Implications of Direct Detection Blind Spots at the LHC

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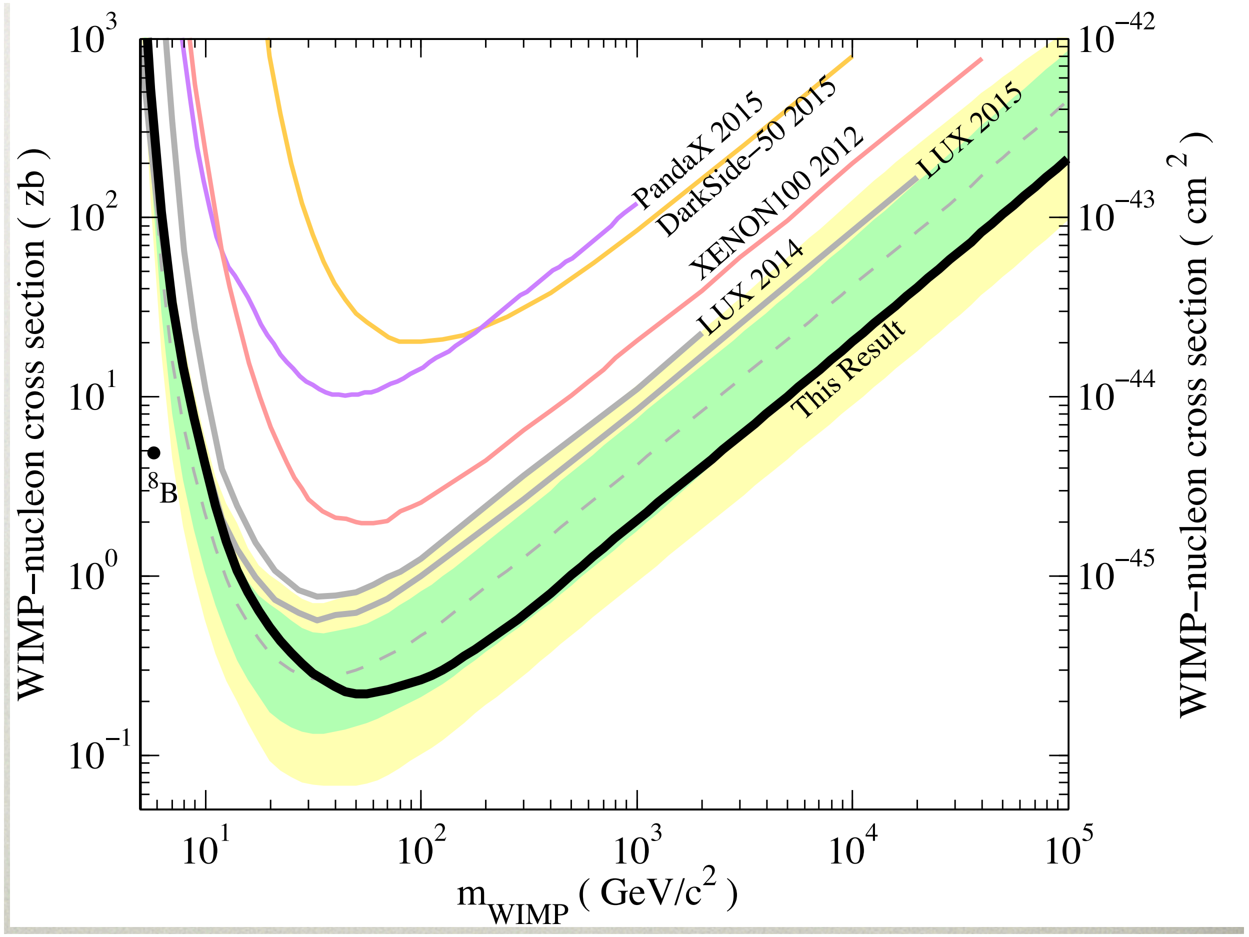
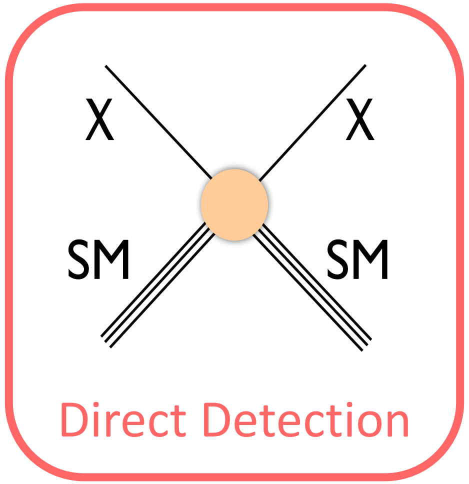
NP Interpretations at the LHC Workshop, Argonne

PH, C. Wagner arXiv:1404.0392

PH, R. Roglans, D. Spiegel, Y. Sun and C. Wagner arXiv:1701.02737

Direct Detection





- The direct detection experiments are pushing rapidly into the region with a Higgs exchange
- Suppress the neutrlino direct detection rate?

outline

- How to suppress the neutralino direct detection rate?
    - Blind Spot scenarios
- Deviations from the Blind Spots
    - current constraints
    - future reaches
- How to probe the blind spot scenarios at the LHC?
    - heavy Higgs searches
    - Electroweakino searches

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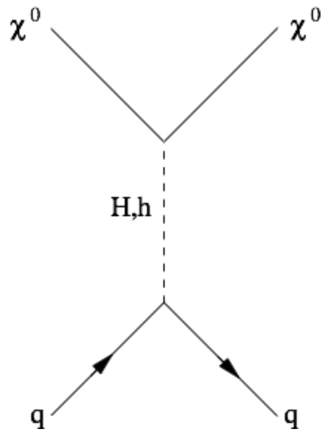
Suppress the neutralino direct detection rate

- Consider a neutralino scattering off a down-type quark.

In gauge eigenstates



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

Amplitude

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

$$\tilde{\chi} = N_{i1}\ \tilde{B} + N_{i2}\ \tilde{W} + N_{i3}\ \tilde{H}_d + N_{i4}\ \tilde{H}_u \qquad L \supset -\sqrt{2}g' Y_{H_u} \tilde{B}\tilde{H}_u H_u^* - \sqrt{2}g\tilde{W}^a \tilde{H}_u t^a H_u^* + (u \leftrightarrow d)$$

Couplings

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

Suppress the neutralino direct detection rate

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

Loop Effects

$$L = f_d \bar{d}_L d_R H_d^0 + \epsilon_d f_d \bar{d}_L d_R H_u^{0*} + h.c.,$$

$$a_d \sim \frac{\bar{m}_d(g_1 N_{i1} - g_2 N_{i2})}{\cos\beta}\left[N_{i4}\sin\alpha\cos\alpha\left(\frac{1-\epsilon_d/\tan\alpha}{m_h^2} - \frac{1+\epsilon_d\tan\alpha}{m_H^2}\right)\right.$$
$$\left. + N_{i3}\left(\frac{\sin^2\alpha(1-\epsilon_d/\tan\alpha)}{m_h^2} + \frac{\cos^2\alpha(1+\epsilon_d\tan\alpha)}{m_H^2}\right)\right]$$

$$\bar{m}_d \equiv \frac{m_d}{1+\epsilon_d\tan\beta} \qquad \epsilon_d \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0(m_0^2, m_R^2, |M_3|^2)$$

$$C_0(X,Y,Z) = \frac{y}{(x-y)(z-y)}\log(y/x) + \frac{z}{(x-z)(y-z)}\log(z/x).$$

When 1st&2nd gen squarks are heavy, ϵ_d is suppressed

Suppress the neutralino direct detection rate

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

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

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

Pierce, Shah, and Freese. arXiv:1309.7351

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

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

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

Blind Spot in Dark Matter Direct Detection

125 GeV Higgs Exchange

Heavy Higgs Exchange

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

$F_d^{(p)} \simeq 0.15$, $F_U^{(p)} \simeq 0.14$

Blind Spot at $(m_{\chi_1^0} + \mu \sin 2\beta) = 0$

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

See Cheung, Hall, Pinner, and Ruderman. arXiv:1211.4873
Han, Kling, Su, and Wu. arXiv:1612.02387

PH, C. Wagner, 14

Higgsino mass $\mu < 0$

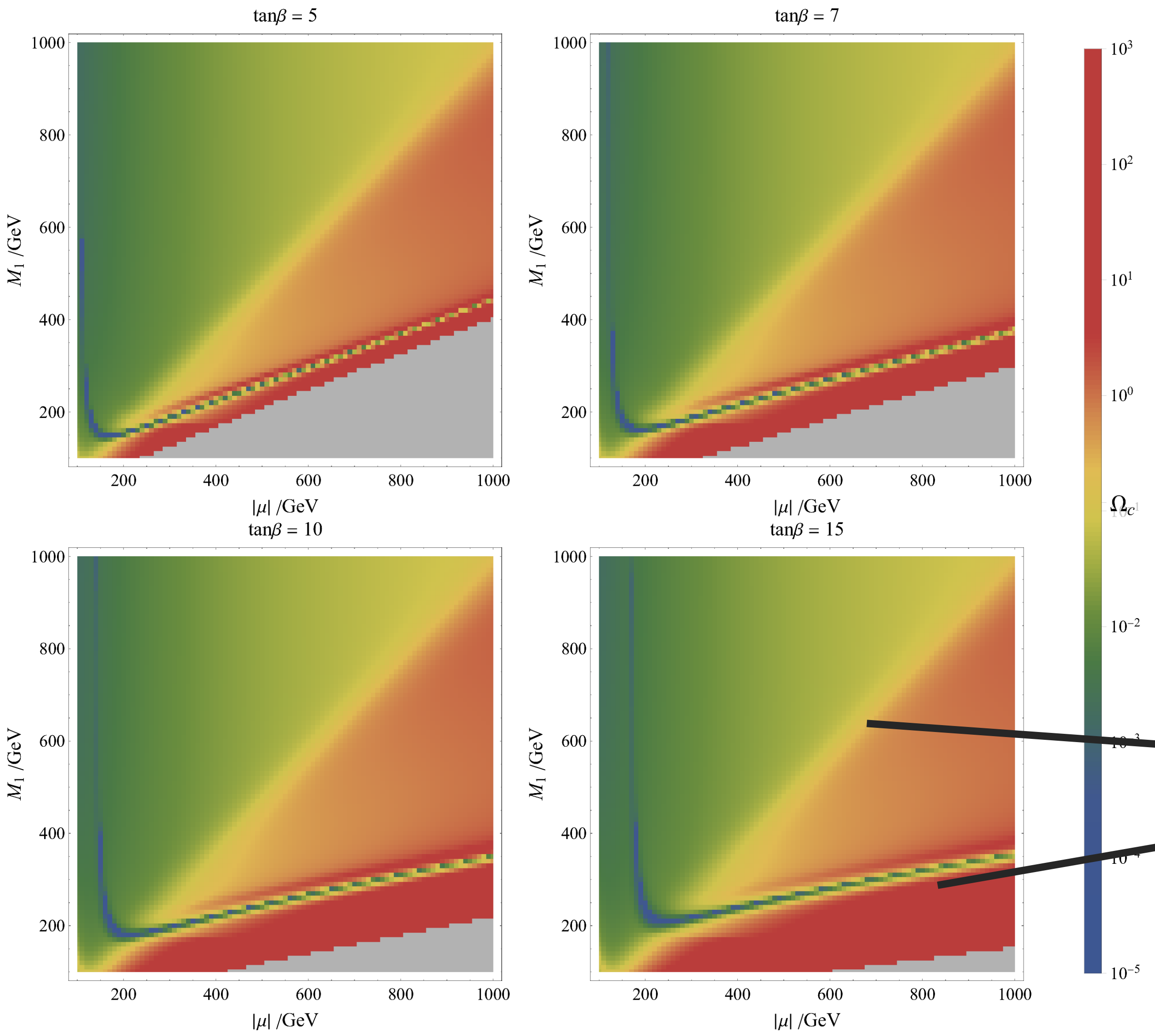
Suppress the lightest neutralino coupling to 125 GeV Higgs

Destructive interference between the 125 GeV Higgs and the heavy Higgs exchange

Reduce the pMSSM parameter space to M_1, μ, $\tan\beta$, and m_A

For a full pMSSM study, see Cahill-Rowley et al, 1405.6716. For a loop level analysis, see Berlin, Hooper, and McDermott, arXiv:1508.05390

Blind Spot and the Relic Density



Relevant parameters:
M_1 , μ, tanβ, and m_A

Under Abundant Over Abundant

m_A is chosen to minimize the DD rate

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

Two branches

well tempered $M_1 \sim \mu$

A-funnel $m_\chi \sim m_A/2$

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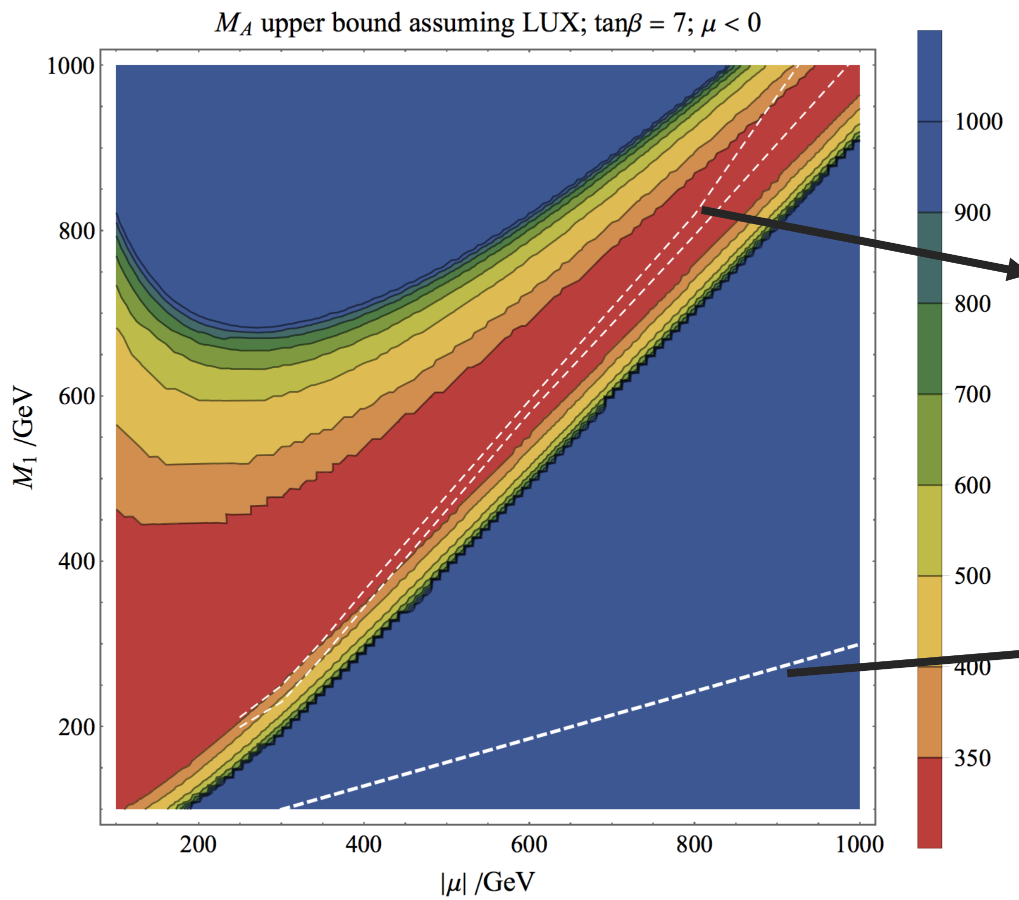
  - future reach
- How to probe the blind spot scenarios at the LHC?
  - heavy Higgs searches
  - Electroweakino searches

Current Direct Detection Constraints

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

→ m_A upper bound



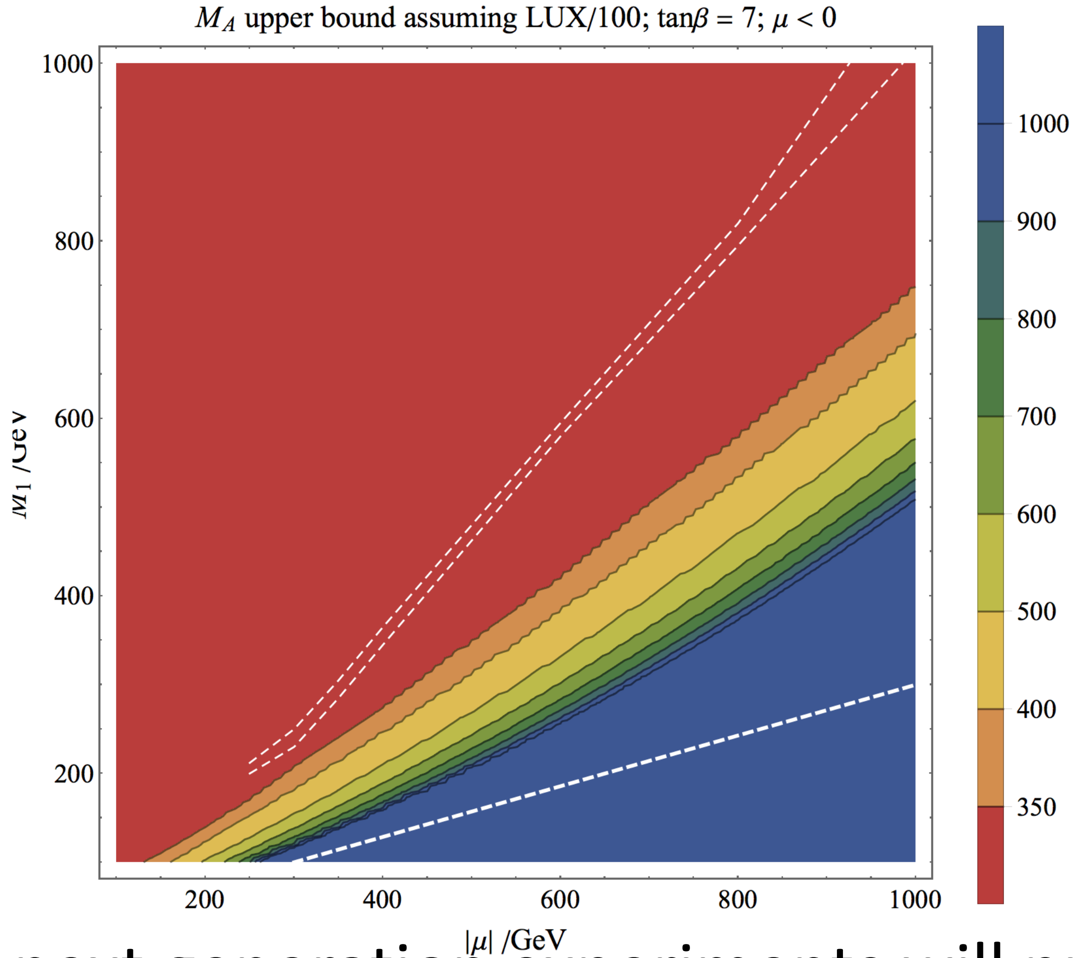
Assume the right relic density

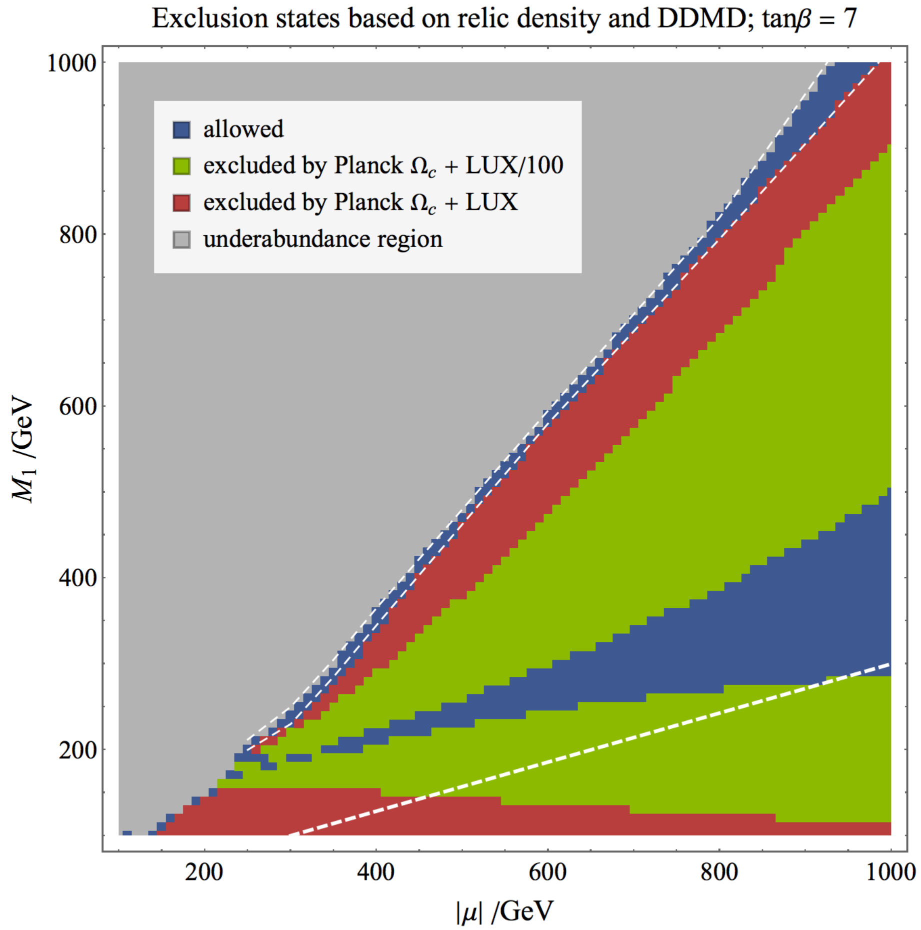
In the well-tempered region, m_A < 350 -400 GeV

The A-funnel region is allowed by LUX and relic density considerations

neutralino higgs coupling vanishes

Future reach





next generation experiments will push m_A to be smaller than 300 GeV in the well-tempered region

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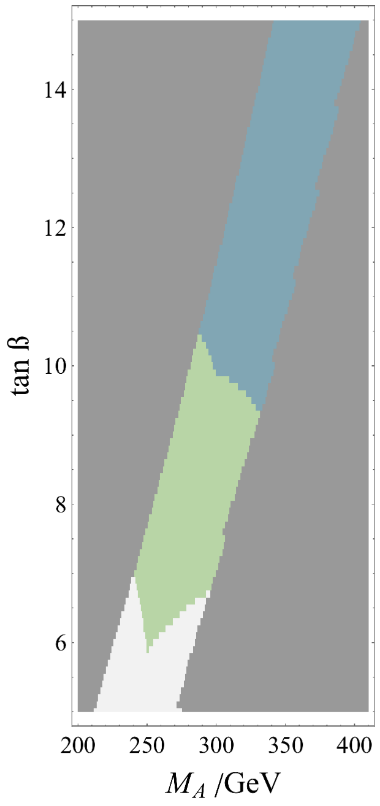
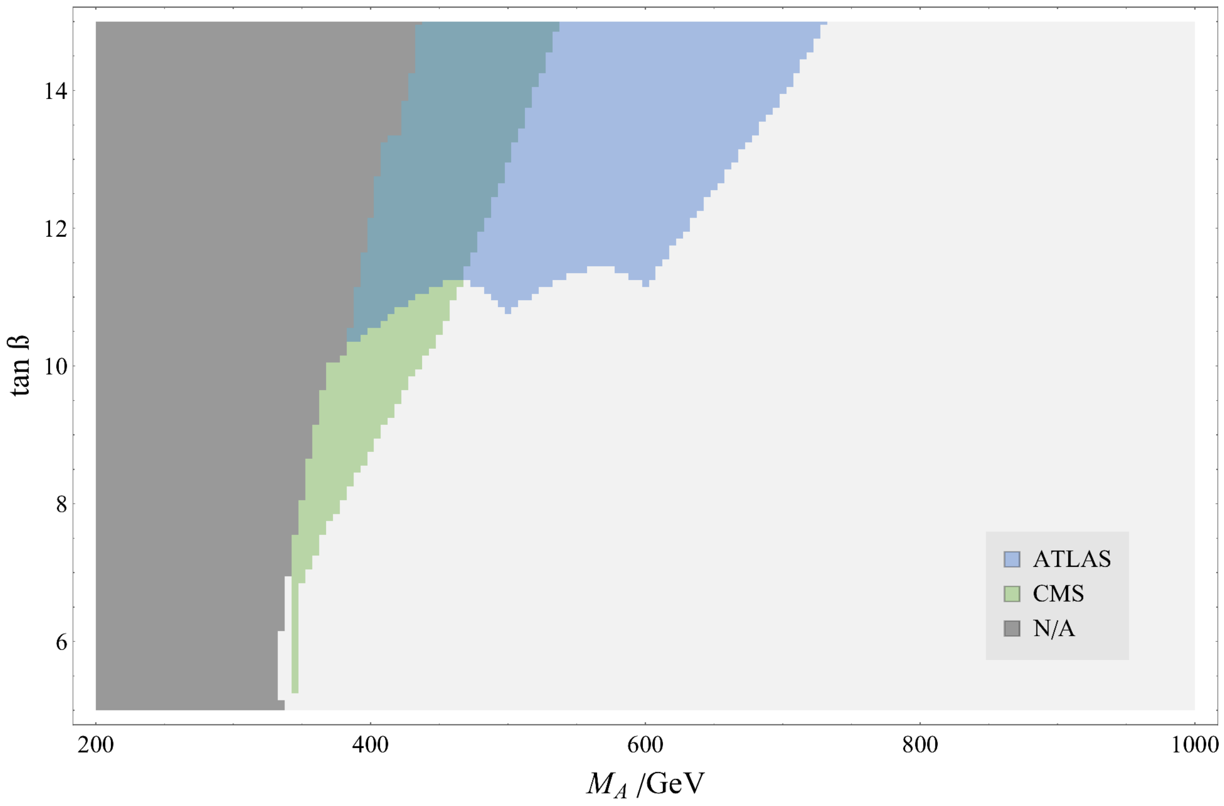
Probe the Blind Spots scenarios – collider searches

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



Well-tempered



A-funnel

Well-tempered region : open for tanβ < 6 completely ruled out for tan$\beta \gtrsim 7$

A-funnel region starts to get excluded as tanβ increases

Probe the Blind Spots scenarios – collider searches

- hbb coupling

$$\frac{g_{hbb}}{g_{hbb}^{SM}} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

hVV coupling ~1 controls the modification

- One loop level, sizable tanβ

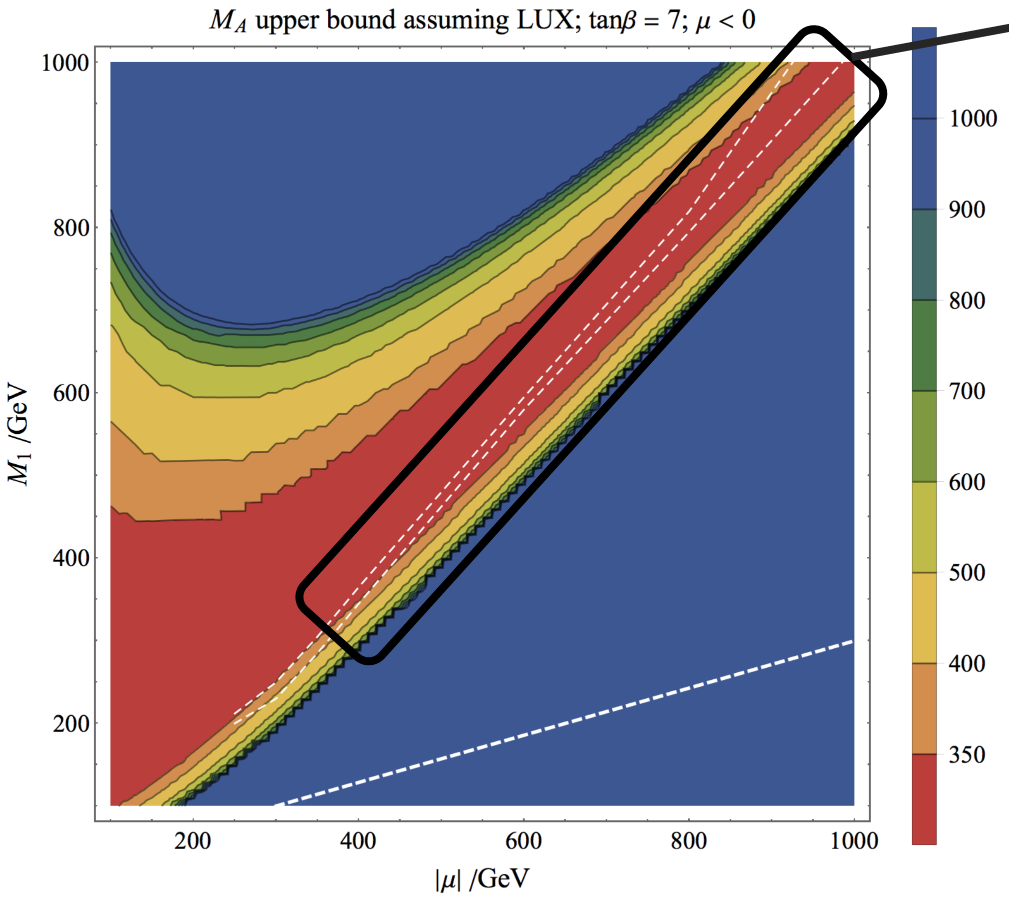
$A_t \lesssim 3$ M_s, vacuum stability

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

Ms $\gtrsim$ TeV, proper Higgs mass

$m_A \gtrsim$ 350 GeV to be consistent with the current Higgs data.

Probe the Blind Spots scenarios – collider searches



In tension with the current Higgs data

Extended the Higgs sector

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

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

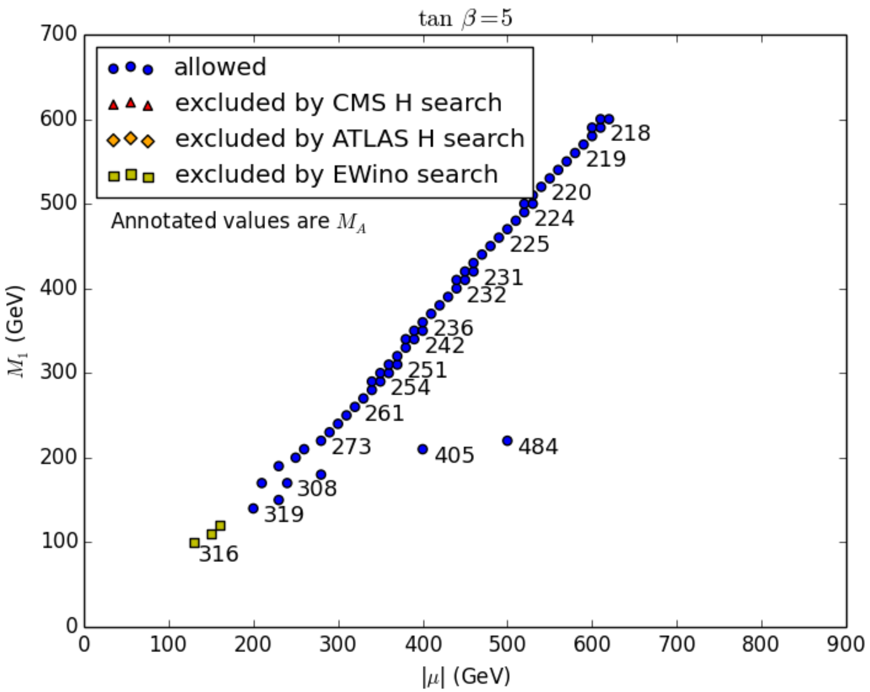
$\lambda \simeq$ 0.6-07, even for $m_H \simeq$ 200 GeV, the modification in SM Higgs coupling is small enough.

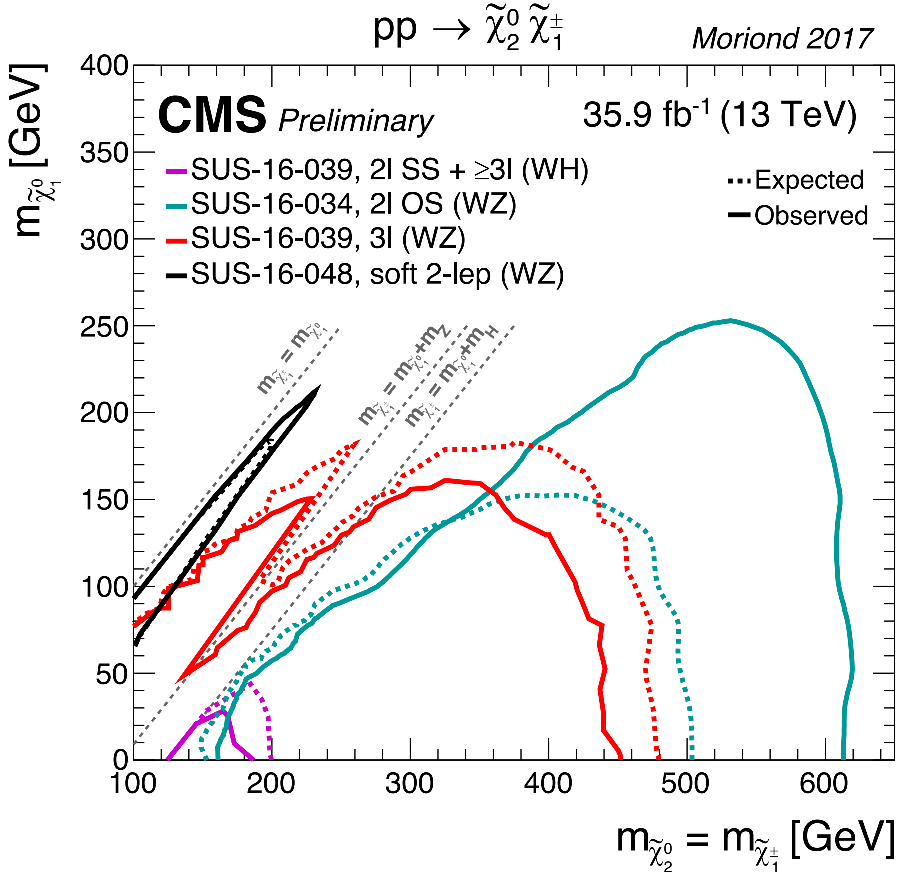
Blind spot scenarios in NMSSM, see Badziak, Olechowski, and Szczerbiak, arXiv:1512.02472

Probe the Blind Spots scenarios – collider searches

- 3 neutralinos, (mixtures of bino and Higgsinos), the lighest chargino(Higgsino-like)

$$\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm \to WZ\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \qquad \widetilde{\chi}_2^0\widetilde{\chi}_1^\pm \to Wh\widetilde{\chi}_1^0\widetilde{\chi}_1^0$$

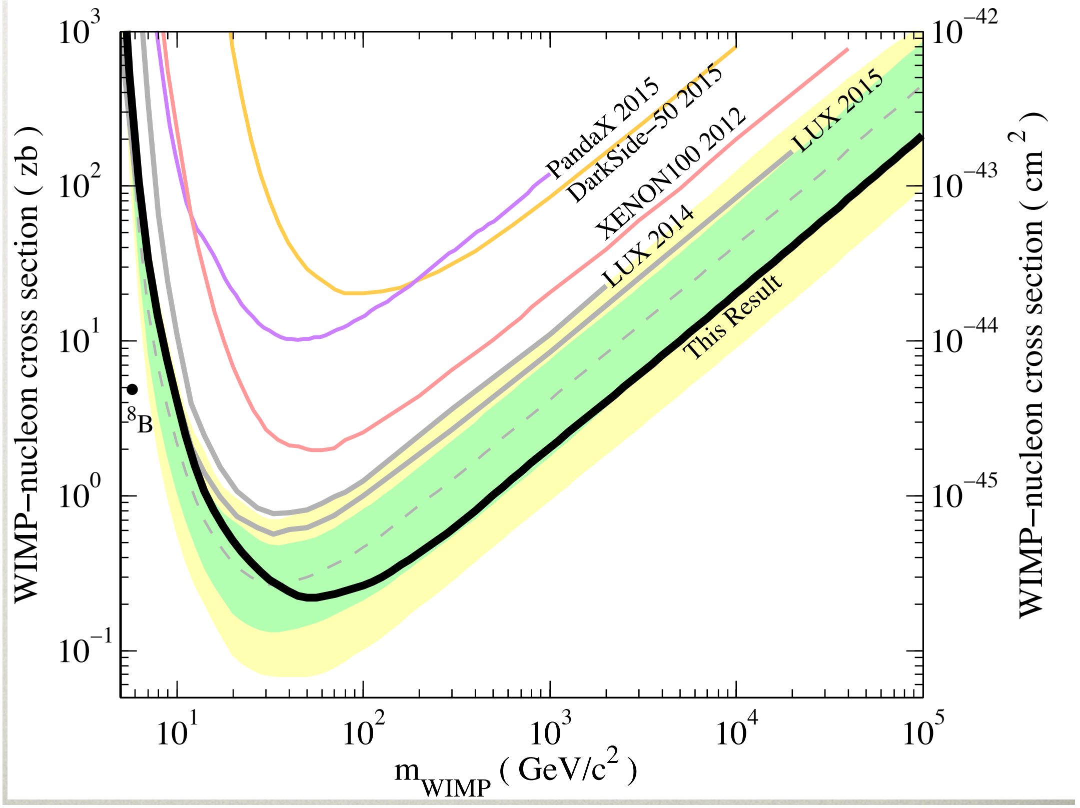




Conclusion

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

- Identify a blind spot scenario for neutralino dark matter
- possible probes at the LHC
  - heavy Higgs searches, precision Higgs, and Electroweakinos searches



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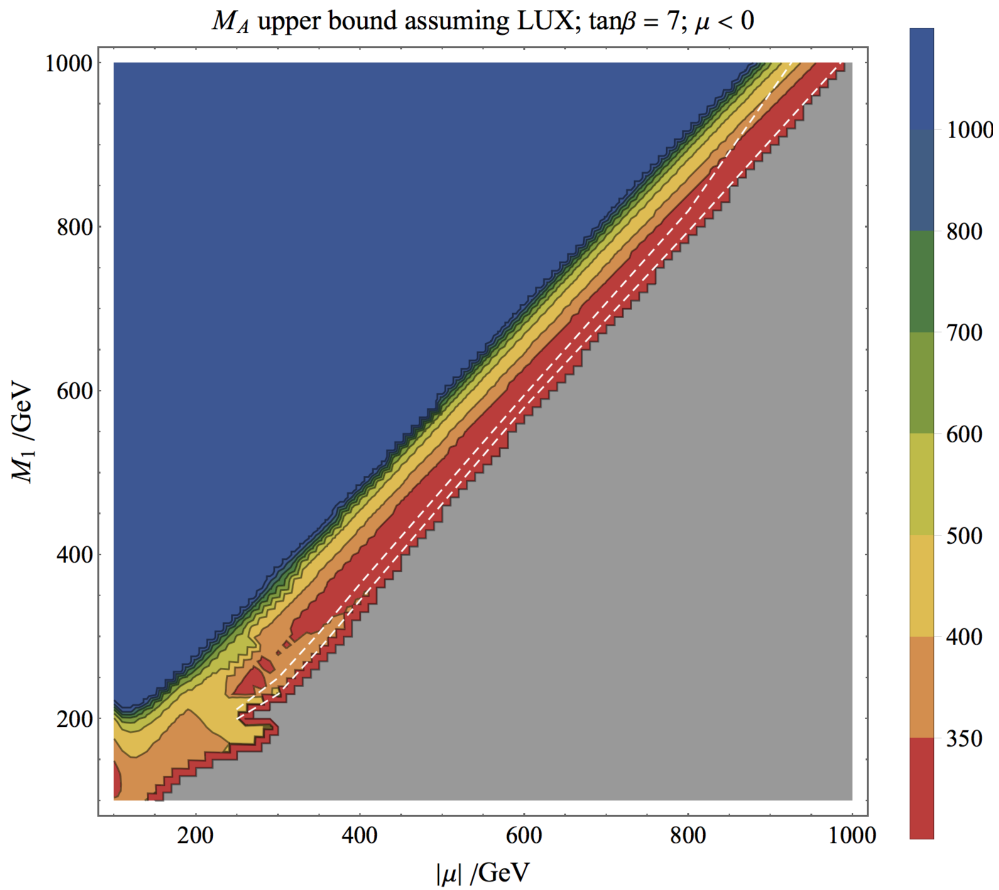
Current Direct Detection Constraints

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

$\Rightarrow$ m_A upper bound



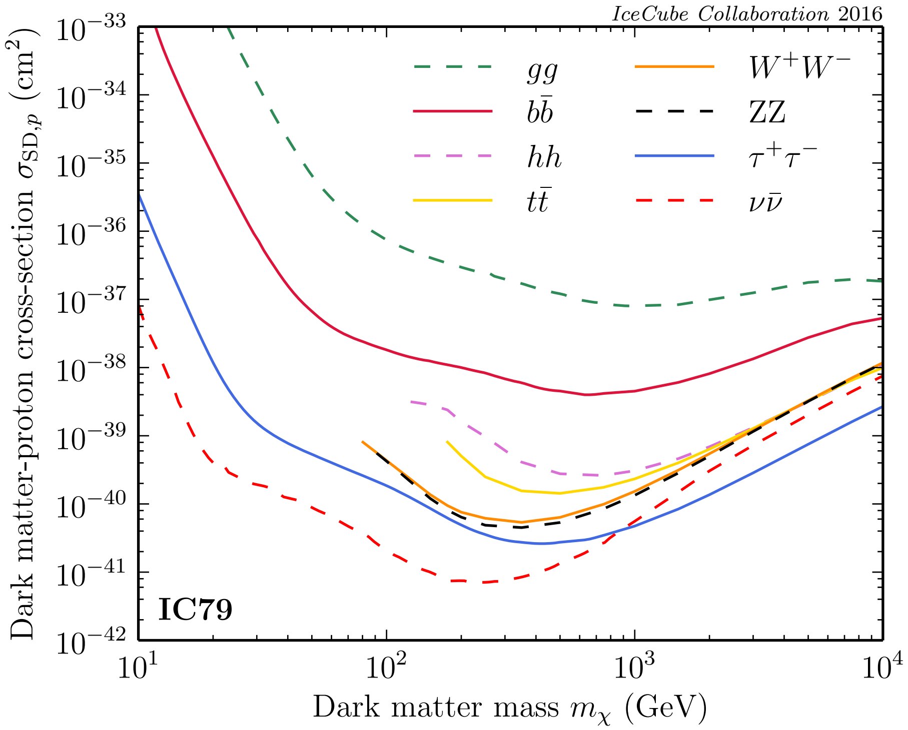
Rescale according to the local density

In the well-tempered region, m_A < 350 -400 GeV

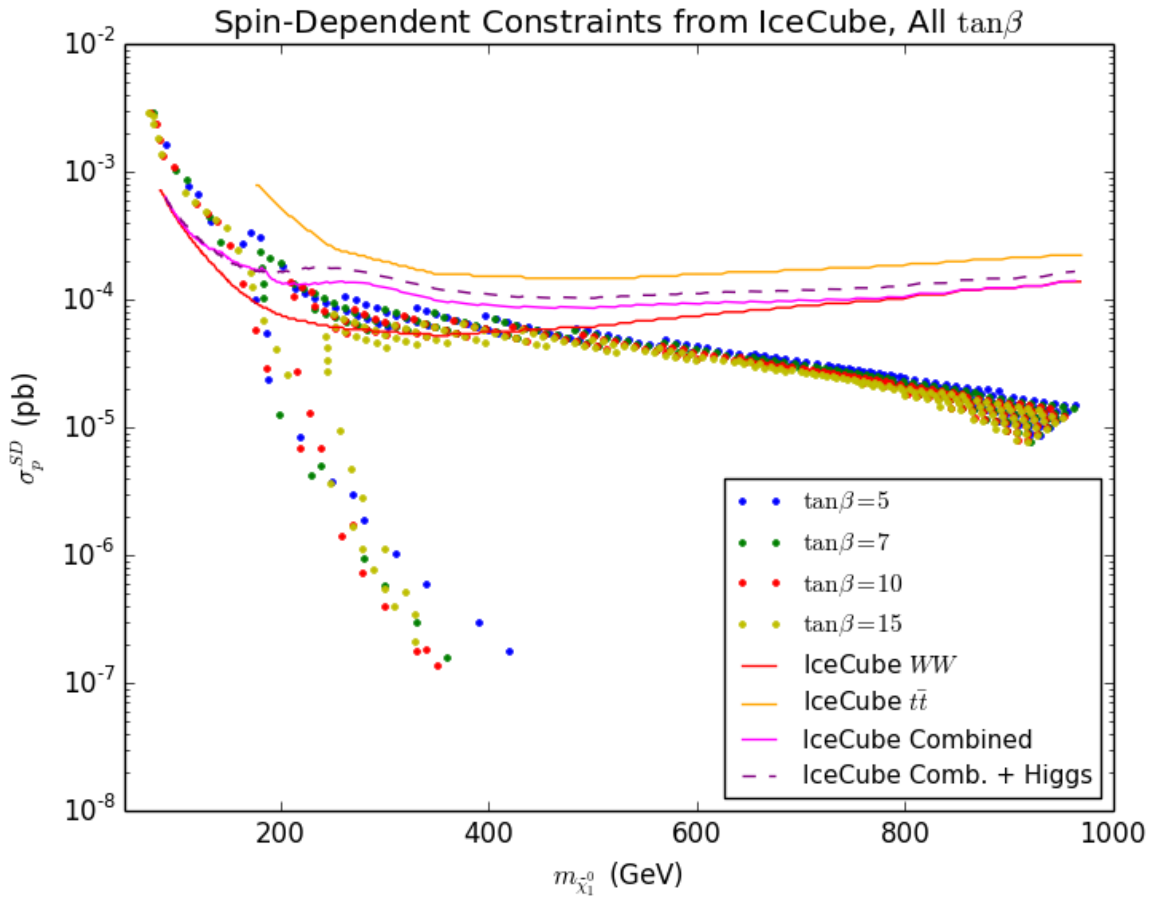
relaxed mA bound to the left of the well-tempered region

Will discuss direct heavy Higgs search and precision Higgs later

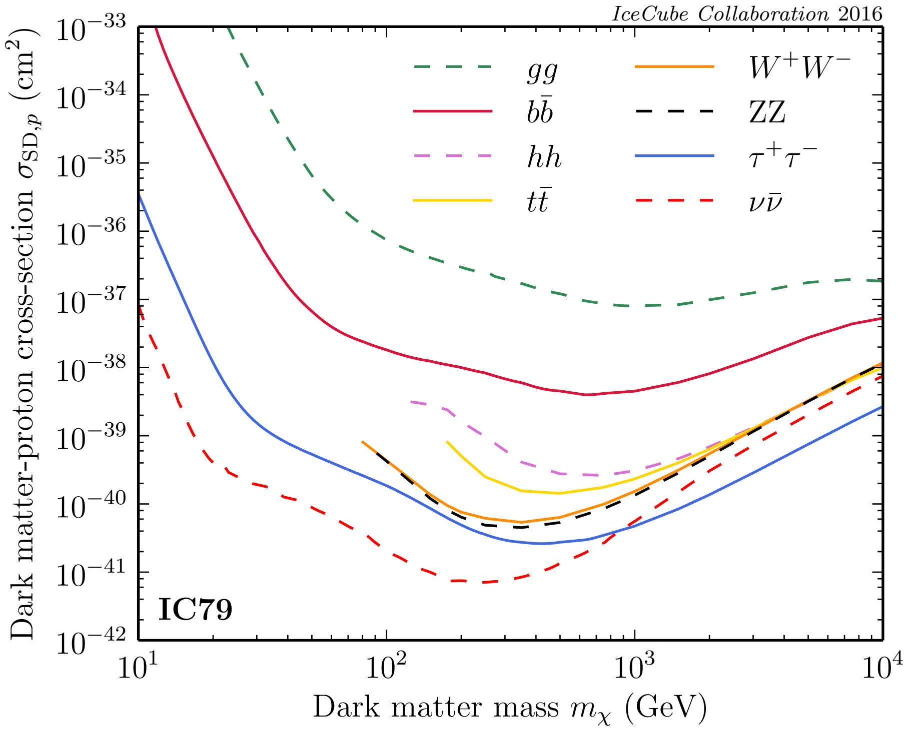
Probe the Blind Spots scenarios – IceCube

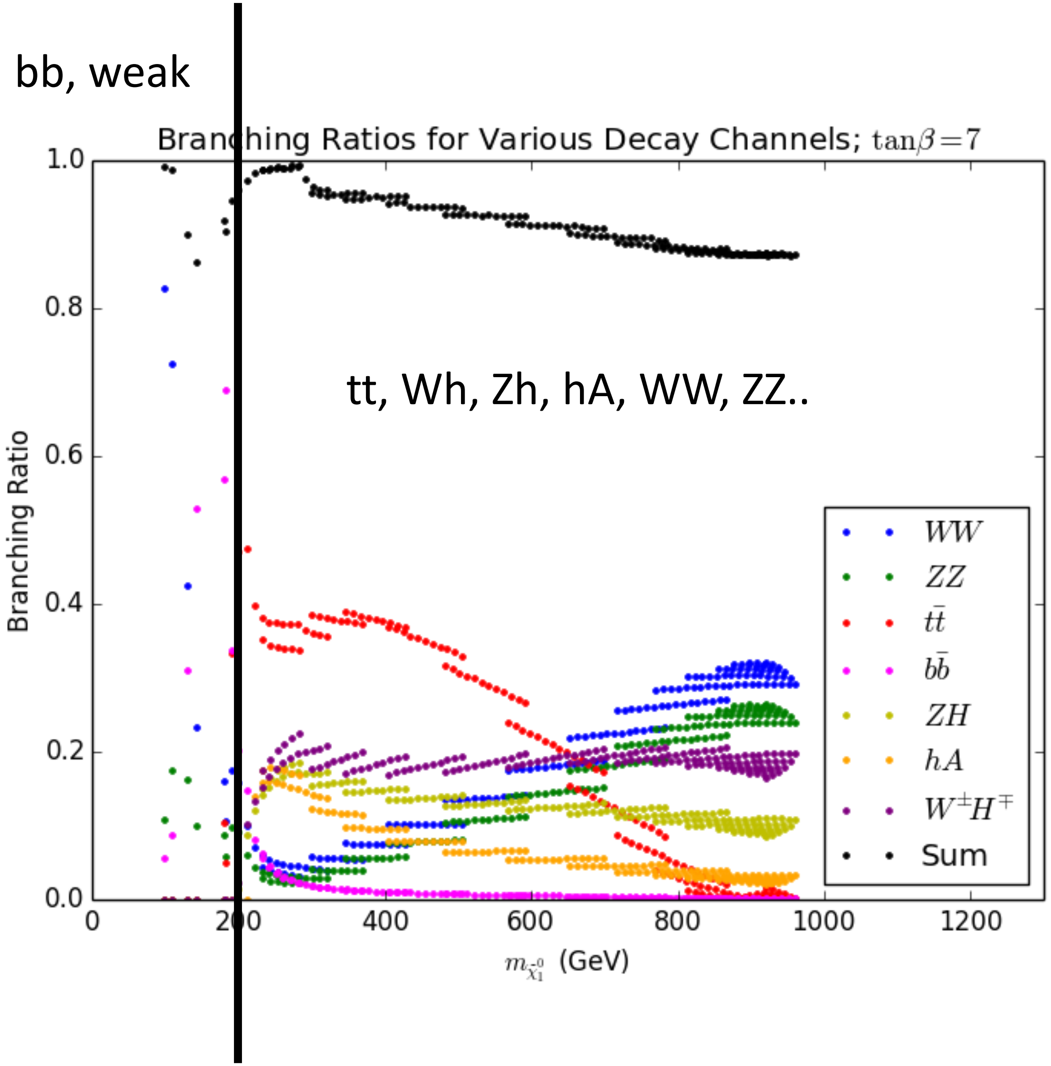


exclude the well-tempered region for $m_\chi \lesssim$ 200 GeV

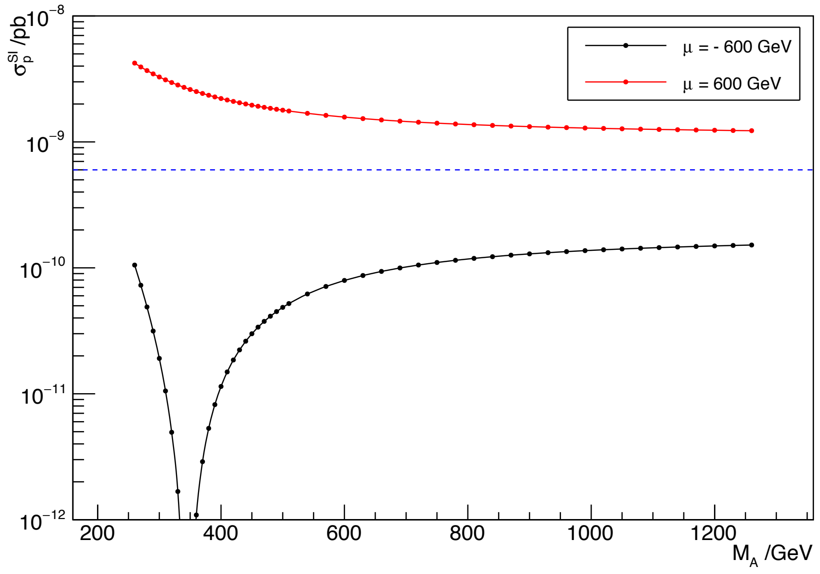


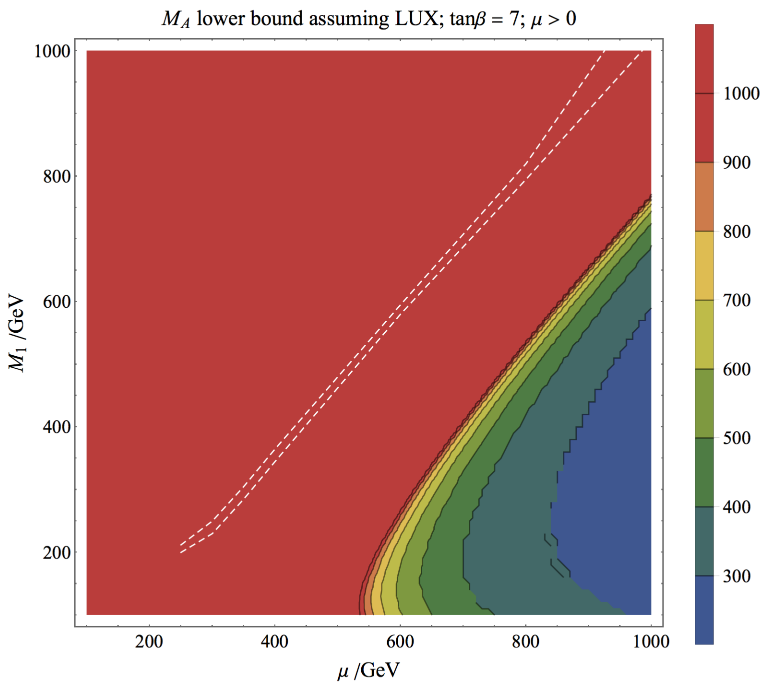
Probe the Blind Spots scenarios – IceCube





Positive μ



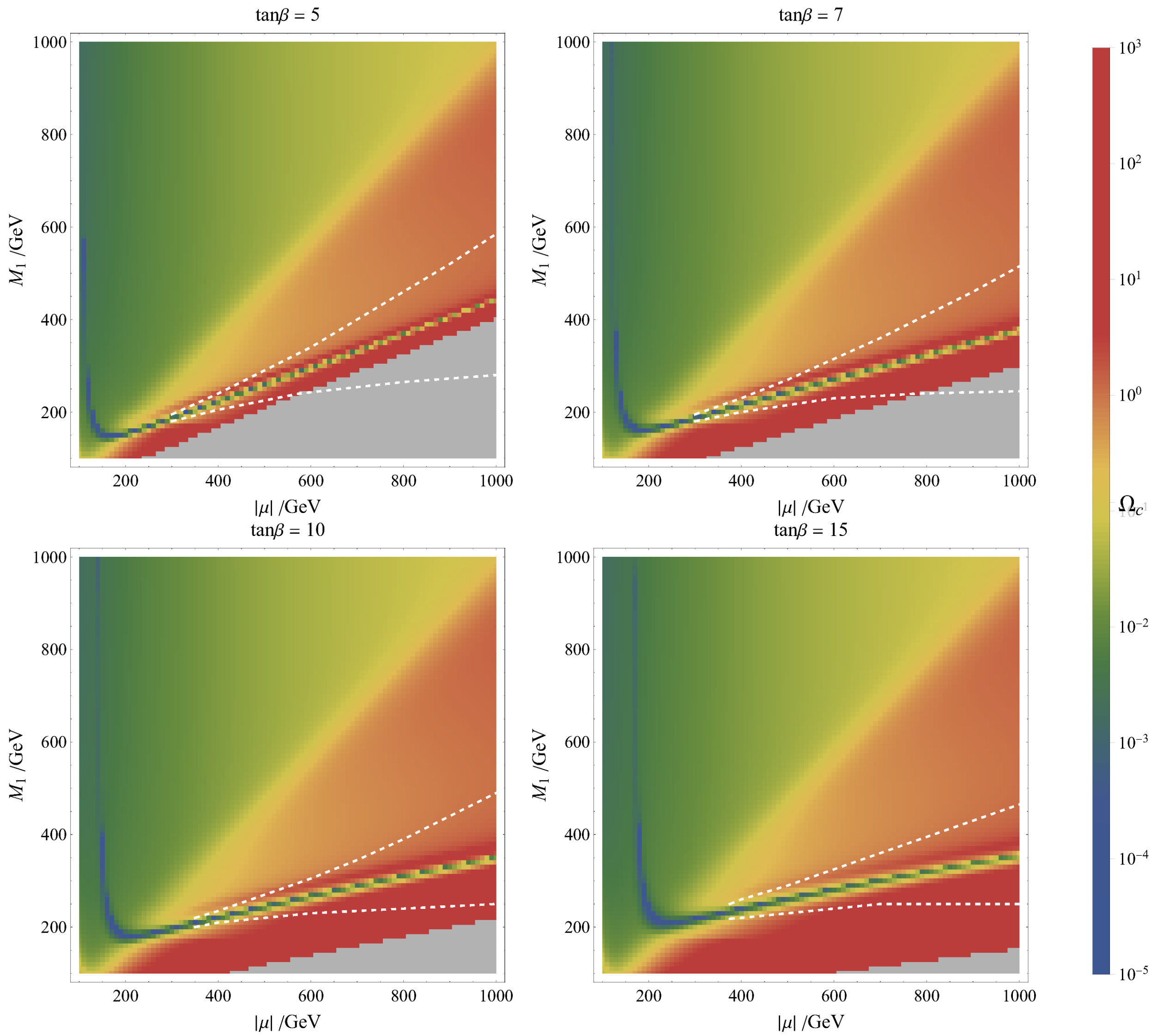


Larger Higgs Neutralino coupling

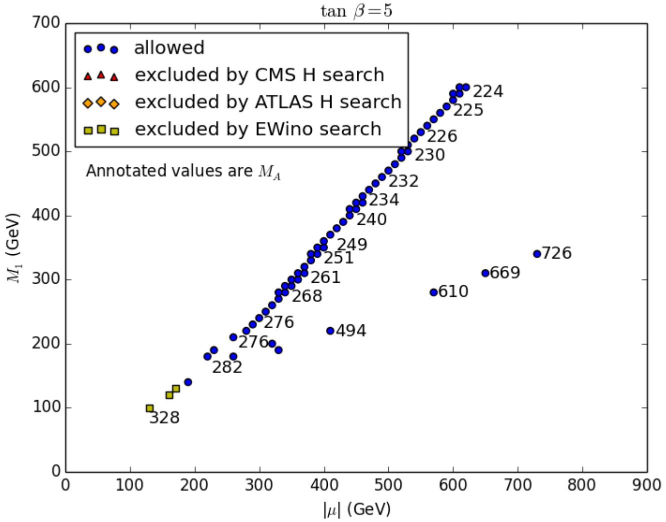
Constructive interference

lower bound on m_A

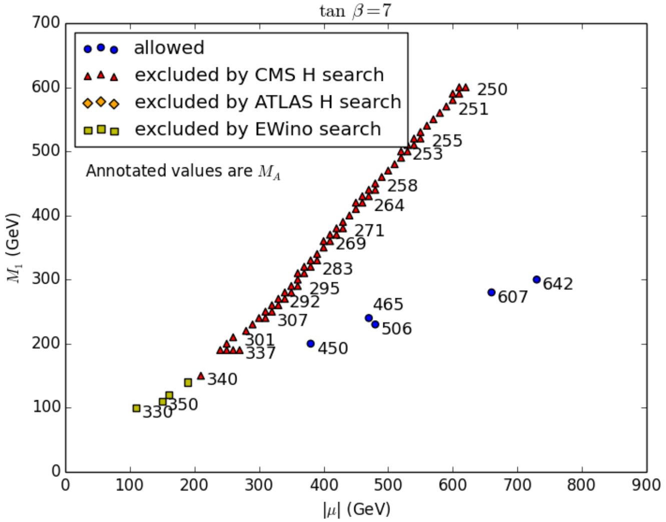
A –funnel and the LUX limit



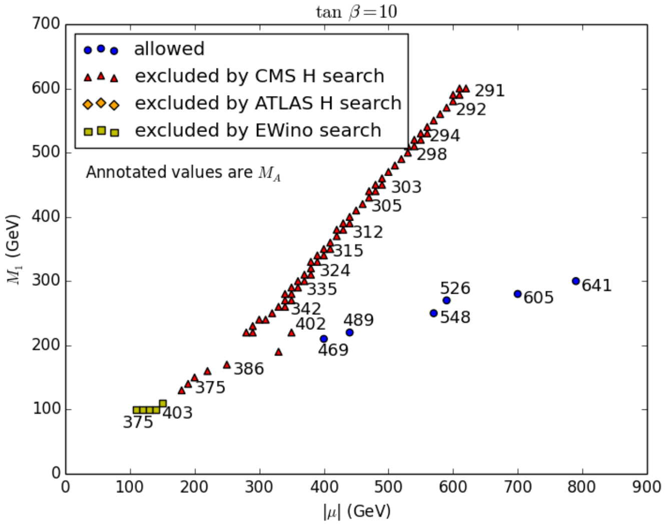
Exclusions



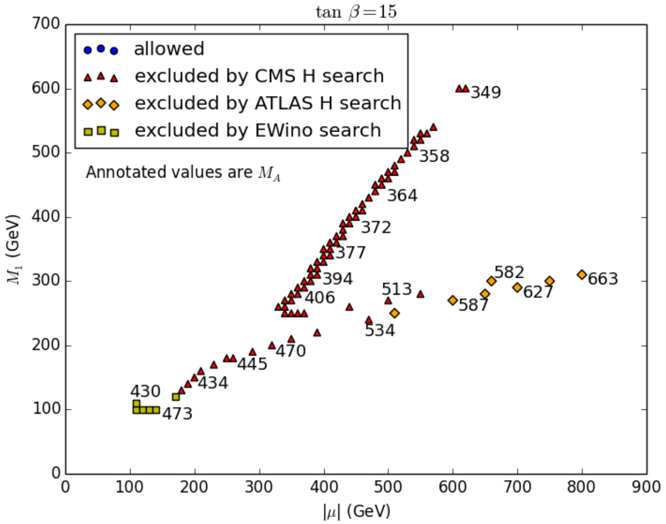
tan β=5
allowed
excluded by CMS H search
excluded by ATLAS H search
excluded by EWino search
Annotated values are M_A
224
225
226
230
232
234
240
249
251
261
268
276
276
282
328
494
610
669
726
M_1 (GeV)
|μ| (GeV)



tan β=7
allowed
excluded by CMS H search
excluded by ATLAS H search
excluded by EWino search
Annotated values are M_A
250
251
255
253
258
264
271
269
283
295
292
307
301
337
340
350
330
465
506
450
607
642
M_1 (GeV)
|μ| (GeV)

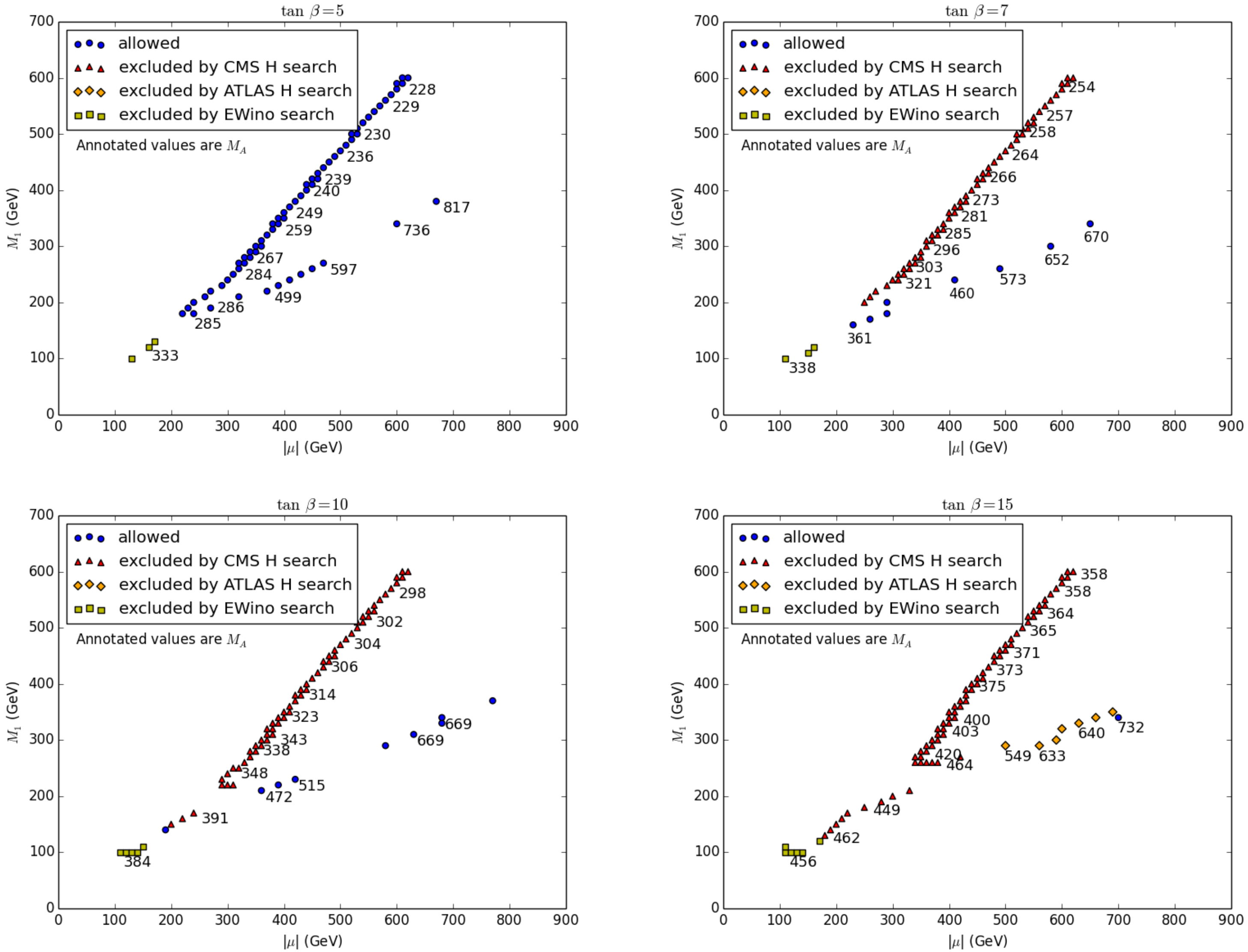


tan β=10
allowed
excluded by CMS H search
excluded by ATLAS H search
excluded by EWino search
Annotated values are M_A
291
292
294
298
303
305
312
315
324
335
342
402
469
489
526
548
605
641
386
375
403
375
M_1 (GeV)
|μ| (GeV)



tan β=15
allowed
excluded by CMS H search
excluded by ATLAS H search
excluded by EWino search
Annotated values are M_A
349
358
364
372
377
394
406
513
534
582
587
627
663
470
445
434
430
473
M_1 (GeV)
|μ| (GeV)

Exclusions, mA upper bound



EW-ino production cross section