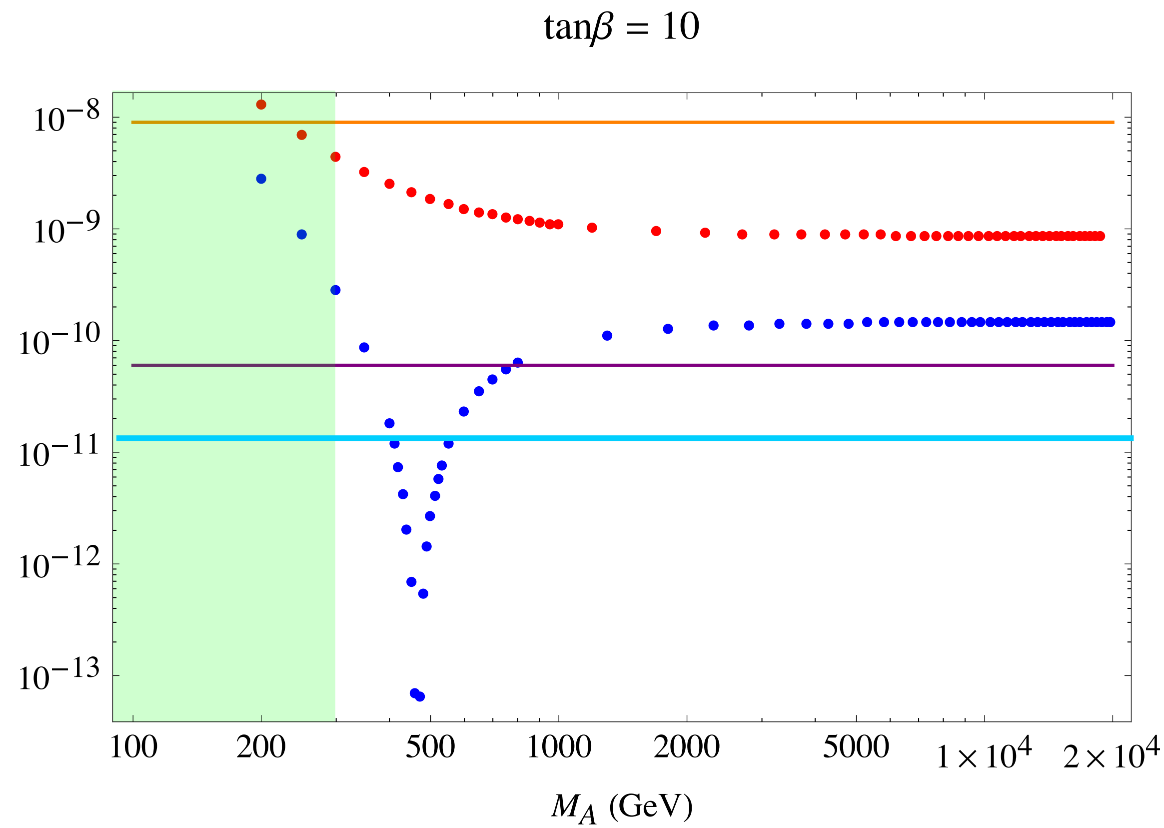


Well tempered region allowed for moderate values of tanβ, but only for low values of the CP-odd Higgs mass

Comments

- Previous plot was performed for values of the Higgs mass consistent with approximate cancellation of the direct DM detection cross section
- We can instead choose the maximal mass consistent with a given cross section, that we chose to be $\sigma \simeq 10^{-11}$ pb



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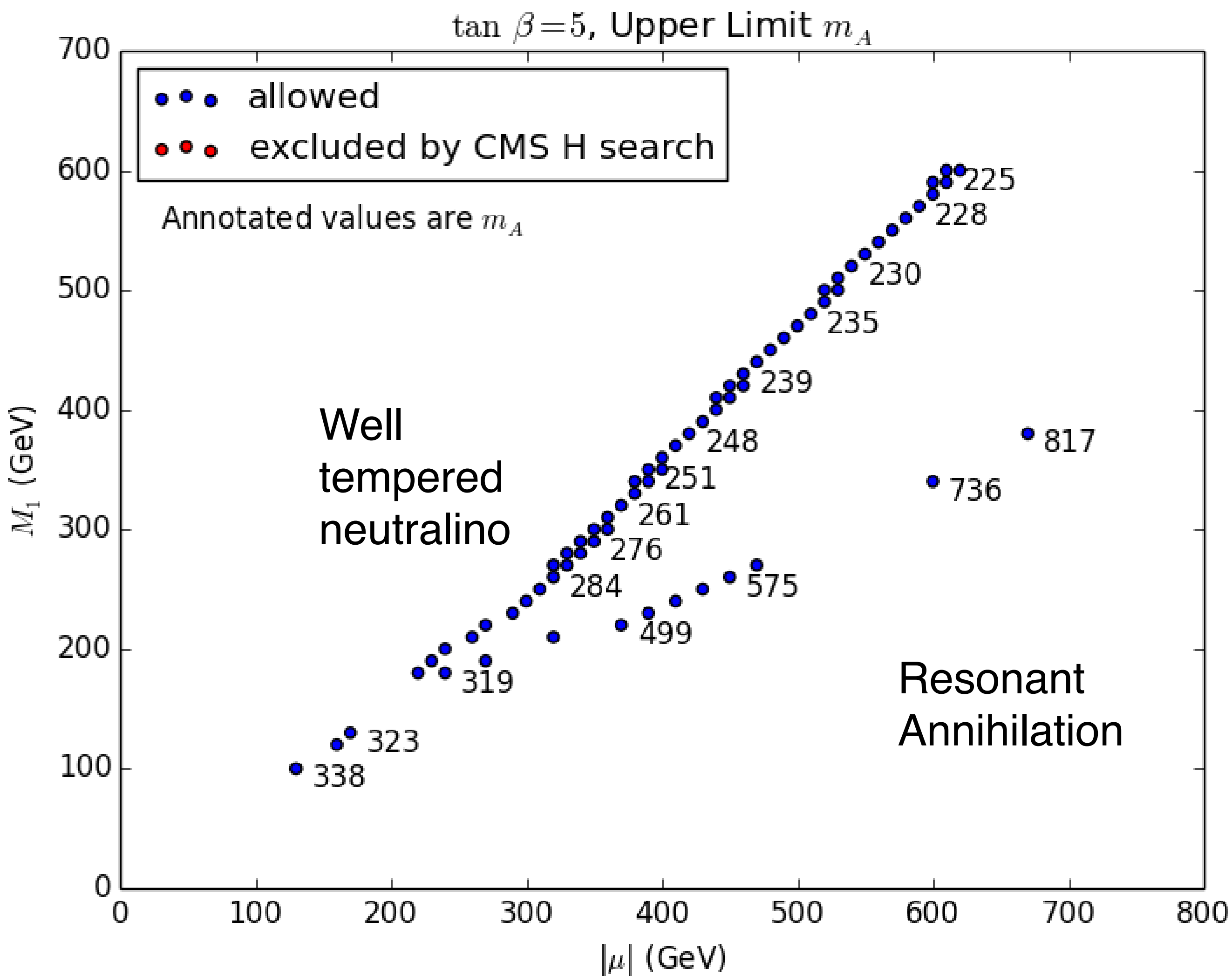
Bounds on the Blind Spot Scenarios coming from Direct Searches for Higgs and Electroweakinos

(Highest CP-odd Higgs mass consistent with a cross section $\sigma < 10^{-47}\ \mathrm{cm}^2$)



Well tempered region allowed for moderate values of tanβ, but only for low values of the CP-odd Higgs mass

Bottom Coupling

$$c_t = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \ ,$$

$$c_b = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \ ,$$

$$c_V = \sin(\beta-\alpha) \ ,$$

In the MSSM, one can compute this deviations

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

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

In general, there is an enhancement of the bottom coupling

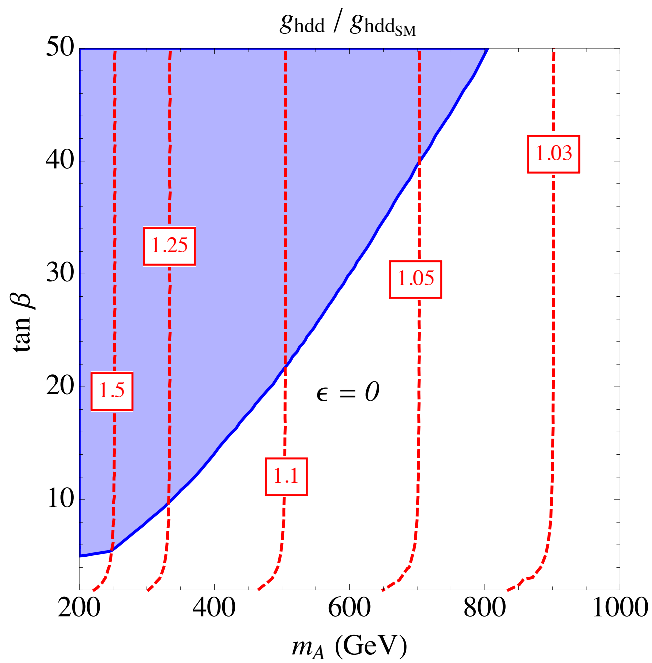
May only be avoided for large values of the heavy Higgs mass
(μ is relatively small and radiative corrections are then negligible)

Down Couplings in the MSSM for low values of μ
(no Alignment)

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

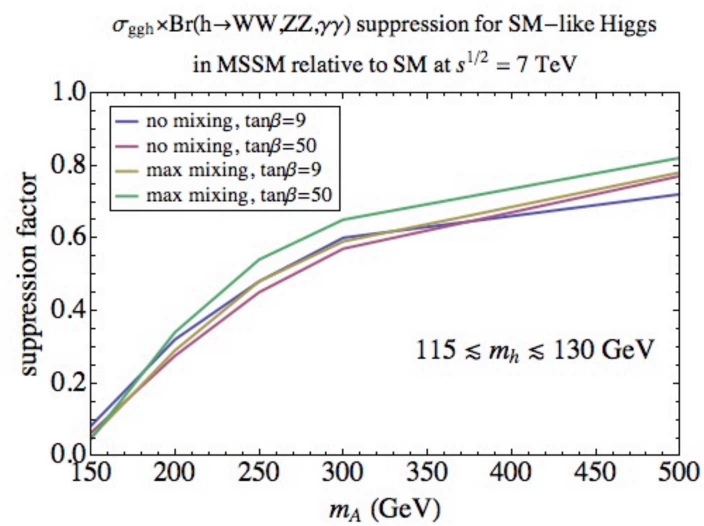
$$\lambda_1 \simeq -\tilde{\lambda}_3 = \frac{g_1^2 + g_2^2}{4} = \frac{M_Z^2}{v^2} \simeq 0.125 \qquad \lambda^{SM} \simeq 0.26$$

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



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

Draper,Liu,C.W.'10



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

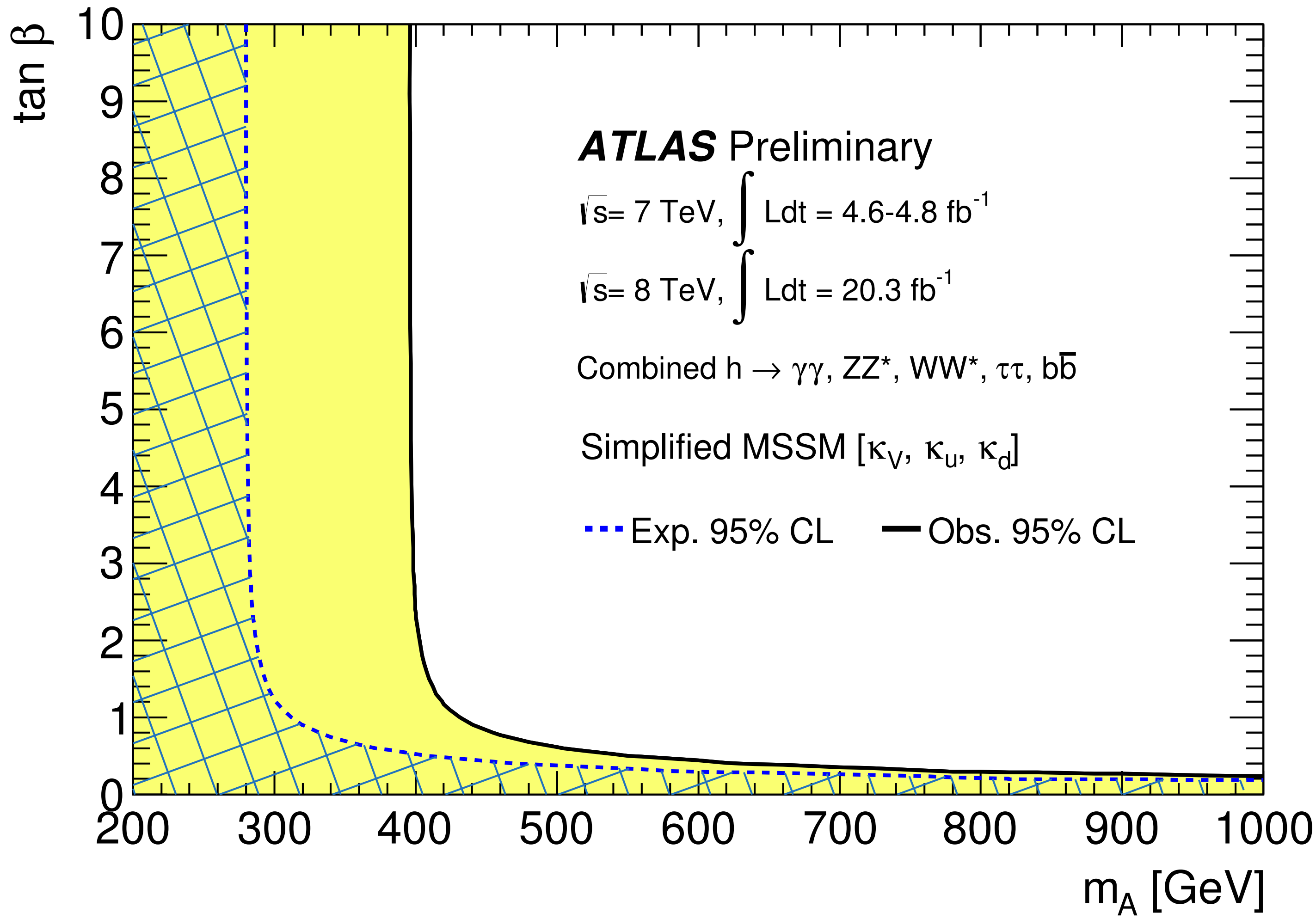
For moderate or large values of tanβ

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

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

Low values of μ similar to the ones analyzed by ATLAS

ATLAS-CONF-2014-010



Bounds coming from precision h measurements

In the MSSM well tempered scenario ruled out.

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

Adding a heavy singlet sector: CP-even Higgs Mixing 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,

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

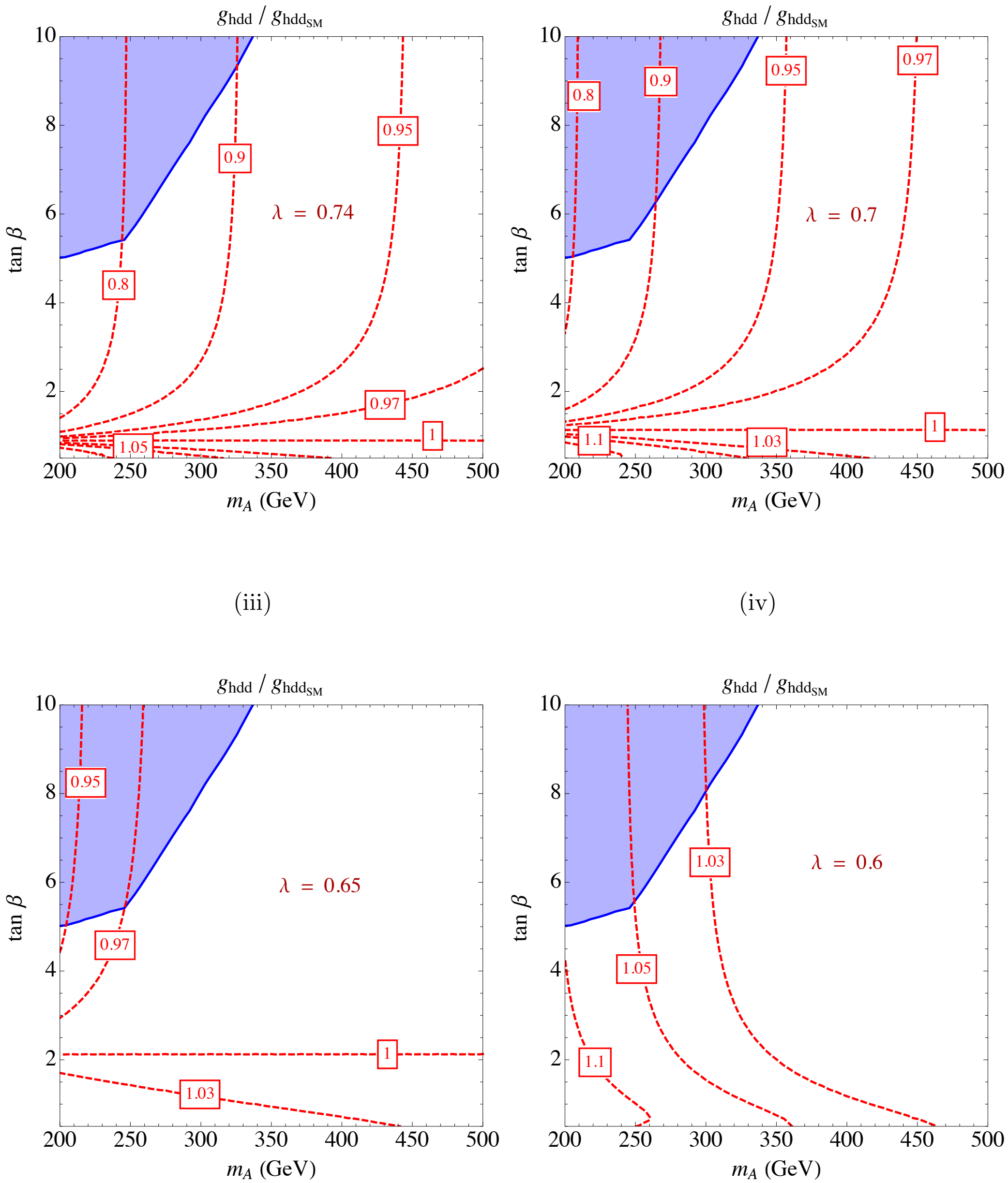
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$. The corrections Δt and δt are the same as in the MSSM.

- 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 all values of tanβ, that are the values that lead to naturalness with perturbative consistency up to the GUT scale

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

SM-like Higgs in the NMSSM (heavy singlets and singlinos)



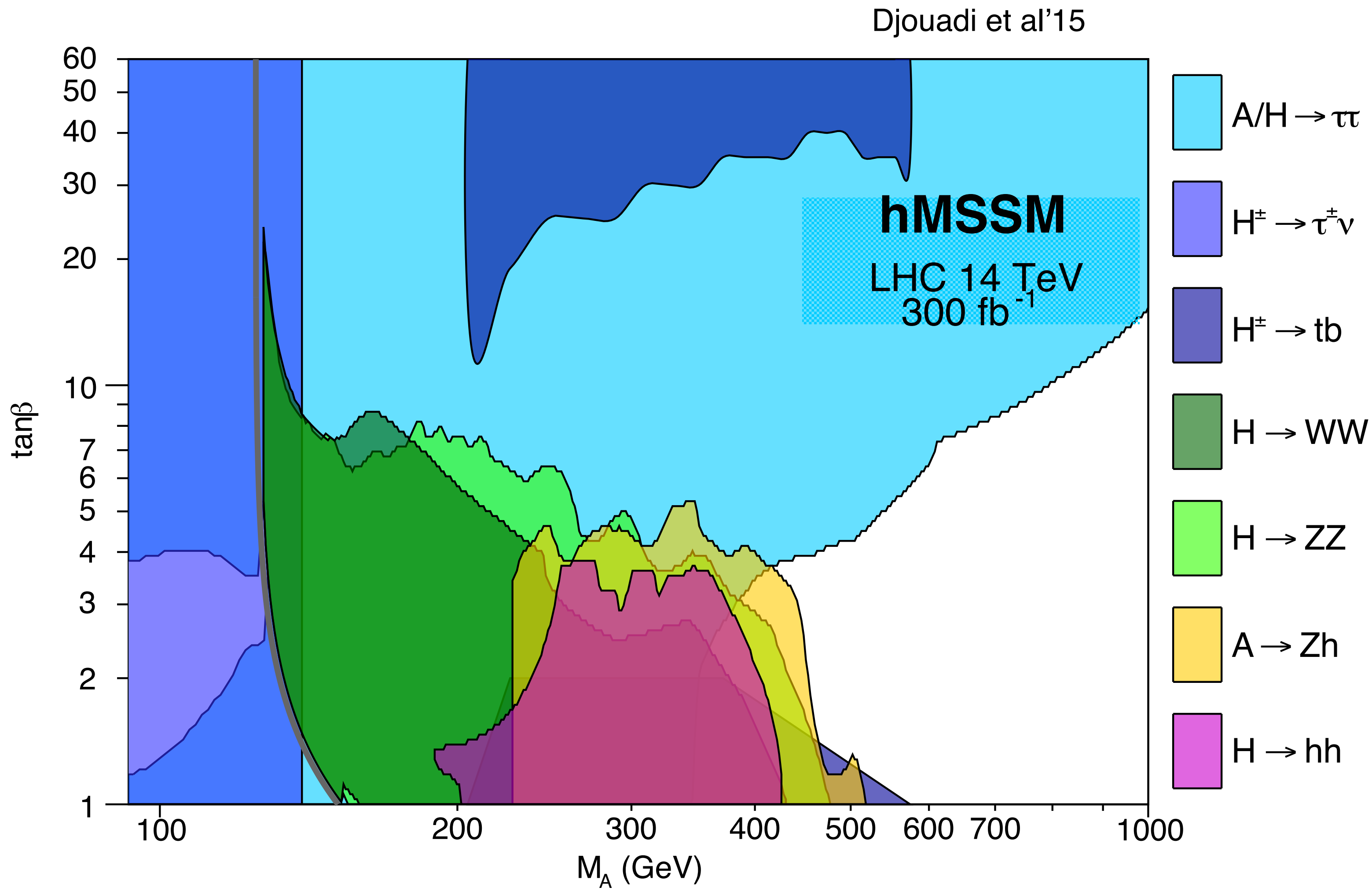
Carena, Low, Shah, C.W.'13

It is clear from these plots that the NMSSM does an amazing job in restoring the SM-like properties of the Higgs, provided λ is about 0.65.

Similar values of λ are needed to obtain the proper Higgs mass without the presence of heavy superpartners of the top quarks.

Well tempered scenario may be realized in such an extension

Prospects for Direct Higgs Searches at the LHC



Well tempered region fully explored

Resonant Annihilation will be explored until fairly large value of |μ|

Conclusions

- Provided R-Parity is conserved, Supersymmetric extensions of the Standard Model contain a Dark Matter candidate.
- Such Dark Matter particle have been searched for at Direct Detection experiments, as well as at colliders.
- Direct Dark Matter constraints are increasingly strong and rule out relevant regions of parameter space.
- Blind spots occur in regions in which the Higgs mediated amplitudes interfere destructively, rendering the Direct Dark Matter cross section consistent with current experiments.
- The realization of these blind spots demand correlations between the ratio of the square of the Higgs masses and the ratio of the gaugino and Higgsino masses.
- These correlations may be tested at the LHC through a combination of electroweakino and non-standard Higgs searches, which have already tested important regions of the allowed parameter space and will test the most natural realization of this scenario in the real future.