Discussion: SUSY via searches for additional Higgs(inos)

Experimental Challenges for the LHC Run II Workshop
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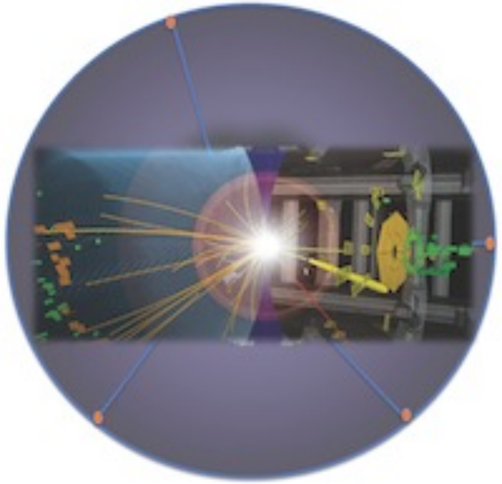
Brian Petersen (CERN),
Keith Ulmer (Texas A&M Univ.),
Stefania Gori (U. of Cincinnati),
Howard E. Haber (UC Santa Cruz)



Higgs sector in SUSY

- The MSSM Higgs sector
  - Constrained 2HDM (two scalar doublets required so that anomalies due to higgsino superpartners cancel)
- The NMSSM Higgs Sector
  - 2HDM plus a complex singlet scalar (no new mass parameters added to the SUSY Higgs Lagrangian)

Critical experimental input

- An (approximate) CP-even scalar h exists with $m_h = 125$ GeV
- The couplings of h are SM-like (to within an accuracy of roughly 20%)

Achieving a SM-like Higgs boson

A neutral Higgs scalar is SM-like if the corresponding mass-eigenstate is approximately aligned in field space with the direction of the doublet vacuum expectation value. This is the so-called *alignment limit*

- In the decoupling limit, all but one of the scalar Higgs states are heavy, i.e. of a mass scale $M \gg v$ (where $v = 246$ GeV). In this limit, the remaining light Higgs scalar is SM-like. Deviations from SM-like behavior are still possible if light SUSY states exist, which can modify Higgs properties at one-loop or lead to new decays (such as $h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$).

- In the alignment limit *without* decoupling, h is SM-like but the other Higgs scalars may have masses of $\mathcal{O}(v)$, and can therefore contribute new deviations to the h properties due to new loop contributions (e.g. charged Higgs loops) or new decays (e.g. $h \to aa$).

The alignment limit of the MSSM Higgs sector

[reference: M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, Phys. Rev. D **91**, 035003 (2015)]

Start with the the two Higgs doublet fields Φ_i (for $i = 1, 2$) such that $\langle \Phi_i^0 \rangle = v_i/\sqrt{2}$, and $v^2 \equiv v_1^2 + v_2^2 = (246\ \mathrm{GeV})^2$ and $\tan\beta \equiv v_2/v_1$. It is convenient to employ the so-called Higgs basis of scalar doublet fields,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1\Phi_1 + v_2\Phi_2}{v}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v},$$

so that $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$. The scalar doublet H_1 has SM tree-level couplings to all the SM particles.

The scalar potential contains the following terms of interest,

$$\mathcal{V} \ni \ldots + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)H_1^\dagger H_2 + \mathrm{h.c.}\right] + \ldots\,,$$

In the Higgs basis, the CP-even neutral Higgs squared-mass matrix is

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

where m_A is the mass of the CP-odd neutral Higgs boson A. The mixing angle of rotation from the Higgs basis to the mass basis is $\alpha - \beta$.

It follows that in both the decoupling limit ($m_H \gg m_h$) and the alignment limit without decoupling [$|Z_6| \ll 1$ and $m_H^2 - Z_1 v^2 \sim \mathcal{O}(v^2)$],

$$\cos^2(\beta - \alpha) = \frac{Z_6^2 v^4}{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)} \ll 1\,,$$

$$Z_1 v^2 - m_h^2 = \frac{Z_6^2 v^4}{m_H^2 - Z_1 v^2} \ll \mathcal{O}(v^2)\,.$$

REMARK: Note the upper bound $m_h^2 \leq Z_1 v^2$ on the mass of h is saturated in the exact alignment limit.

The MSSM values of Z_1 and Z_6 (including the leading one-loop corrections):

$$Z_1 v^2 = m_Z^2 c_{2\beta}^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

$$Z_6 v^2 = -s_{2\beta}\left\{m_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]\right\}.$$

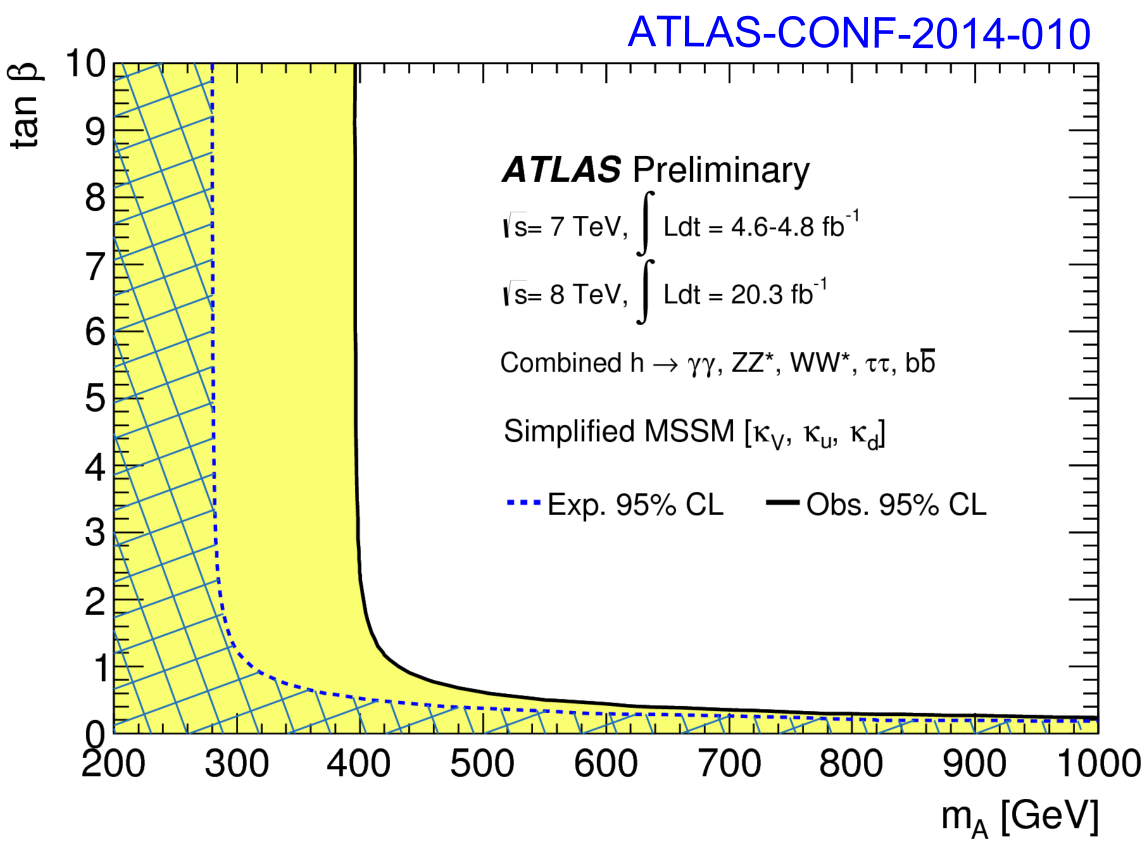
where $M_S^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$, $X_t \equiv A_t - \mu\cot\beta$ and $Y_t = A_t + \mu\tan\beta$.

The upper bound on the Higgs mass, $m_h^2 \leq Z_1 v^2$, can now be consistent with the observed $m_h \simeq 125$ GeV for suitable choices for m_S and X_t. The exact alignment condition, $Z_6 = 0$, can now be achieved due to an accidental cancellation between tree-level and loop contributions,

$$m_Z^2 c_{2\beta} = \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t+Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right].$$

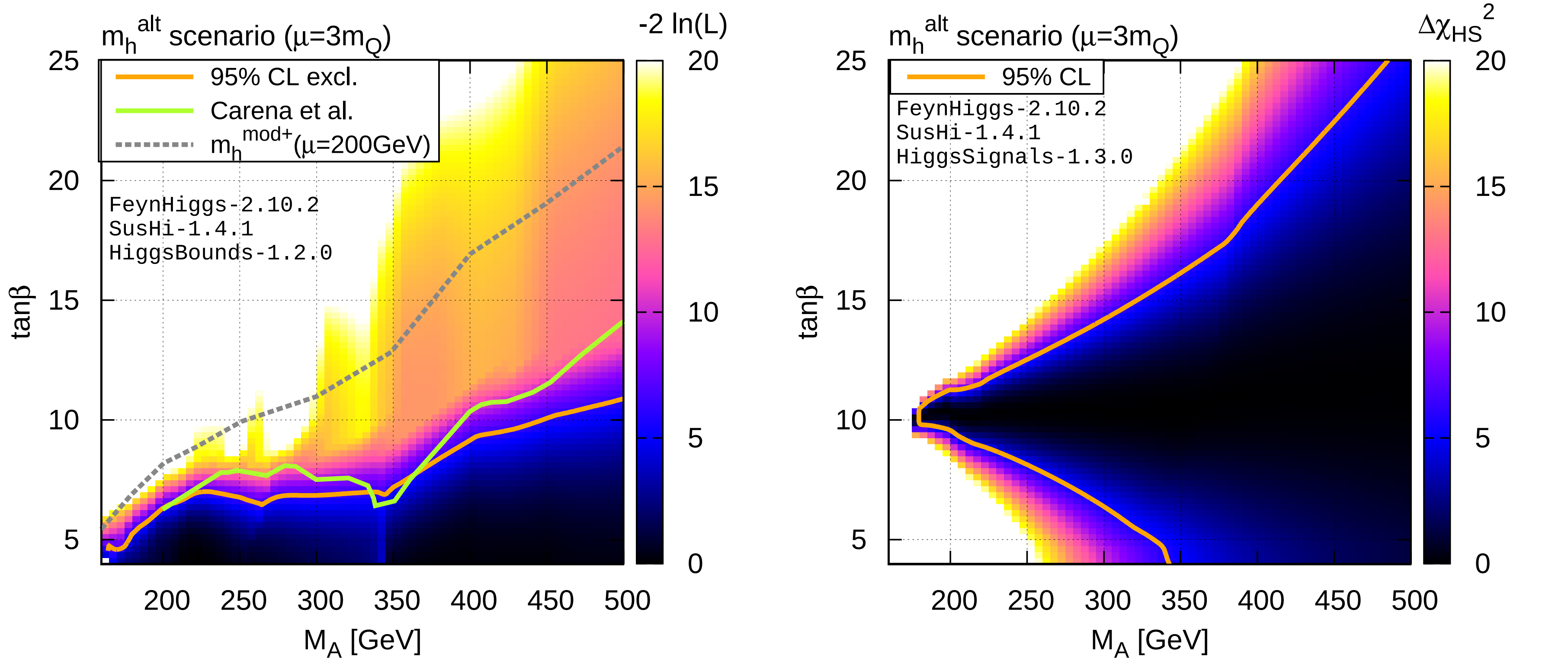
That is, $Z_6 \simeq 0$ is possible for a particular choice of $\tan\beta$.

Bounds from the 125 GeV Higgs boson



So far limits are weak.

Even if we do not have alignment, we do not need much decoupling

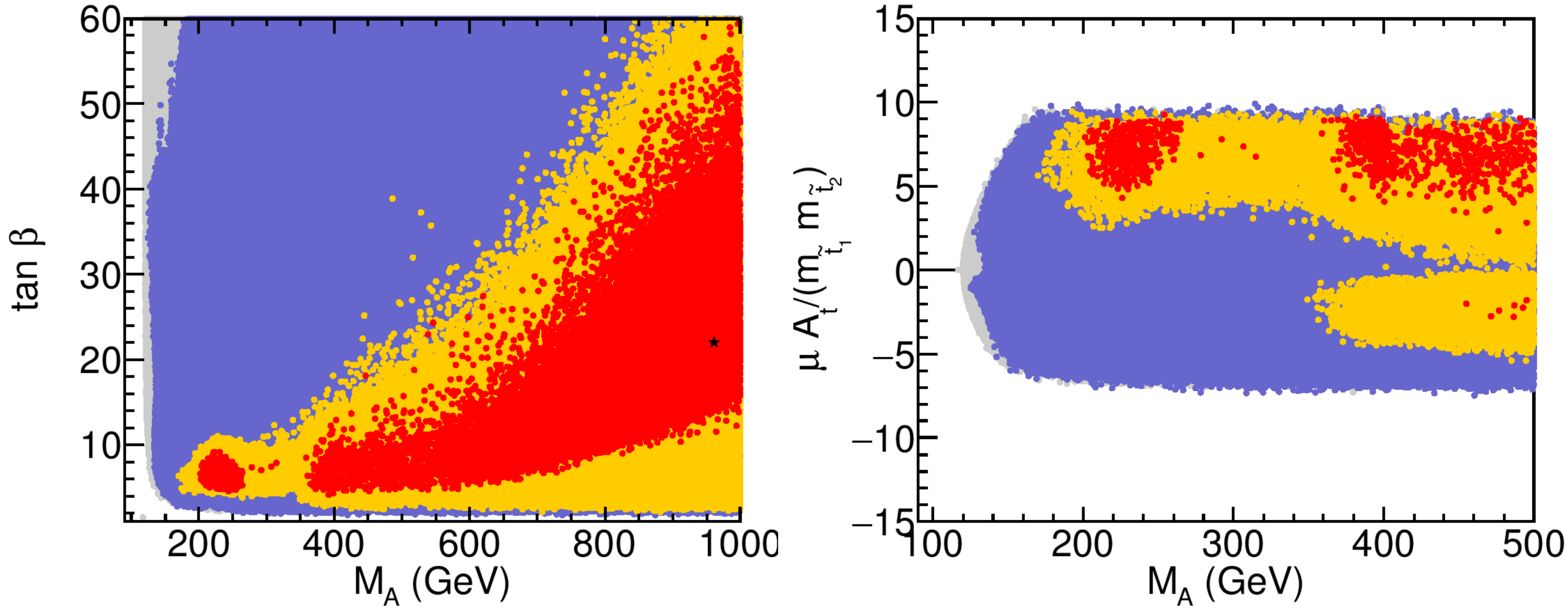


Constraints from LHC Higgs searches in the alignment benchmark scenario (with $\mu = 3M_S$).
Left panel: distribution of the exclusion likelihood from the CMS $\phi \to \tau^+\tau^-$ search and the observed 95% CL elcusion line as obtained from `HiggsBounds`.

Right panel: likelihood distribution, $\Delta\chi^2_{\mathrm{HS}}$ obtained from testing the signal rates of the Higgs boson h against a combination of Higgs rate measurements from the Tevatron and LHC experiments, obtained with `HiggsSignals`.

From P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, EPJC **75**, 421 (2015).

Likelihood analysis: allowed regions in the $\tan\beta$–m_A plane



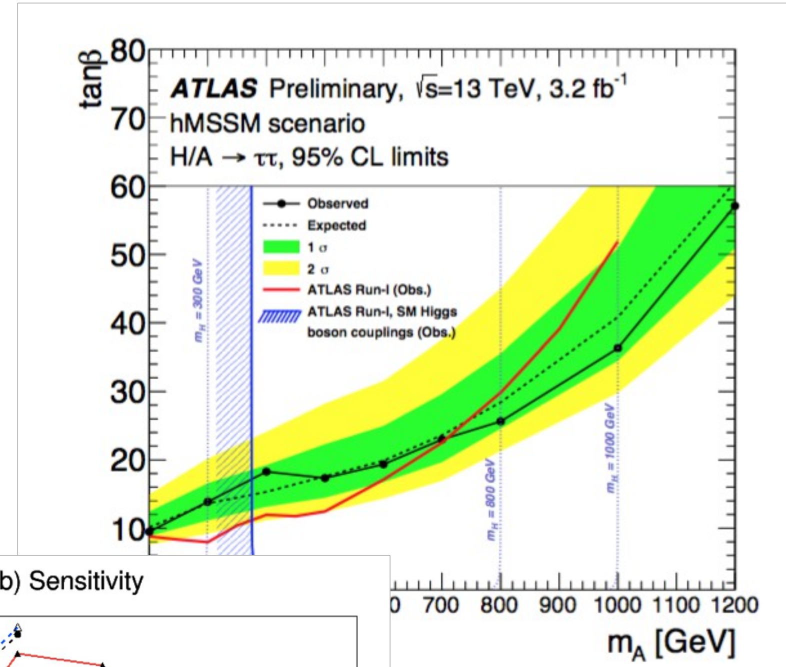
Preferred parameter regions in the $(M_A,\, \tan\beta)$ plane (left) and $(M_A,\, \mu A_t/M_S^2)$ plane (right), where $M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$, in a pMSSM-8 scan. Points that do not pass the direct constraints from Higgs searches from `HiggsBounds` and from LHC SUSY particle searches from `CheckMATE` are shown in gray. Applying a global likelihood analysis to the points that pass the direct constraints, the color code employed is red for $\Delta\chi_h^2 < 2.3$, yellow for $\Delta\chi_h^2 < 5.99$ and blue otherwise. The best fit point is indicated by a black star. (Taken from P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and L. Zeune, in preparation.)

Searches for new Higgs bosons to date

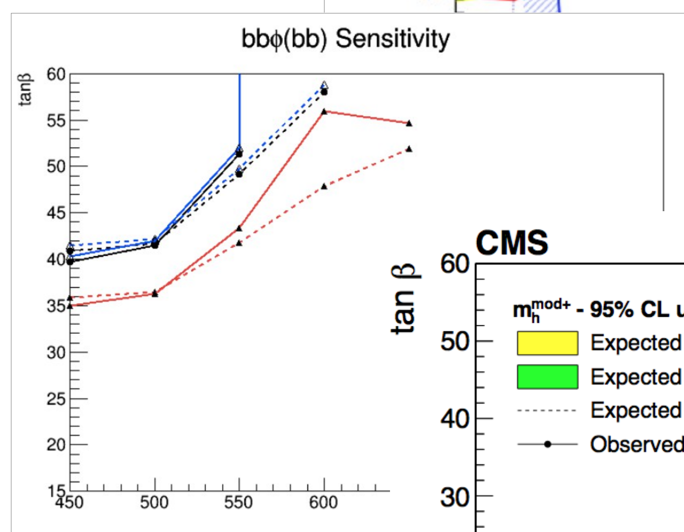
In the alignment/decoupling limit:

		H	A
Standard Model	WW, ZZ	–	
Decay Channels	$tt, bb, \tau\tau, \mu\mu$	✓	✓
	$\gamma\gamma$	✓	✓
	Zh		–
	hh	–	

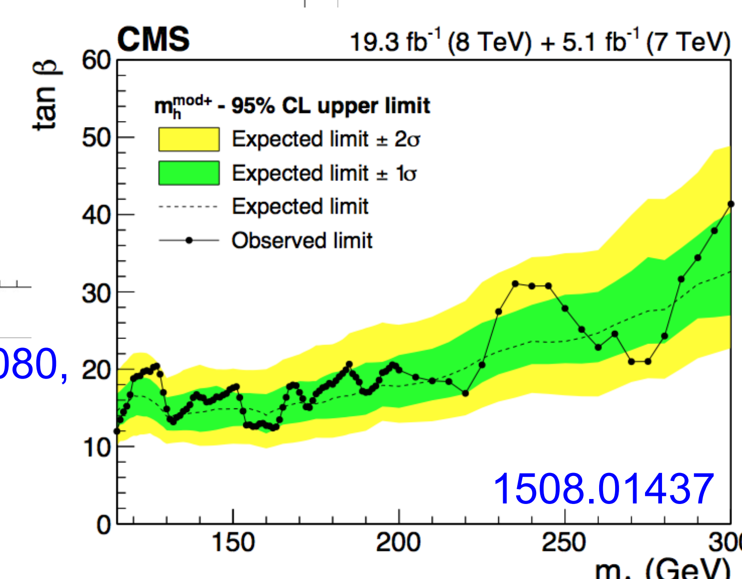
From Craig, D'Eramo, Draper, Thomas, Zhang, 1504.04630



ATLAS-CONF-2015-061



CERN-THESIS-2015-080, Malone



1508.01437

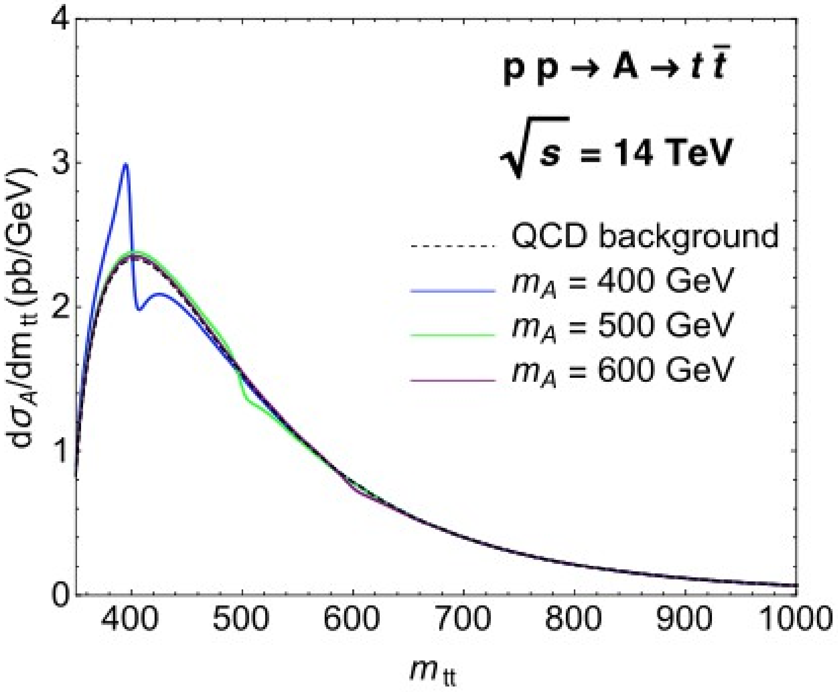
At large tanβ the heavy Higgs couplings to

- bottoms, muons and taus are enhanced
- tops are suppressed

Regime of low tanβ

The (heavy) Higgs mainly decays into tops and EW-inos (in some specific scenarios)

- Tops, Gluon fusion production



Very nice

Craig et al, 1504.04630

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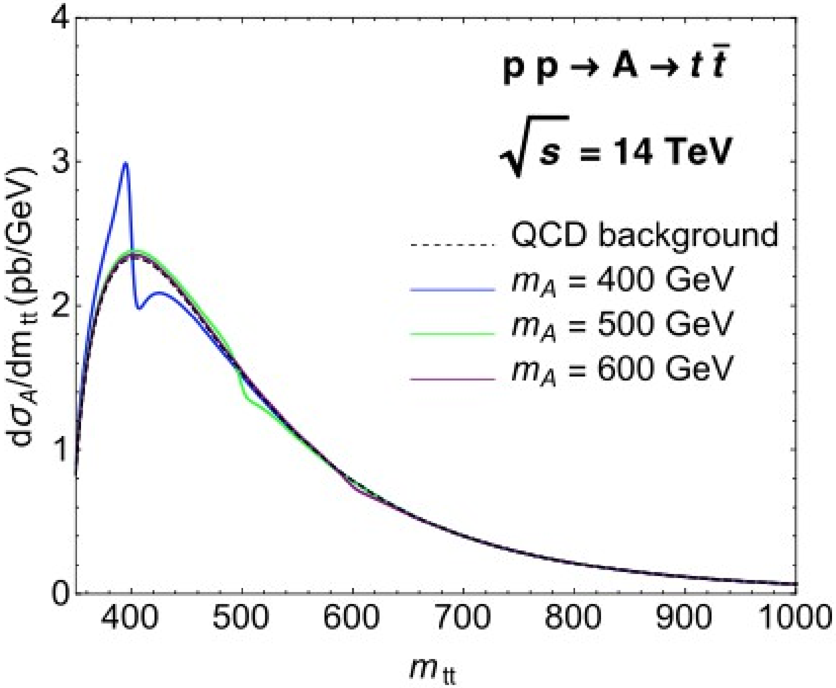

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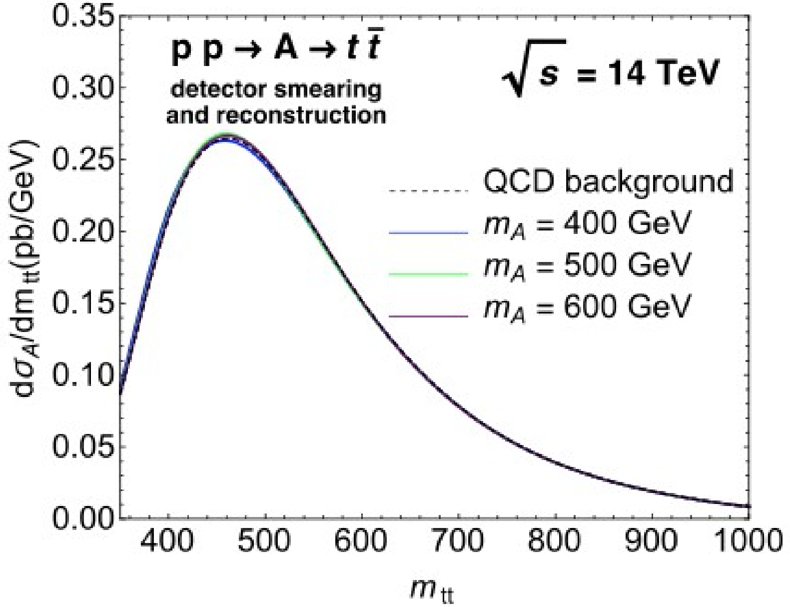

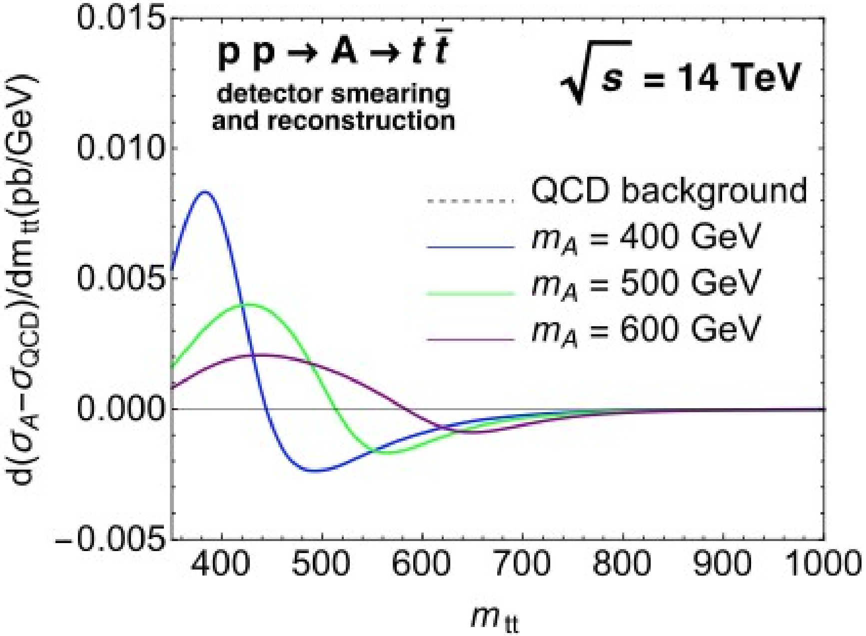

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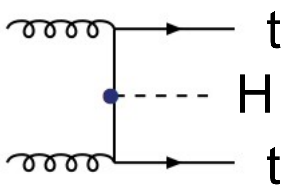
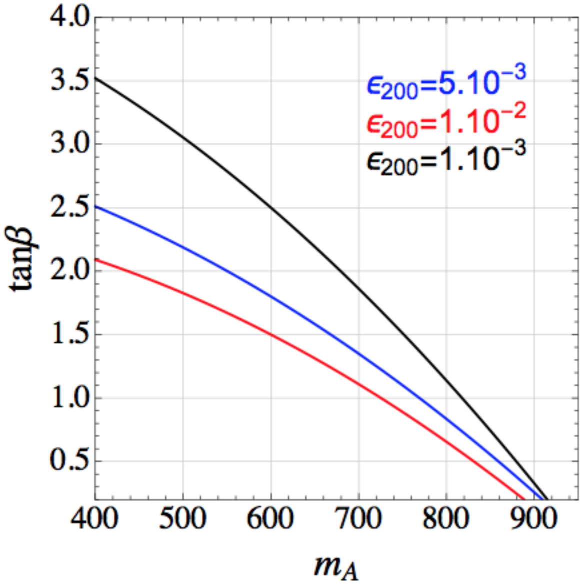
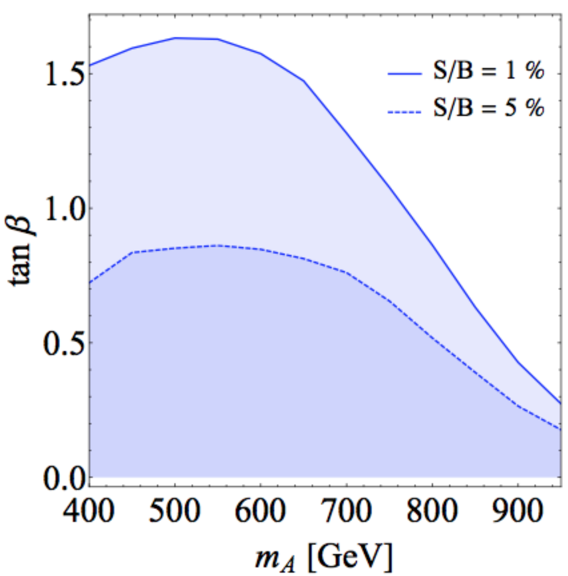
SG, Kim, Shah, Zurek, 1602.02782

- Tops, t associated production





3 leptons, >1b, >2jets



1 lepton, >1b, >5jets

Regime of low tanβ

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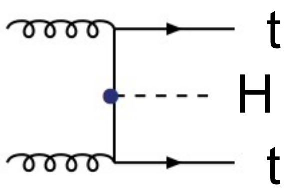
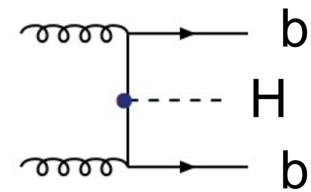
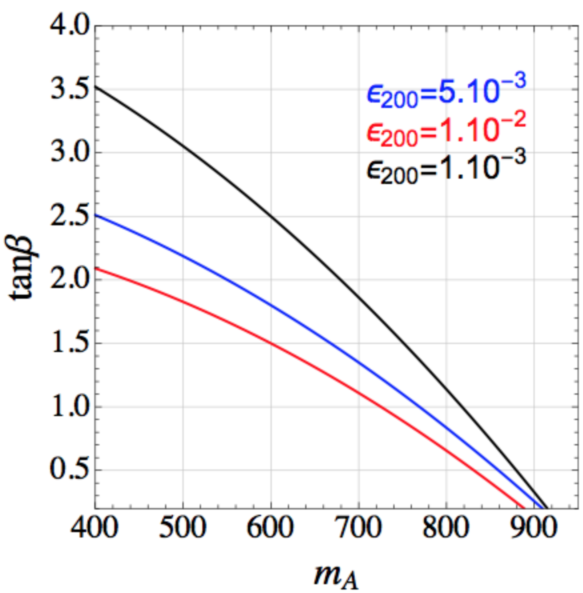


- Tops, b associated production





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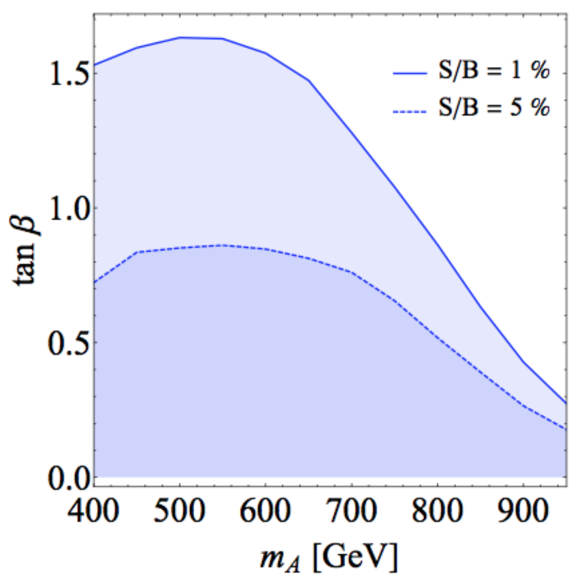

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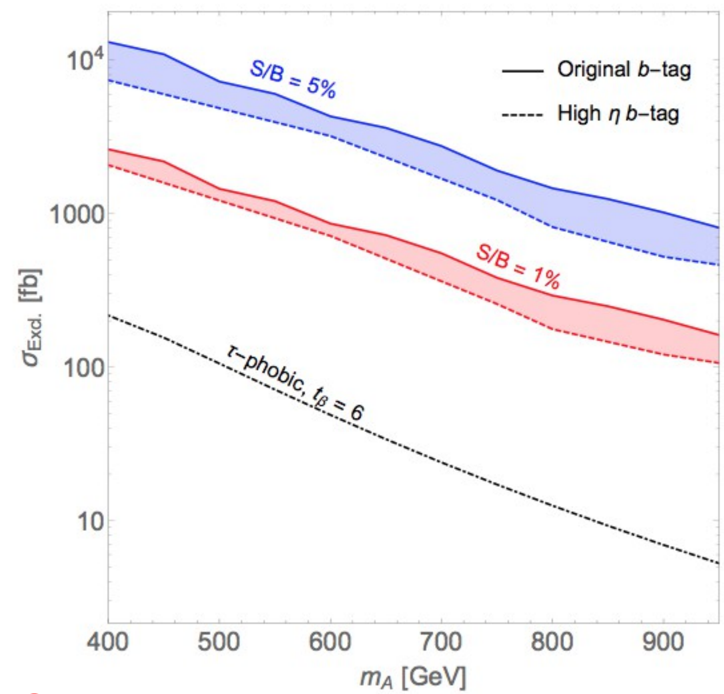

Better/complementary ideas?

Interpretation of the limits

Carena et al, 1302.7033

Typically the cross section limits are interpreted in the

$m_h^{\mathrm{mod}+}$

$m_h^{\mathrm{mod}-}$

m_h^{max}

$\tau - \mathrm{phobic}$

scenarios

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scenarios

$$M_1 = \frac{5}{3}\frac{s_w^2}{c_w^2}M_2$$

$$\begin{aligned} m_t &= 173.2 \text{ GeV}, \\ M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 200 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 1000 \text{ GeV} . \end{aligned}$$

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Tanβ = 5, m_H = 500GeV

$$\text{BR}(H \to \chi_1^\pm\chi_1^\pm,\ \chi_1^\pm\chi_2^\pm,\ \chi_1^0\chi_1^0) \sim 0.15,\ 0.35,\ 3\times10^{-2}$$

Tanβ = 20, m_H = 900GeV

$$\text{BR}(H \to \tilde{\tau}_1\tilde{\tau}_1) \sim 0.25$$

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Typically the cross section limits are interpreted in the

$m_h^{\rm mod+}$

$m_h^{\rm mod-}$

$m_h^{\rm max}$

$\tau - \text{phobic}$

scenarios

$m_t = 173.2$ GeV,

$m_t = 173.2$ GeV,

$M_1 = \frac{5}{3}\frac{s_w^2}{c_w^2} M$

Question:
is there any region of the EW-ino parameter space that can be better/complementary probed by new Higgs searches?

Typically cross sections are smaller...
σ(pp→H) ~ 500 fb (tanβ=5, m_H= 300GeV, 8TeV)
σ(pp→$\chi_2\chi_1$) ~ O(1pb) ($m_{\chi 2}$~ $m_{\chi 1}$~ 150GeV, 8TeV)

Cross sections for stau pair production are closer...

$$m_t = 173.2 \text{ GeV}, \quad M_{\rm SUSY} = 1000 \text{ GeV}, \quad \mu = 200 \text{ GeV}, \quad M_2 = 200 \text{ GeV}, \quad X_t^{\rm OS} = 2\,M_{\rm SUSY} \text{ (FD calculation)}, \quad X_t^{\overline{\rm MS}} = \sqrt{6}\,M_{\rm SUSY} \text{ (RG calculation)}, \quad A_b = A_\tau = A_t, \quad m_{\tilde g} = 1500 \text{ GeV}, \quad M_{\tilde l_3} = 1000 \text{ GeV}.$$

Tanβ = 5, m_H = 300GeV

$$\text{BR}(H \to \chi_1^\pm \chi_1^\pm,\ \chi_1^\pm \chi_2^\pm,\ \chi_1^0 \chi_1^0) \sim 0.15,\ 0.35,\ 3\times 10^{-2}$$

Tanβ = 20, m_H = 900GeV

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$$M_{\rm SUSY} = 1500 \text{ GeV}, \quad \mu = 2000 \text{ GeV}, \quad M_2 = 200 \text{ GeV}, \quad X_t^{\rm OS} = 2.45\,M_{\rm SUSY} \text{ (FD calculation)}, \quad X_t^{\overline{\rm MS}} = 2.9\,M_{\rm SUSY} \text{ (RG calculation)}, \quad A_b = A_\tau = A_t, \quad m_{\tilde g} = 1500 \text{ GeV}, \quad M_{\tilde l_3} = 500 \text{ GeV}.$$

The alignment limit of the NMSSM Higgs sector

[reference: M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, Phys. Rev. D **93**, 035013 (2016)]

Add a complex singlet scalar field S. The analog Higgs basis fields are:

$$h \equiv \sqrt{2}\,\mathrm{Re}\ H_1^0 - v\,, \qquad H \equiv \sqrt{2}\,\mathrm{Re}\ H_2^0\,, \qquad H^{\mathrm{S}} \equiv \sqrt{2}\,(\mathrm{Re}\ S - v_s)\,,$$

$$G \equiv \sqrt{2}\,\mathrm{Im}\ H_1^0\,, \qquad A \equiv \sqrt{2}\,\mathrm{Im}\ H_2^0\,, \qquad A^{\mathrm{S}} \equiv \sqrt{2}\,\mathrm{Im}\ S\,,$$

Assume a CP-conserving tree-level Higgs sector. The symmetric squared-mass matrix for the CP-even scalars in the Higgs basis is

$$\mathcal{M}_S^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 & \sqrt{2}\,v\left[C_1 + (Z_{s1} + 2Z_{s5})v_s\right] \\ & \overline{M}_A^2 + Z_5 v^2 & \dfrac{v}{\sqrt{2}}\left[C_3 + C_4 + 2(Z_{s3} + Z_{s7} + Z_{s8})v_s\right] \\ & & -C_1\dfrac{v^2}{2v_s} + 3(C_5 + C_6)v_s + 4(Z_{s4} + 2Z_{s9} + 2Z_{s10})v_s^2 \end{pmatrix},$$

where $\overline{M}_A^2 \equiv 2\mu(A_\lambda + \kappa v_s)/s_{2\beta}$ and $\mu \equiv \lambda v_s$.

The coefficients of the scalar potential appear in the squared-mass matrix $\mathcal{M}^2$,

$$\begin{aligned}\mathcal{V} \ni \ldots &+ \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)H_1^\dagger H_2 + \text{h.c.}\right] + \ldots \\ &+ S^\dagger S\left[Z_{s1}H_1^\dagger H_1 + \ldots + (Z_{s3}H_1^\dagger H_2 + \text{h.c.}) + Z_{s4}S^\dagger S\right] \\ &+ \left\{Z_{s5}H_1^\dagger H_1 S^2 + \ldots + Z_{s7}H_1^\dagger H_2 S^2 + Z_{s8}H_2^\dagger H_1 S^2 + Z_{s9}S^\dagger S\, S^2 + Z_{s10}S^4 + \text{h.c.}\right\} \\ &+ \left[C_1 H_1^\dagger H_1 S + \ldots + C_3 H_1^\dagger H_2 S + C_4 H_2^\dagger H_1 S + C_5(S^\dagger S)S + C_6 S^3 + \text{h.c.}\right].\end{aligned}$$

Exact alignment occurs when $\mathcal{M}^2_{12} = \mathcal{M}^2_{13} = 0$. That is,

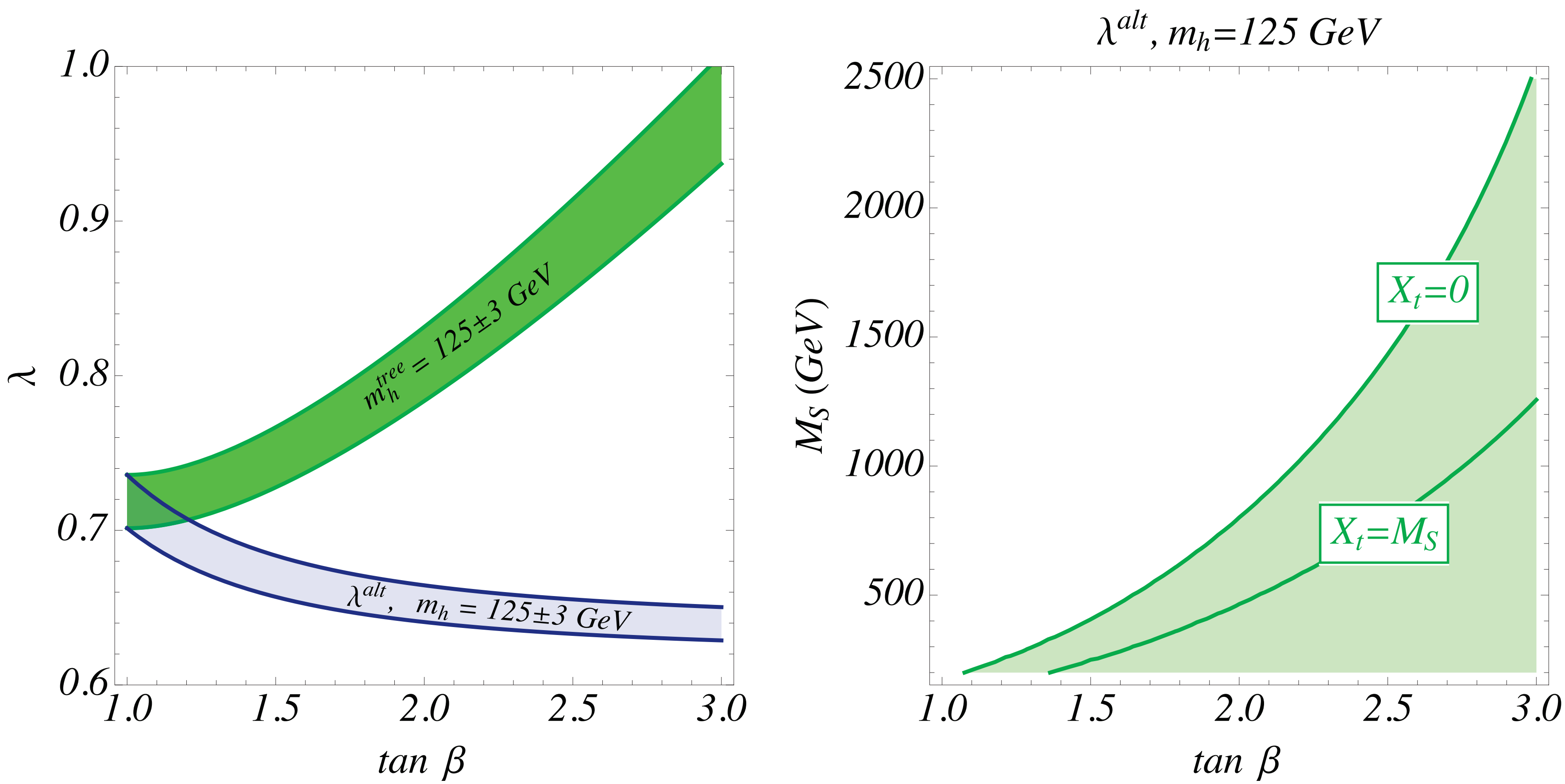
$$Z_6 = 0\,, \qquad\qquad C_1 + (Z_{s1} + 2Z_{s5})v_s = 0\,.$$

In the NMSSM, including the leading one-loop radiative corrections,

$$\begin{aligned}Z_1 v^2 &= (m_Z^2 - \tfrac{1}{2}\lambda^2 v^2)c^2_{2\beta} + \tfrac{1}{2}\lambda^2 v^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right], \\ Z_6 v^2 &= -s_{2\beta}\left\{(m_Z^2 - \tfrac{1}{2}\lambda^2 v^2)c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t + Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]\right\}.\end{aligned}$$

In contrast to the MSSM, in the NMSSM one can set $Z_6 = 0$ and obtain $m_h = 125$ GeV, with only small contributions from the one-loop radiative corrections. This leads to a preferred choice of NMSSM parameters,

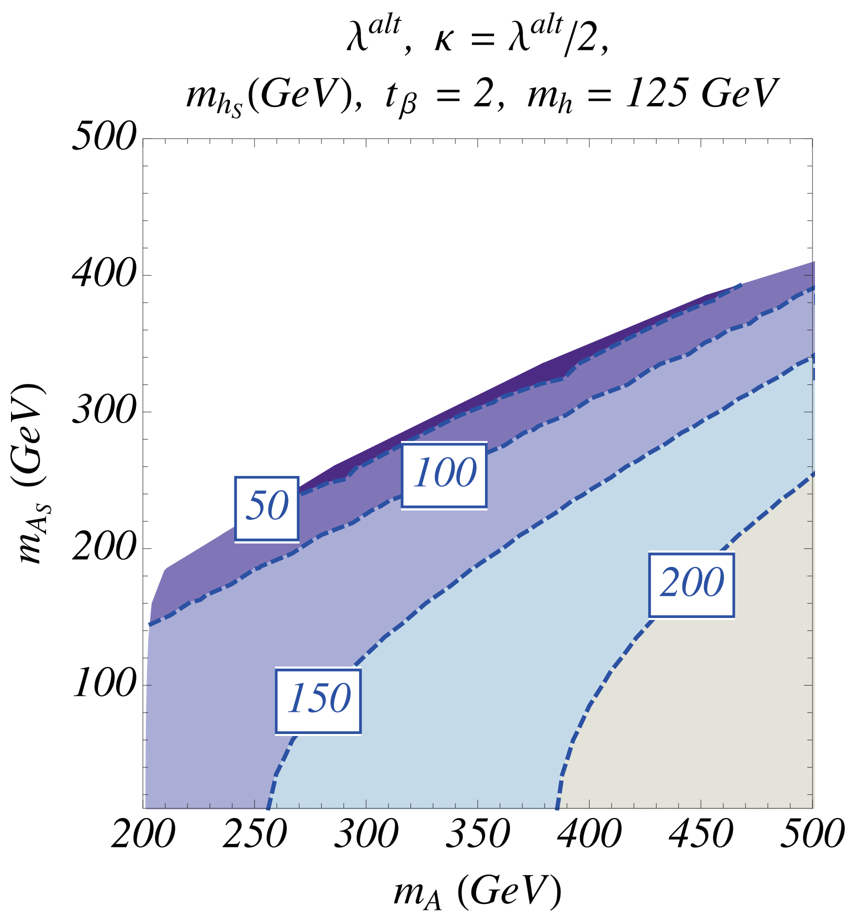
$$\lambda \sim 0.65\,, \qquad \tan\beta \sim 2$$



The exact alignment limit also requires that $\mathcal{M}^2_{13} = 0$. In the NMSSM,

$$\frac{\overline{M}_A^2 s_{2\beta}^2}{4\mu^2} + \frac{\kappa s_{2\beta}}{2\lambda} = 1 \ .$$

which lead to further correlations of the NMSSM parameter space. For example,



Near the alignment limit, we have $m_A \simeq m_H \simeq \overline{M}_A$.

Phenomenological Implications of the NMSSM Higgs sector

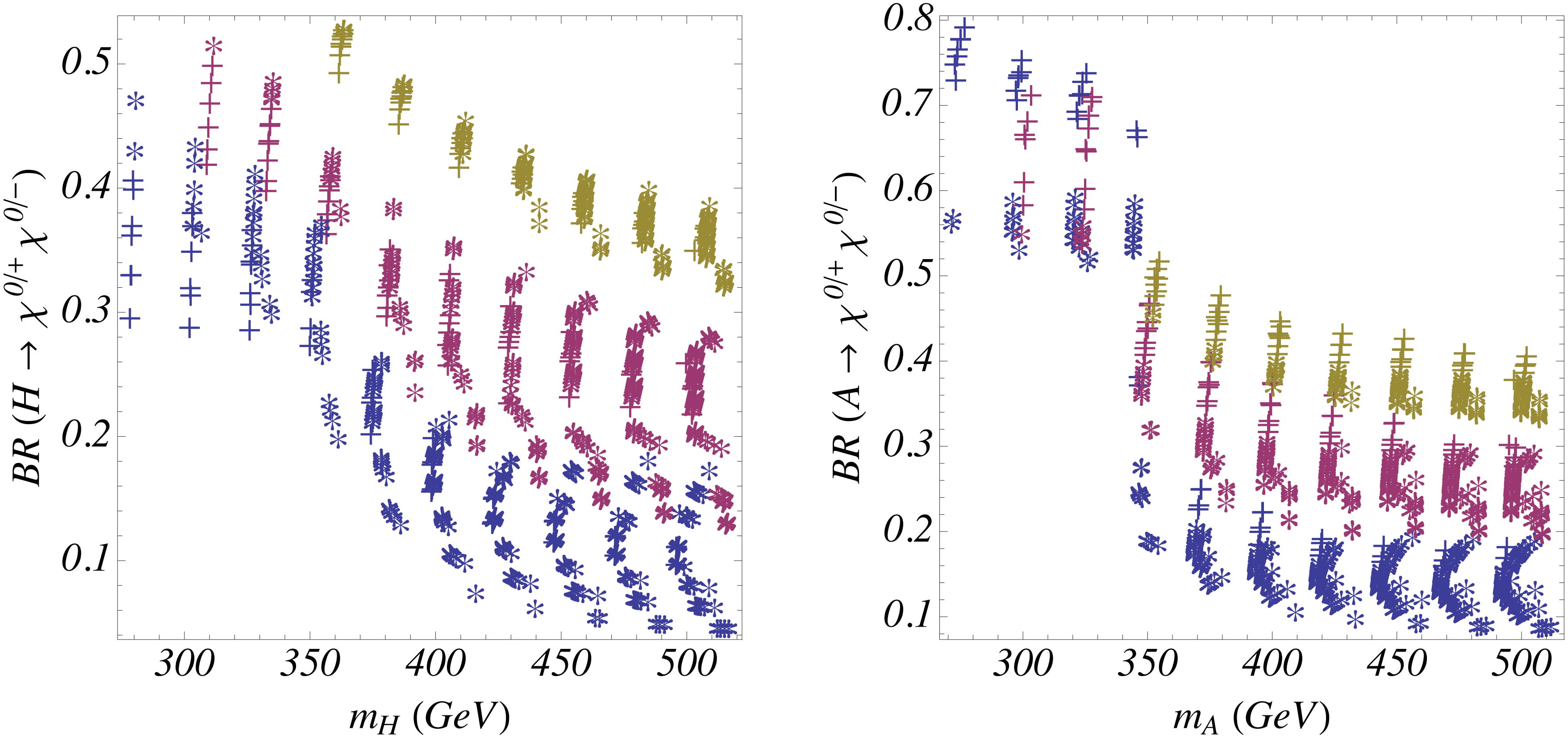
- Numerous $H \to HH$ and $H \to VH$ channels are kinematically allowed.

- The parameters μ and $\overline{M}_A$ are correlated by the alignment conditions.

- Typical values of $|\mu| \sim 100$–300 GeV yield chargino/neutralinos states that are approximately unmixed higgsino (with mass $\sim |\mu|$) and singlino (with mass $\sim 2|\kappa\mu/\lambda|$) states. Thus, we expect significant branching ratios of

$$H, A \to \widetilde{\chi}^+\widetilde{\chi}^- \,,\, \widetilde{\chi}_i^0\widetilde{\chi}_j^0 \,, \qquad\qquad H^\pm \to \widetilde{\chi}^\pm\widetilde{\chi}_i^0 \,.$$

- Imposing perturbativity up to the Planck scale implies that $\kappa \lesssim \frac{1}{2}\lambda$. Consequently, the singlino is the LSP (denoted as $\widetilde{\chi}_1^0$). A potential decay mode of the neutral higgsino is $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 + h$.



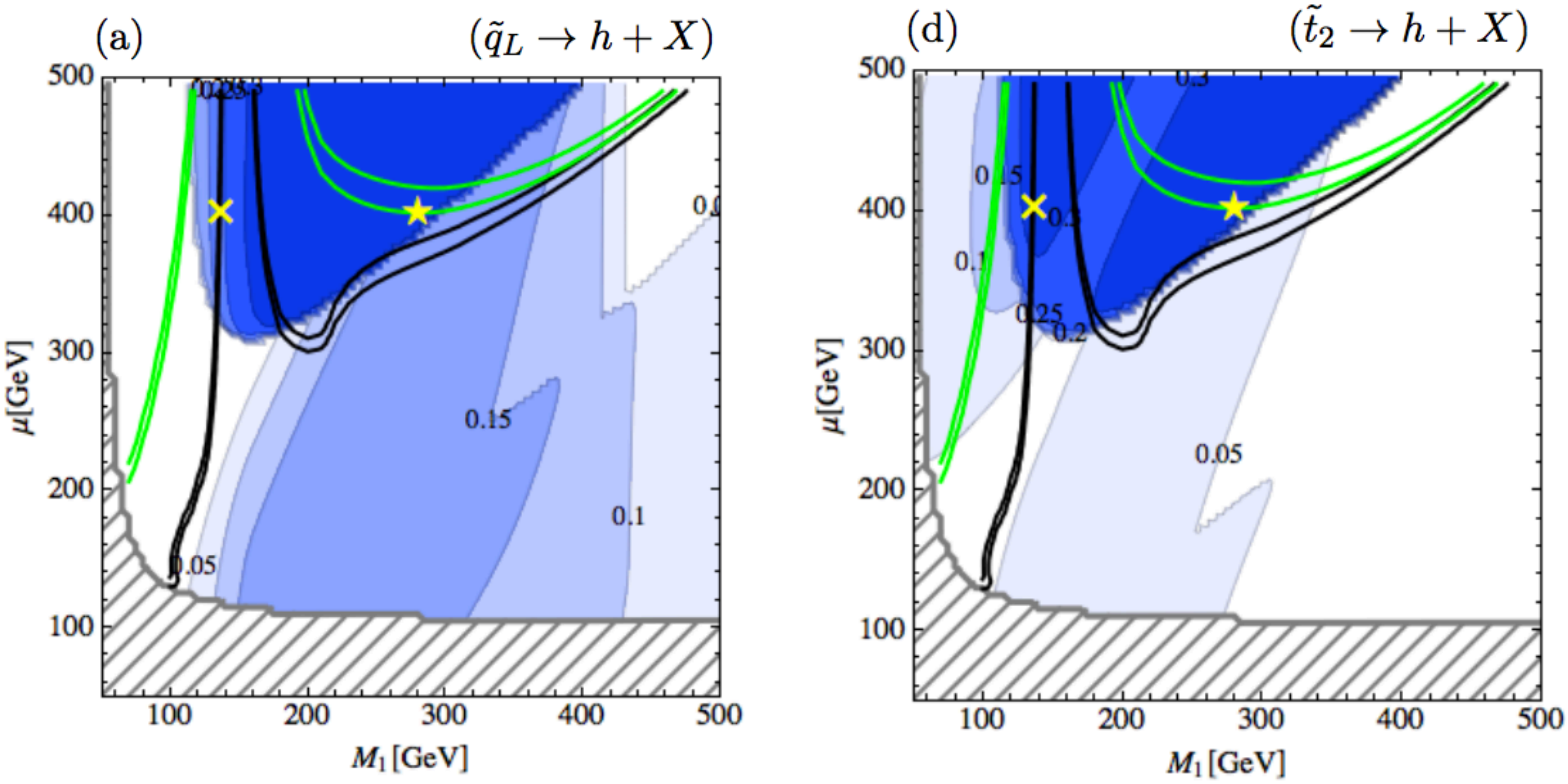
Branching ratio of the decay of the heaviest CP-even (left panel) and CP-odd (right panel) Higgs bosons into charginos and neutralinos. Blue, red and yellow represent values of $\tan\beta = 2$, 2.5 and 3, respectively, $\lambda = 0.65$, and and other NMSSM parameters (κ, A_κ, A_λ and v_s) are scanned subject to the alignment conditions.

Some thoughts on SUSY searches with Higgs in cascades

squarks→ Higgs+X

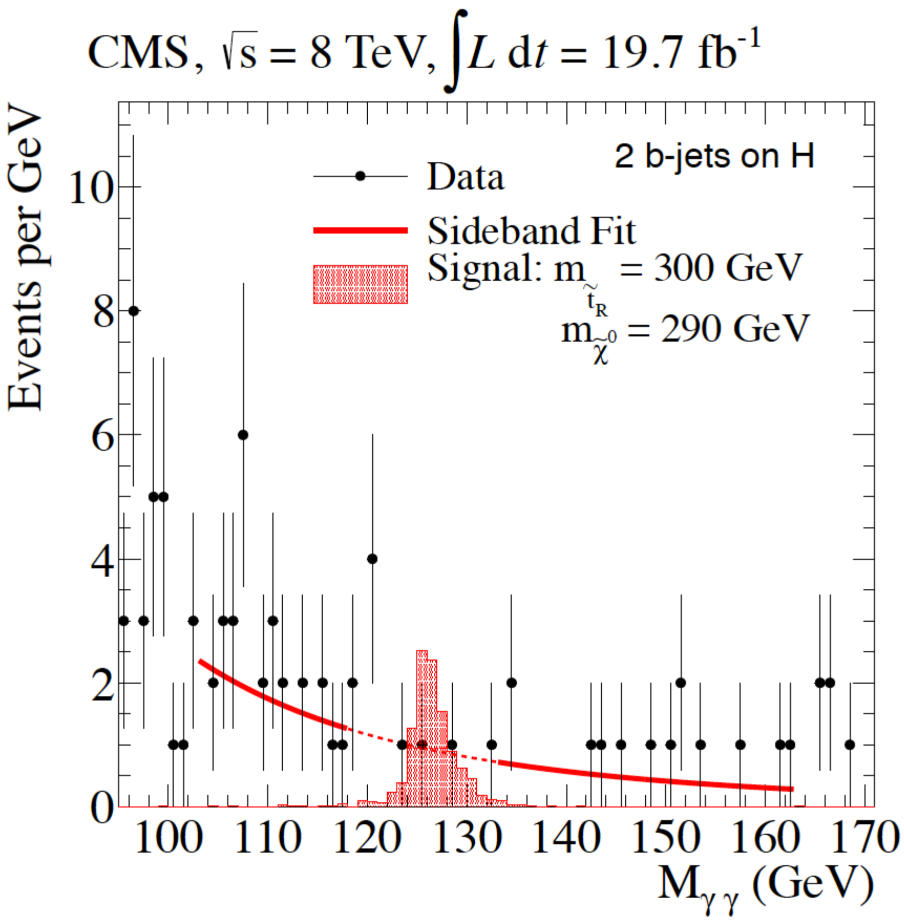
- Model dependent, but BR(squark→h+X) around 25% is fairly common

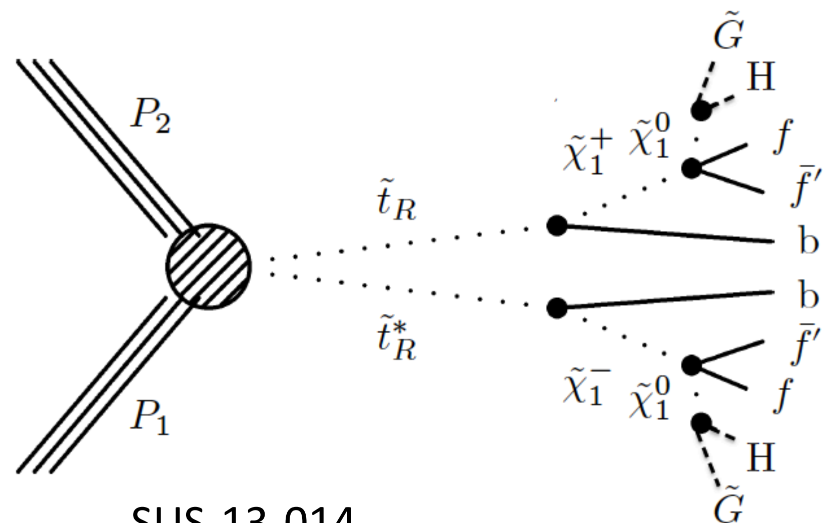
1103.4138
Gori et al.



Higgs in SUSY cascades: H→γγ

- Add Higgs tag to jets + MET search

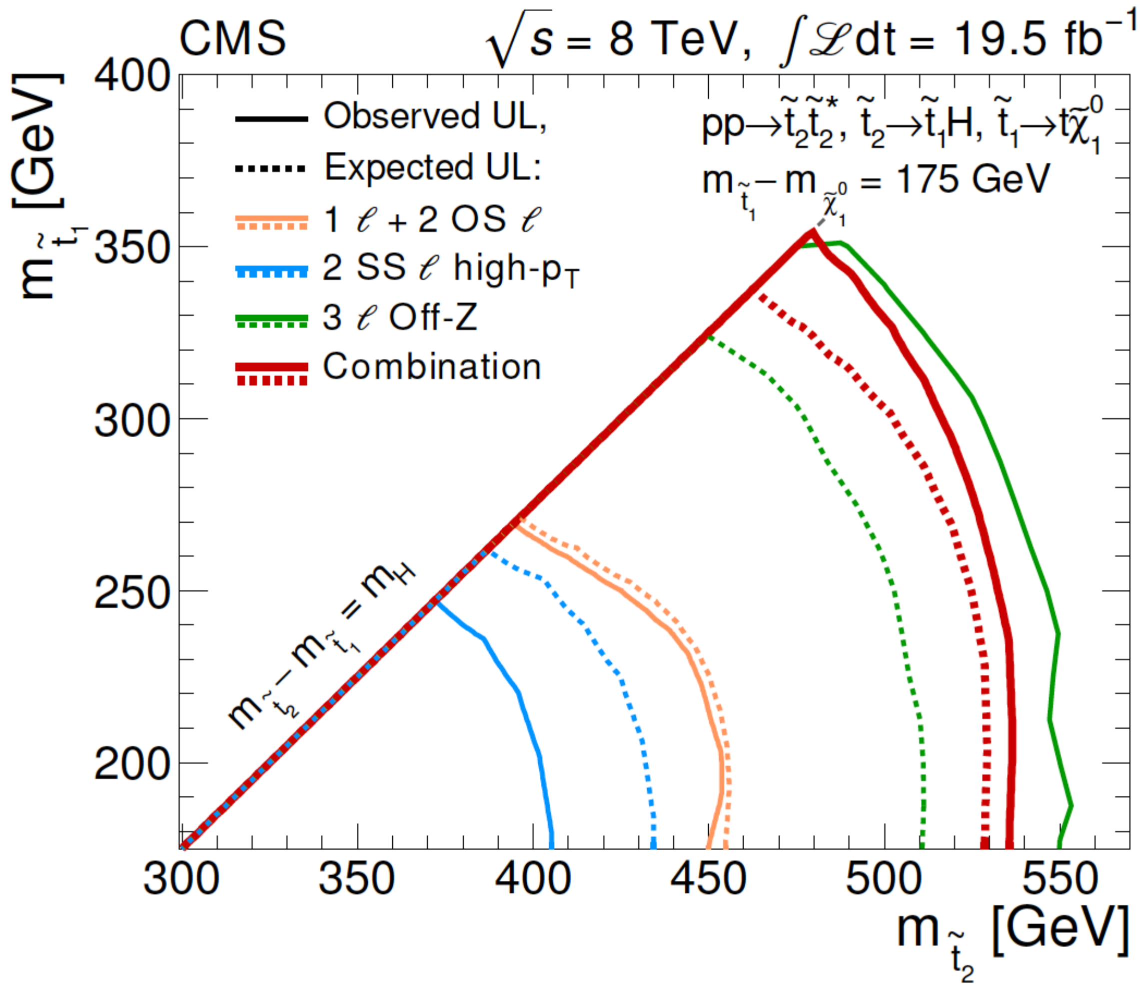


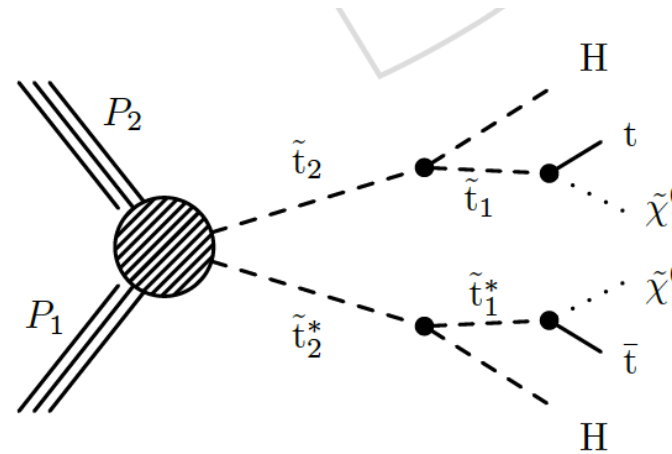


SUS-13-014

Higgs in SUSY cascades: H→leptons

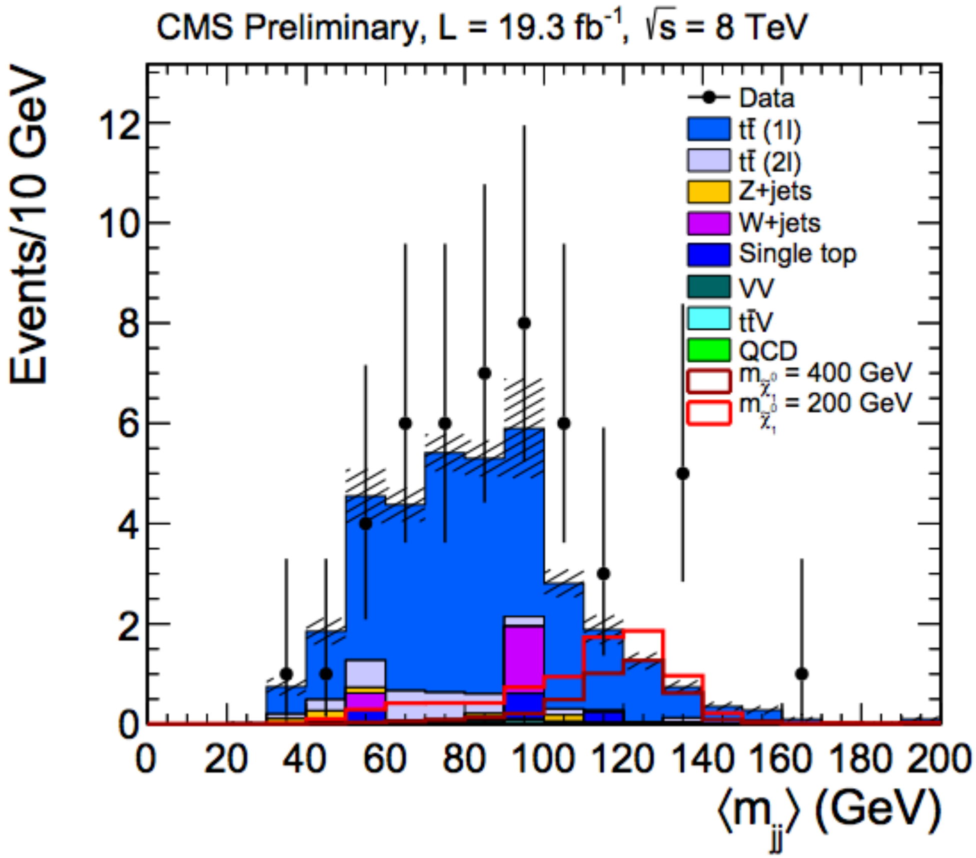
- Multi-lepton + b reinterpretation also catches a lot of Higgs signatures

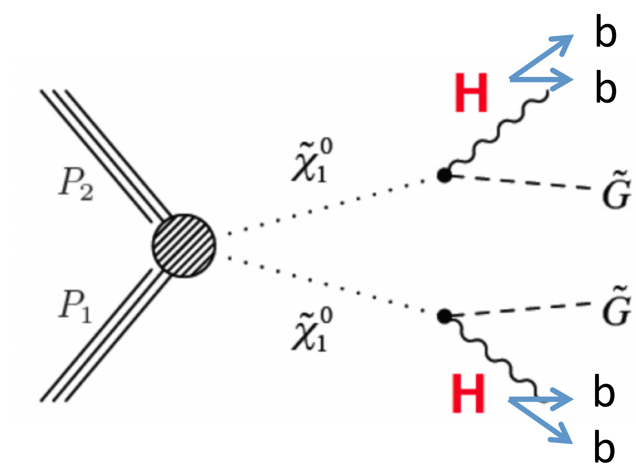




SUS-13-024

Higgs in SUSY cascades: H→bb



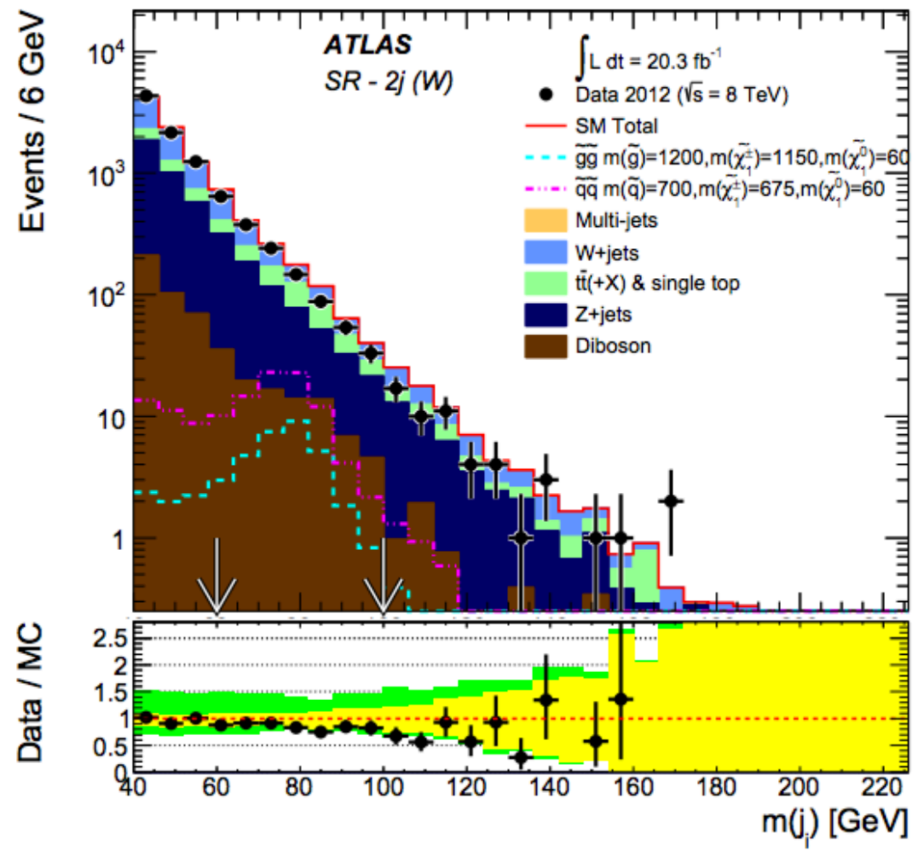


SUS-13-022

Boosted H→bb

- For $p_T >> m_H$ merged jets can help
- More broadly utilized in exotic searches for now

1405.7875



Charged Higgs in cascades

- Many possibilities for charged Higgs production along with jets and MET

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \;\to\; \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X$$
$$\to\; \chi_1^{\pm}, \chi_2^0, \chi_1^0 + H^{\pm} \;+ X$$

$$\tilde{Q} \to \tilde{Q}' H^{\pm} \;\text{ with }\; \tilde{Q}, \tilde{Q}' = \tilde{t}, \tilde{b}$$

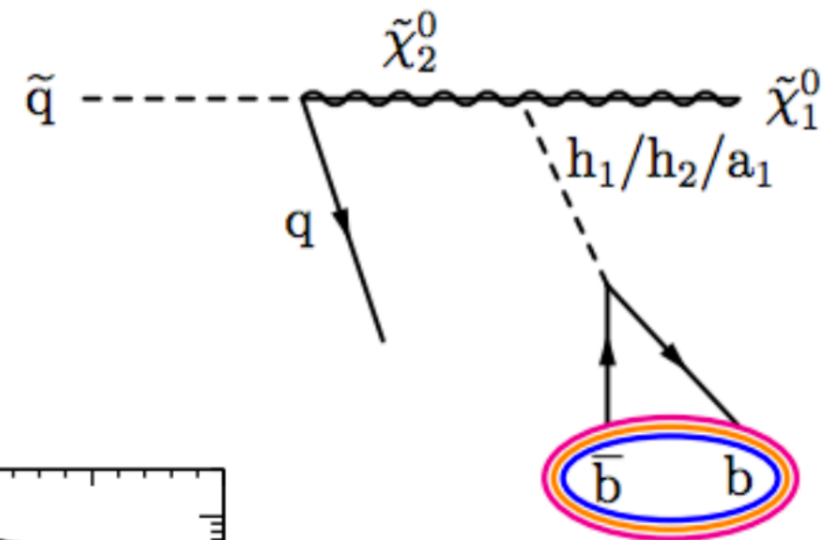
$$\tilde{g} \to Q' \tilde{Q} H^{\pm} \;\text{ with }\; \tilde{Q} = \tilde{t}, \tilde{b}$$

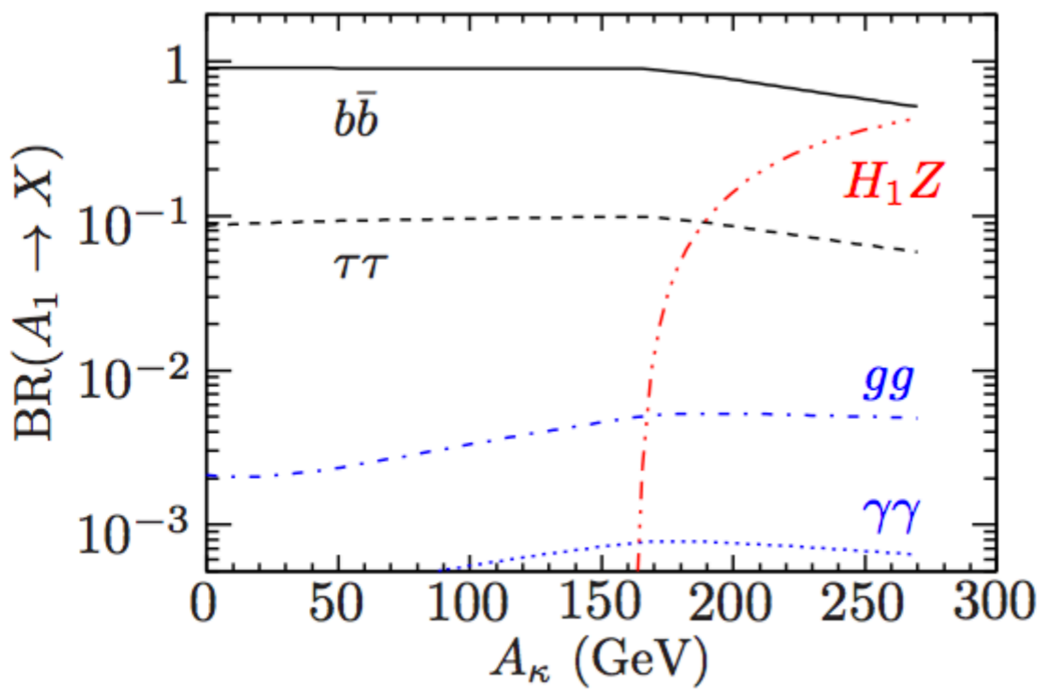
0107271
Datta et al

- Also mentioned by JiJi yesterday

NMSSM singlets in cascades

- Could utilize resonant structure as additional handle in jets + MET (+ lepton) events

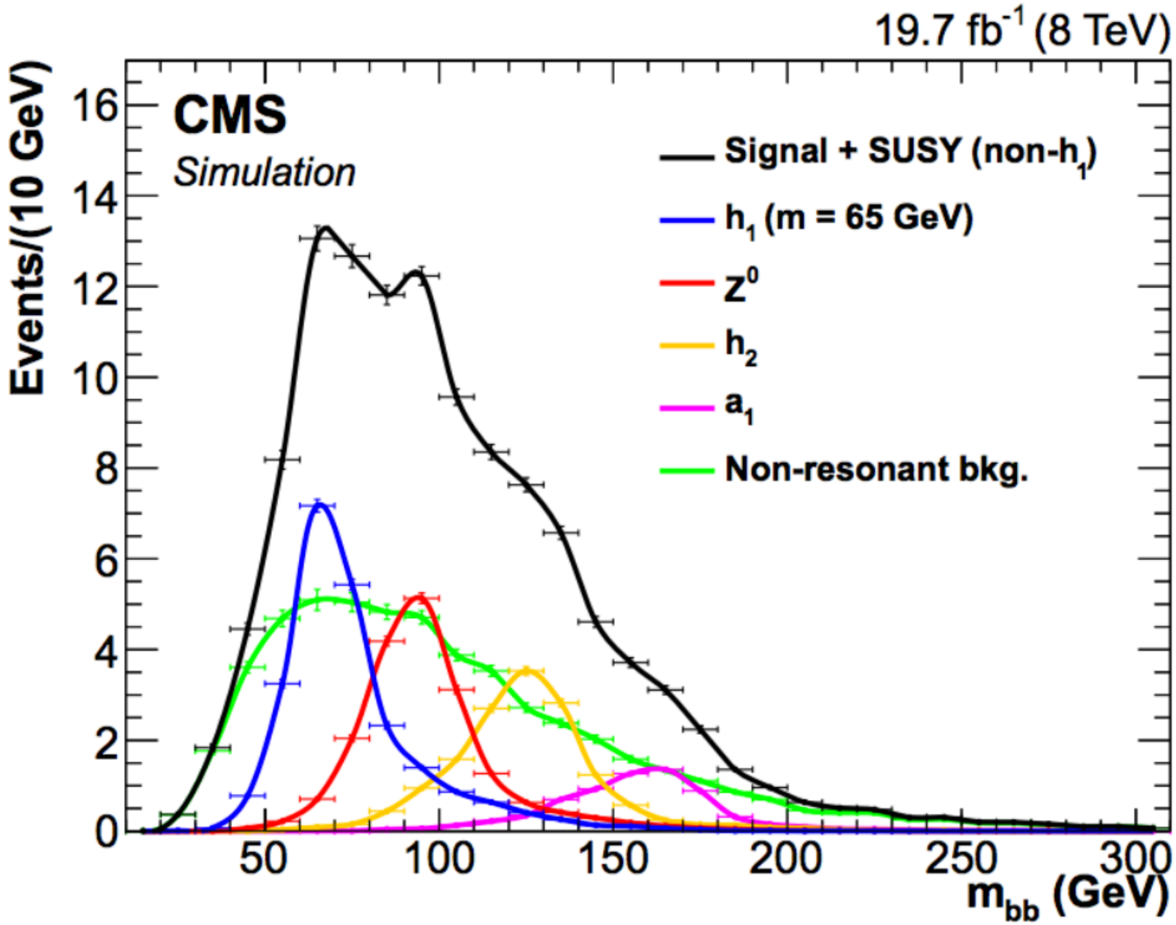




1108.0595
Stal, Weiglein

NMSSM Singlets in cascades

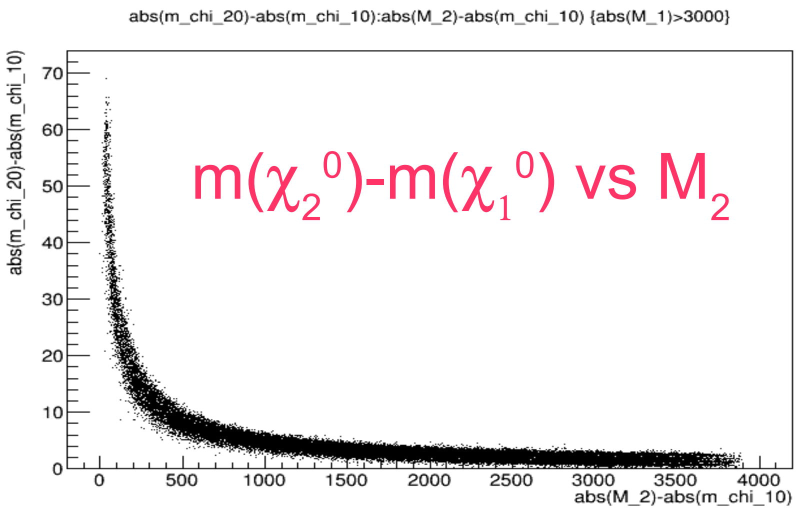
- Jets + MET + h_1(bb) search HIG-14-030



Higgsino LSP

Higgsino LSP

- If LSP is pure Higgsino, will be very difficult to observe as mass splitting between Higgsino states O(350 MeV)
  - Not long-lived enough to see chargino and too soft decay
- If M_1 or M_2 is O(TeV) mass splitting can be larger and possible can see ISR+soft ℓ
- Last week showed splitting in ATLAS pMSSM models
  - See backup slides

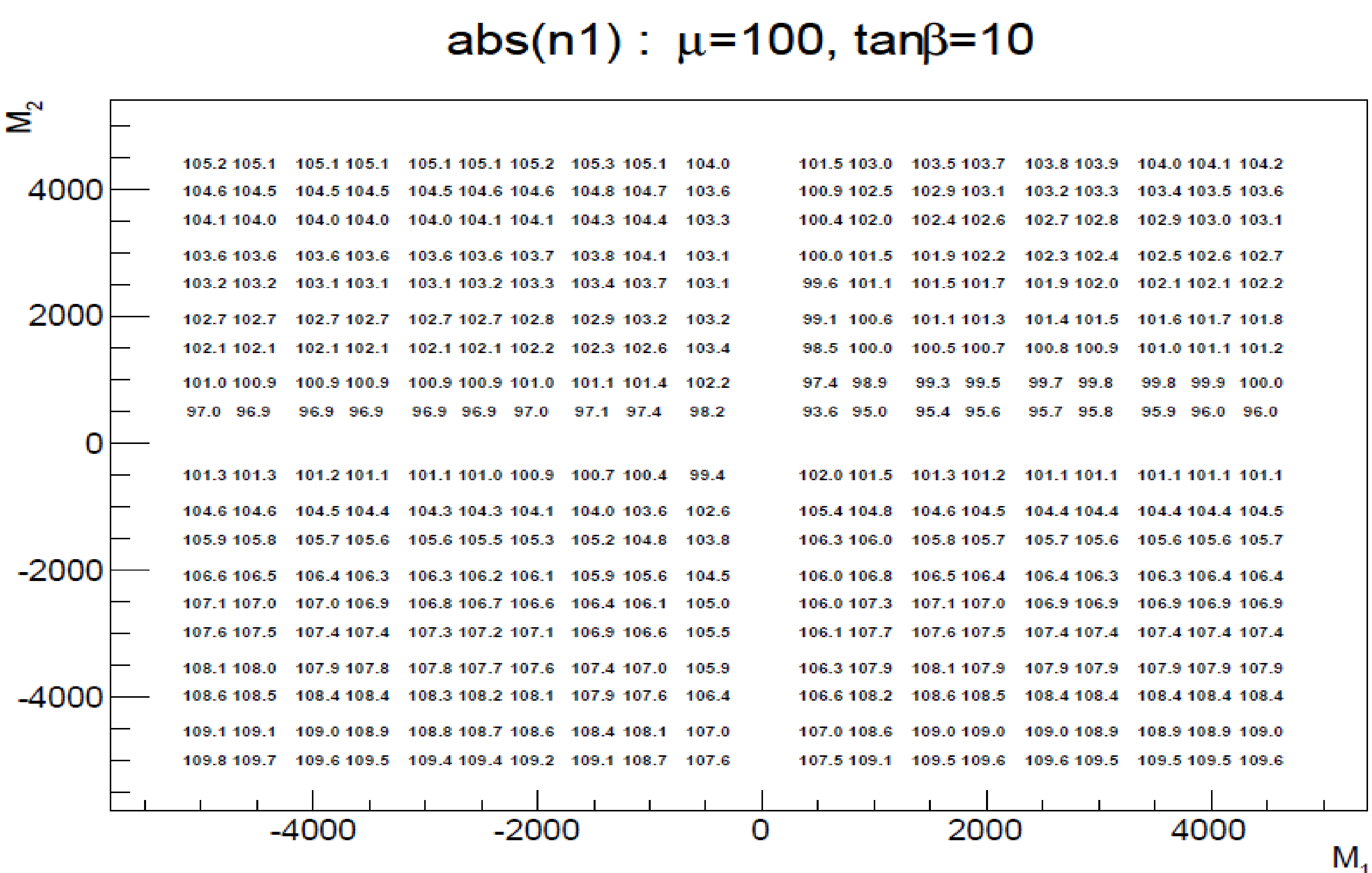


- Now did a bit more systematic scan for LSP~100 GeV
  - Trying to determine most relevant mass splittings/decays
  - Use spectrum generator rather than reverting mass matrix:

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

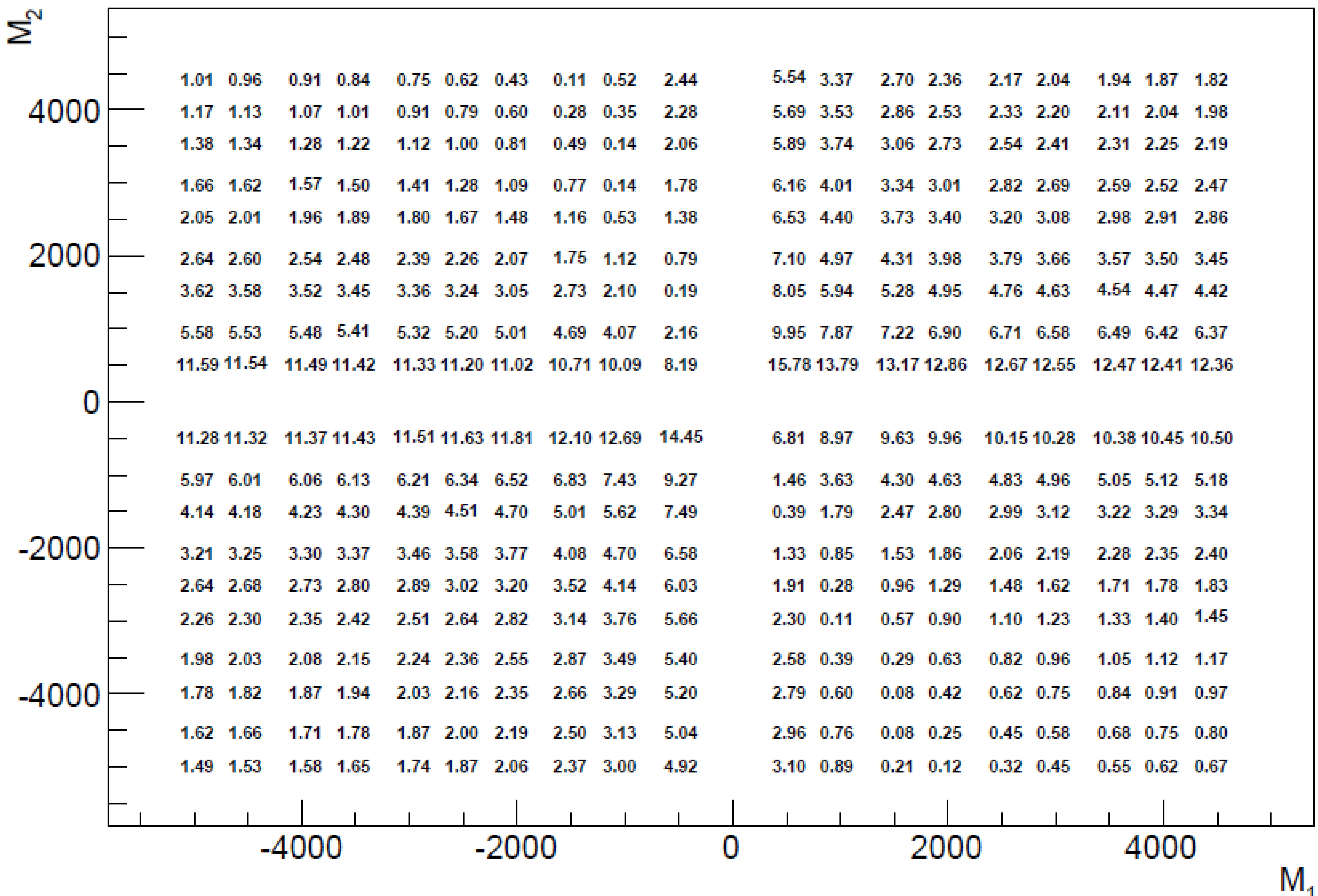
Scan

- Use Spheno-3.3.8 to calculate masses and decays
  - Cross-checked mass splittings against SoftSUSY-3.7.1
- Set $\mu=\pm100$ GeV, $\tan\beta=10,20,30,40,50$ and scan $M_1=-4000:4000$ GeV and $M_2=-4000:4000$ GeV
  - All other parameters at 5 TeV

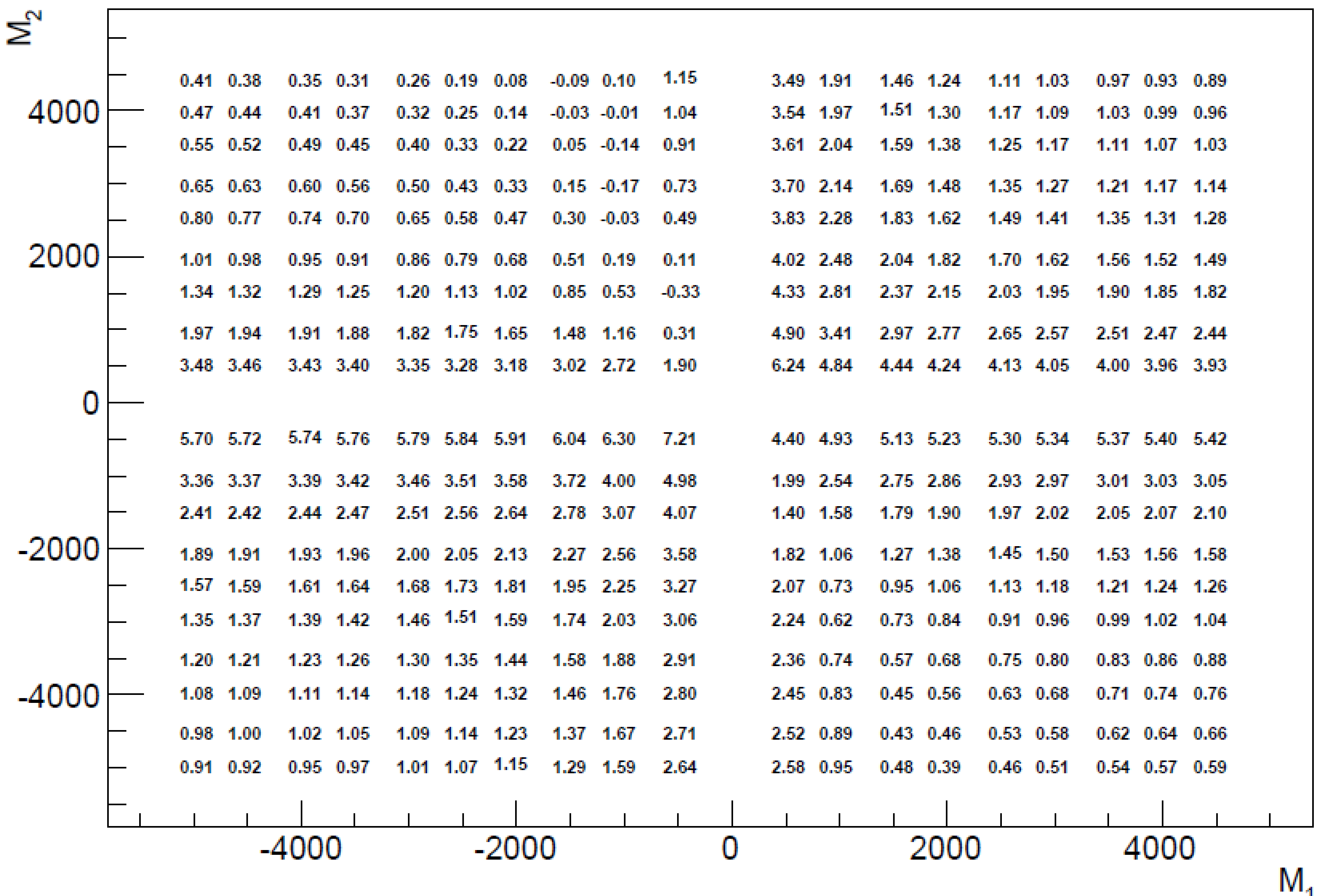


Some, but not large dependence on sign(μ) and $\tan\beta$

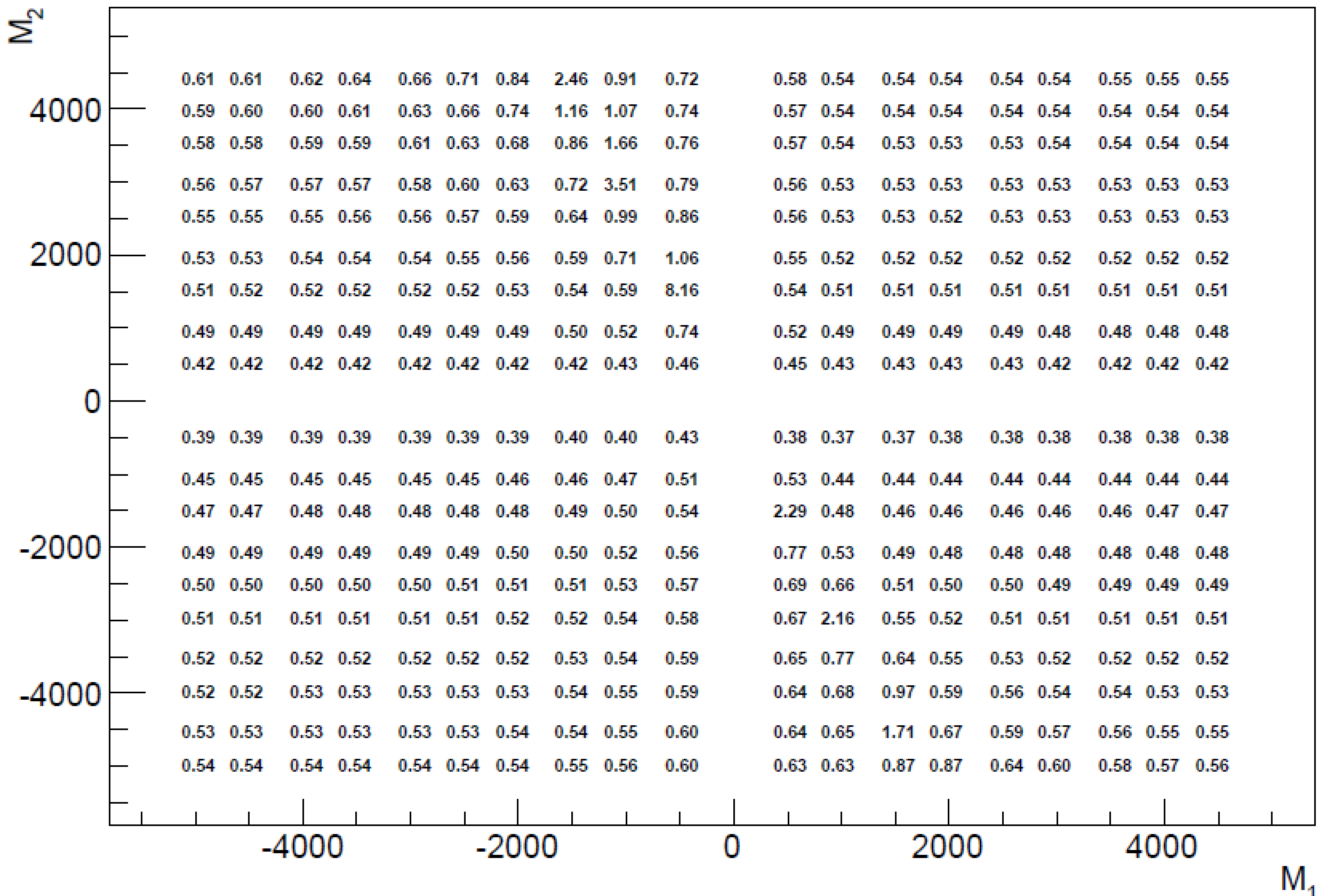
$m(\chi_2^0)-m(\chi_1^0)$ [GeV]



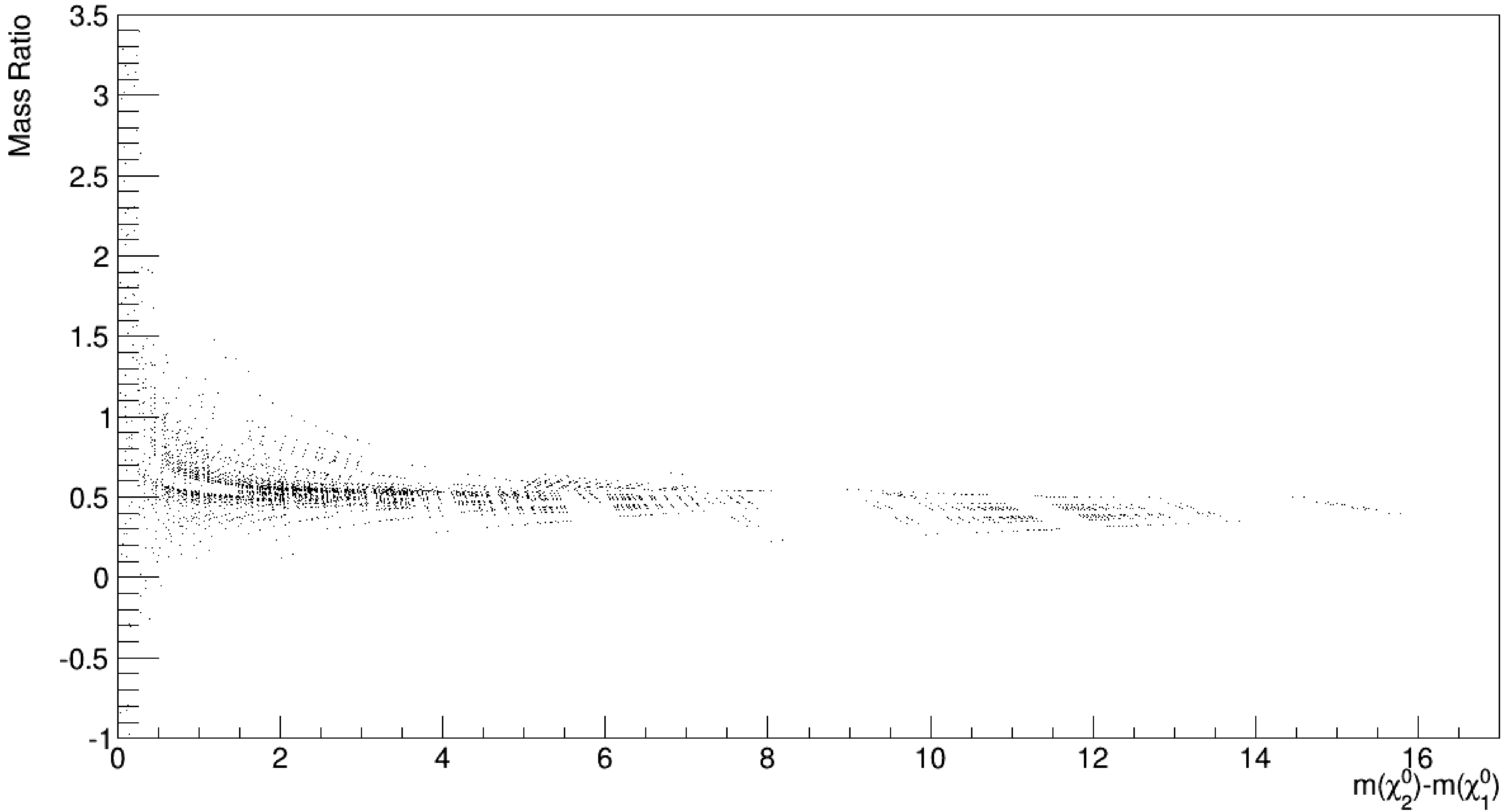
$m(\chi_1^+)-m(\chi_1^0)$ [GeV]



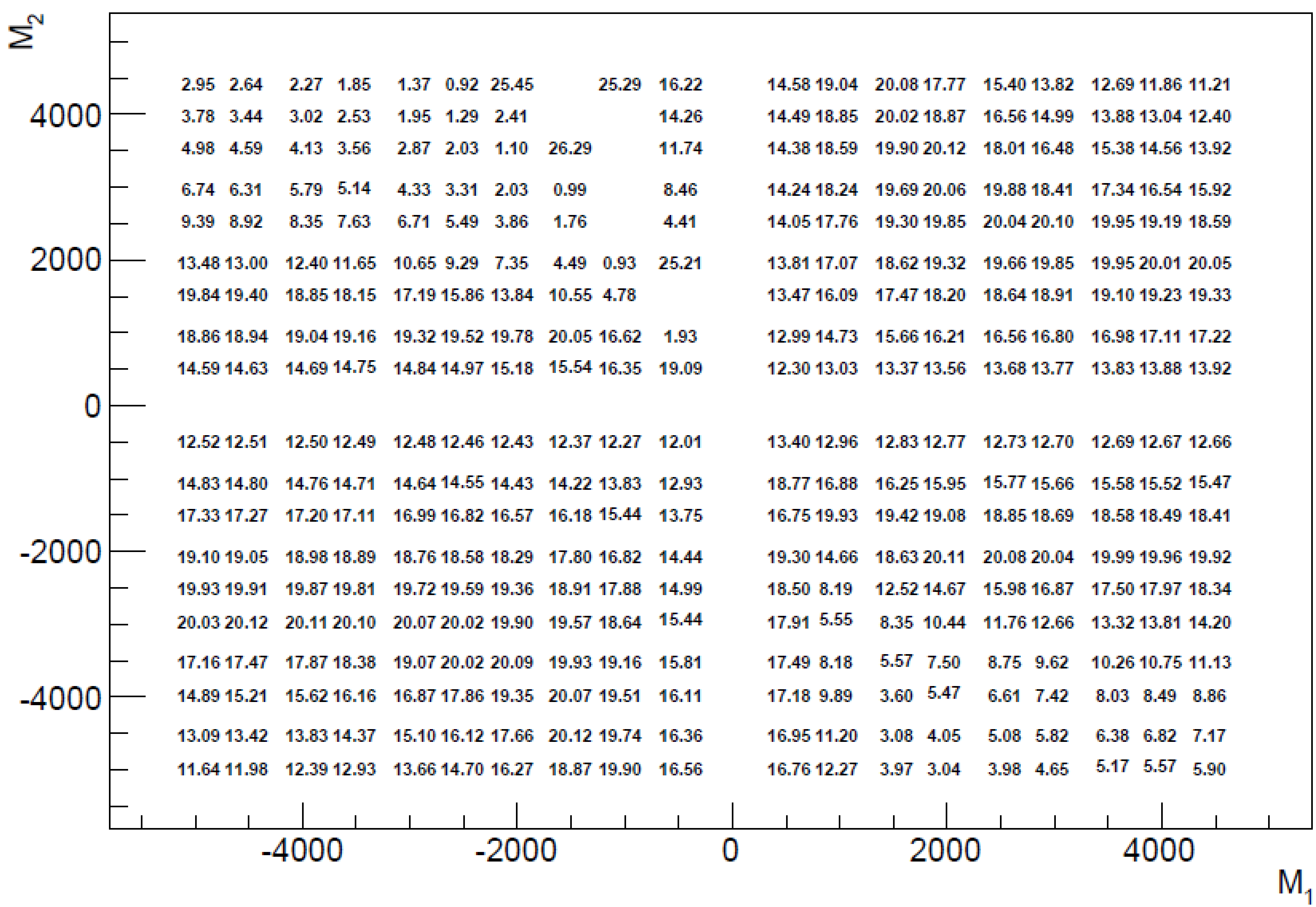
$(m(\chi_1^+)-m(\chi_1^0))/(m(\chi_2^0)-m(\chi_1^0))$



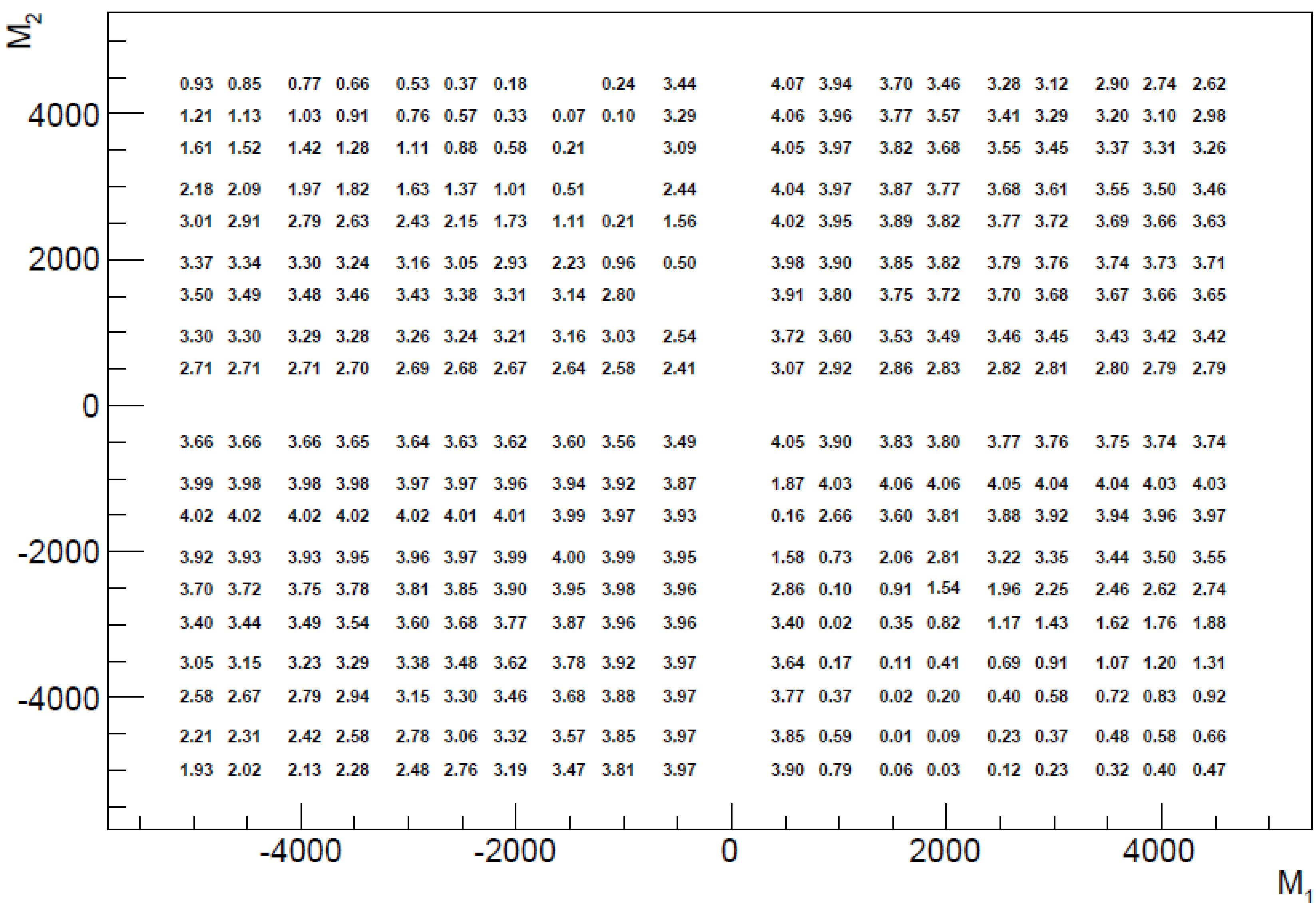
Mass Ratio vs χ_2^0



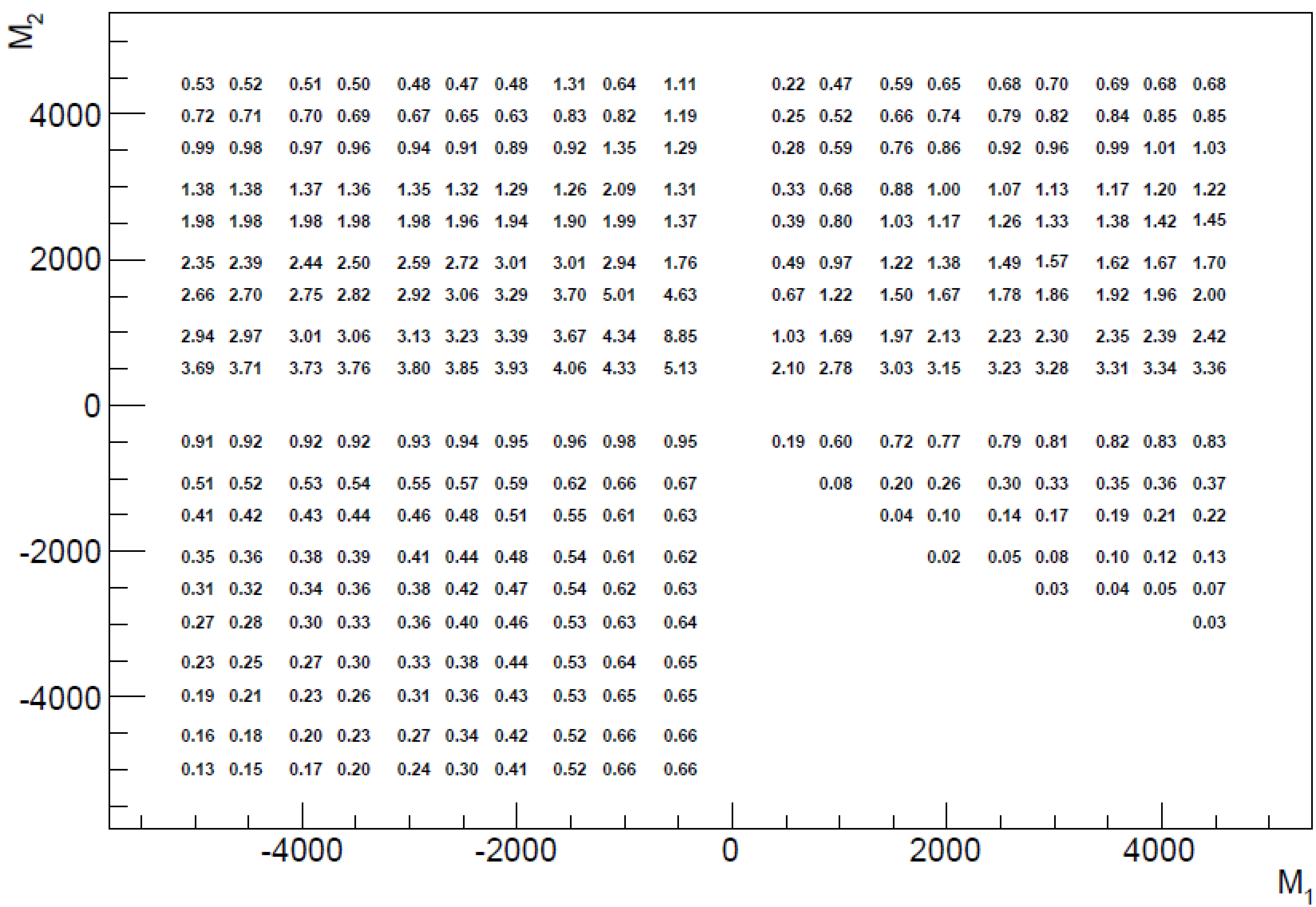
BF($\chi_1^+ \to e^+ \nu \chi_1^0$) [%]



BF($\chi_2^0 \to e^+e^-\chi_1^0$) [%]



BF($\chi_2^0 \to e^{+-}\nu\chi_1^{-+}$) [%]

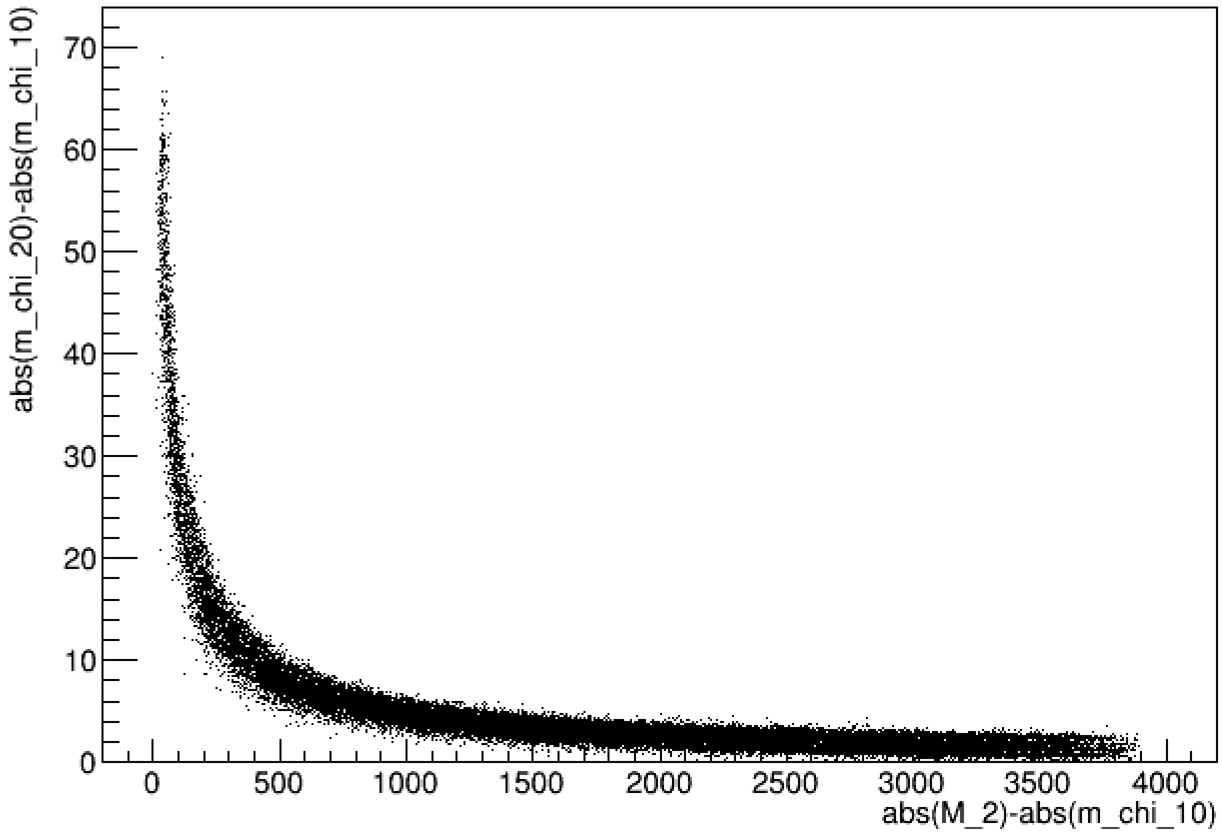


Backup

pMSSM scan

- ATLAS did scan over 19-parameter pMSSM in Run-1
  - Published in JHEP 10 (2015) 134 [arXiv:1508.06608]
- About 300k pMSSM models generated after pre-LHC SUSY constraints (see backup for details)
  - Generation done by T. Rizzo, M. Cahill-Rowley, J. Hewett and A Ismail
  - Use SoftSUSY 3.4.0 for spectrum generation
  - SUSY-HIT 1.3 for SUSY decays with some corrections
- About 40% of the models excluded by ATLAS Run-1
- All models and whether they are excluded available on HEPDATA: http://hepdata.cedar.ac.uk/view/ins1389857
- Used these to look at typical Higgsino mass splittings and decays when LSP is predominantly Higgsino-like

$m(\chi_2^0)$-$m(\chi_1^0)$ for M_1>3000 GeV

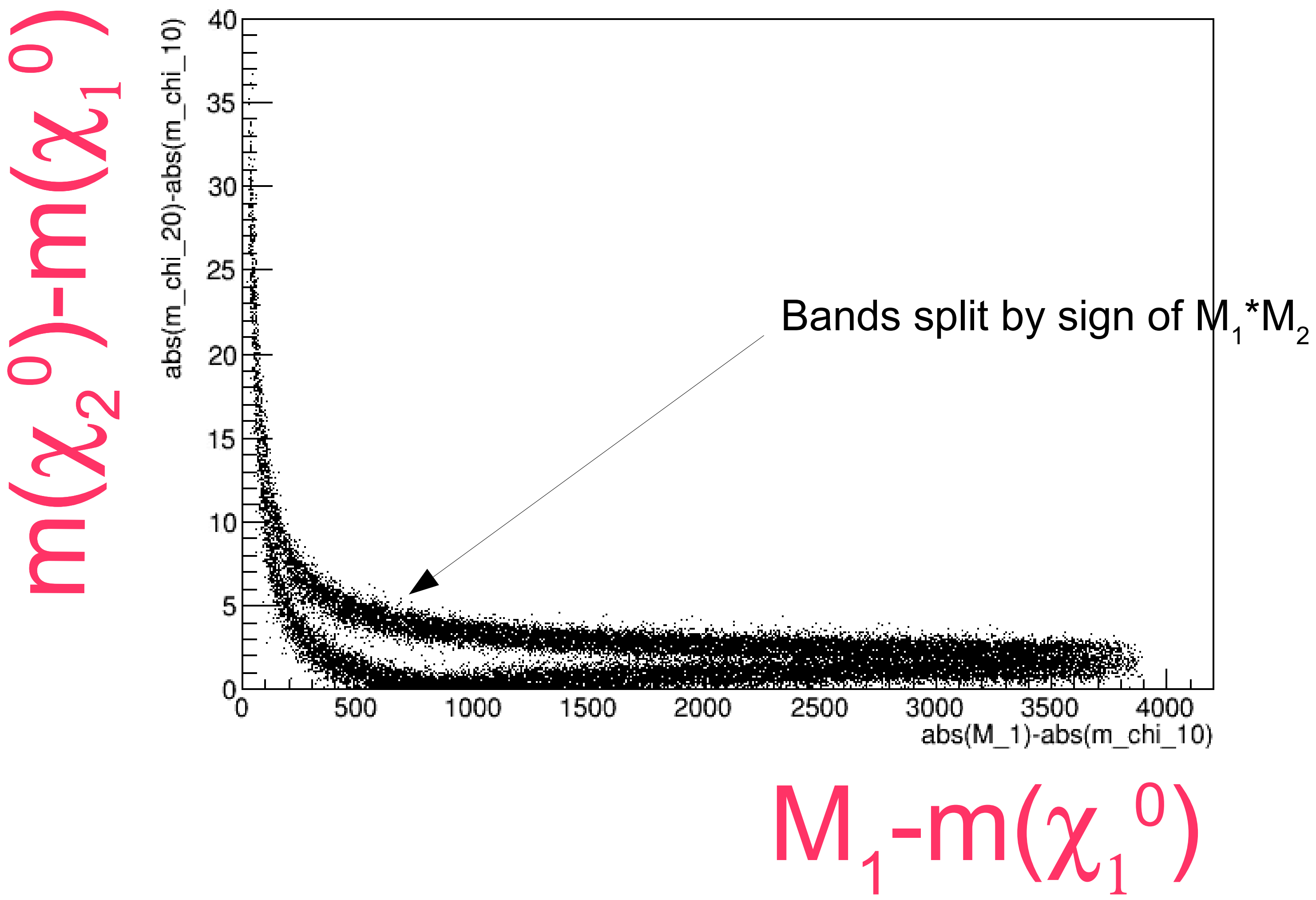


$m(\chi_2^0)$-$m(\chi_1^0)$

M_2-$m(\chi_1^0)$

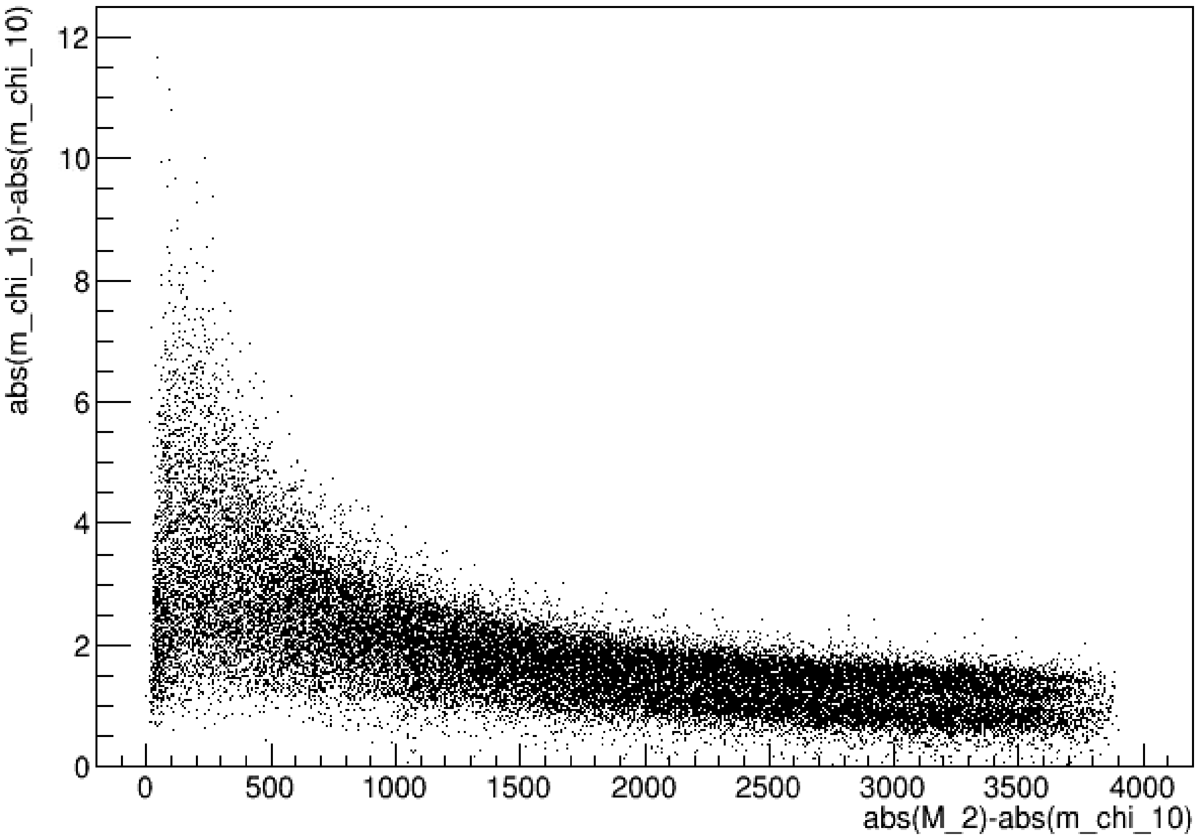
Note:
Looking at all models, not just the non-excluded ones

$m(\chi_2^0)-m(\chi_1^0)$ for $M_2>3000$ GeV



$m(\chi_1^+)-m(\chi_1^0)$ for M_1>3000 GeV

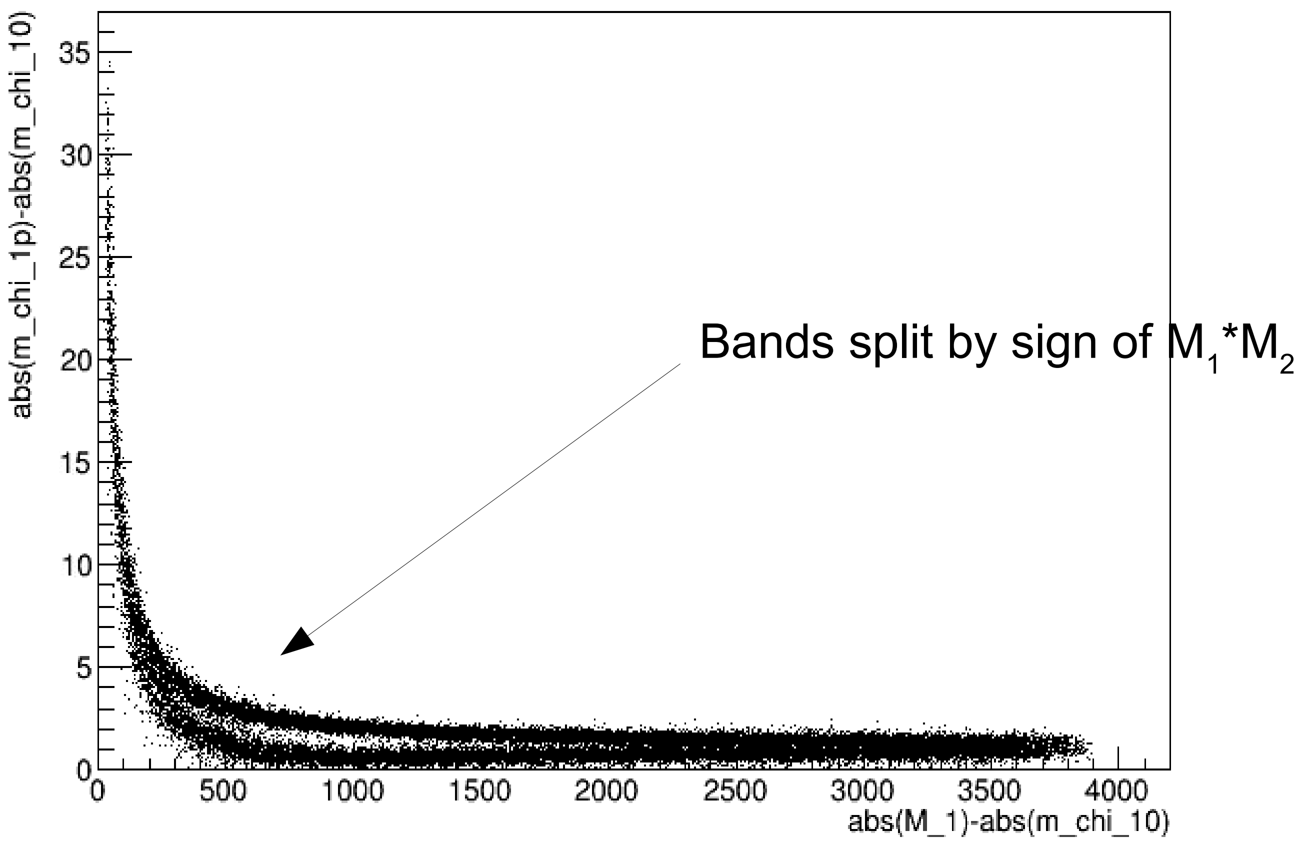
$m(\chi_1^+)-m(\chi_1^0)$



$M_2-m(\chi_1^0)$

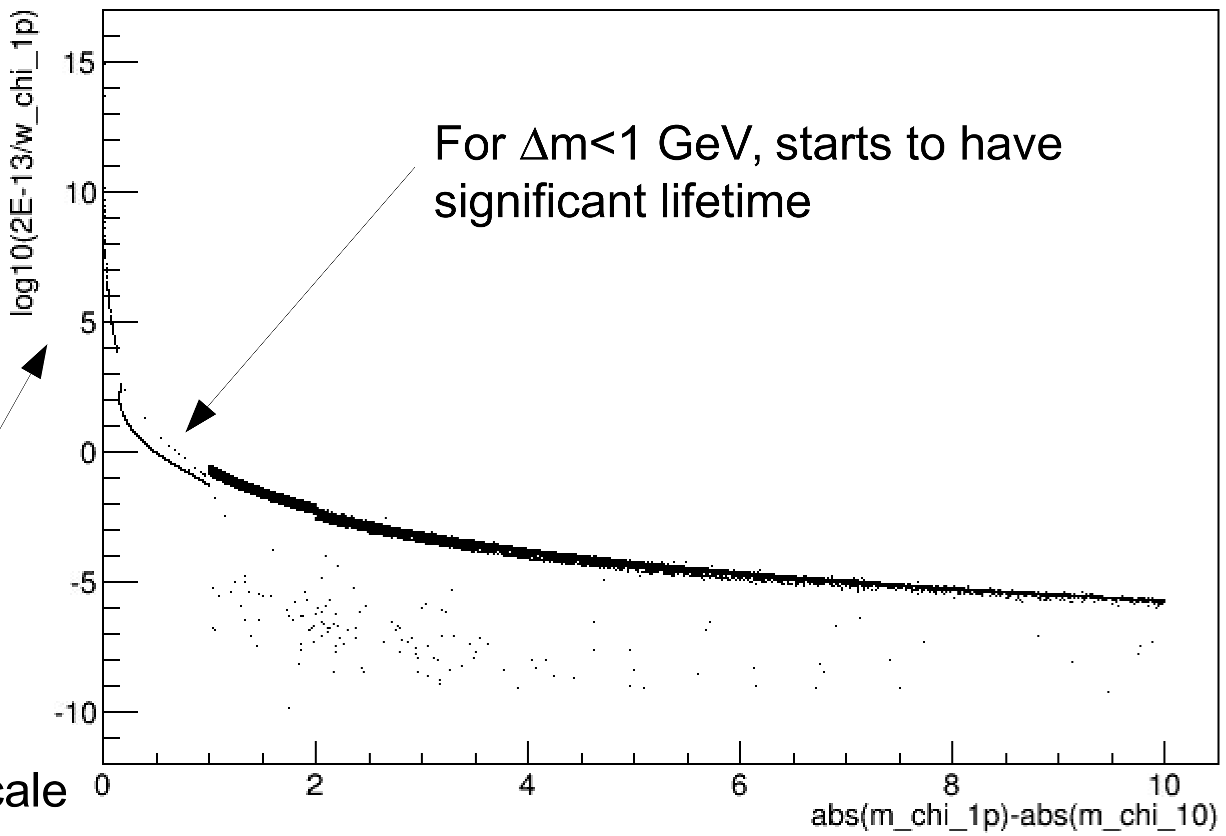
$m(\chi_1^+)-m(\chi_1^0)$ for $M_2>3000$ GeV

$m(\chi_1^+)-m(\chi_1^0)$



$M_1-m(\chi_1^0)$

$c\tau$ for χ_1^+



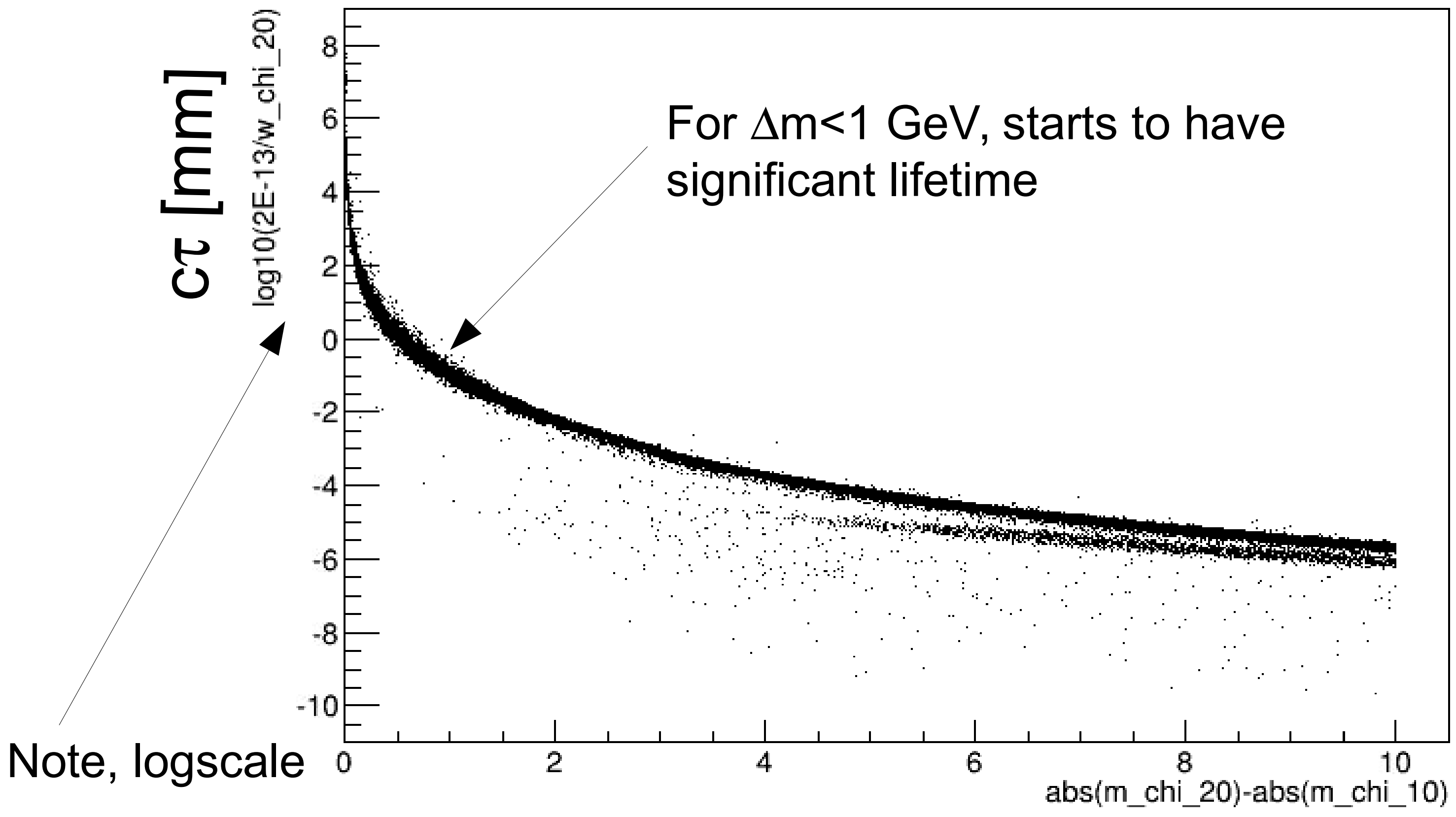
$c\tau$ [mm]

For Δm<1 GeV, starts to have significant lifetime

Note, logscale

$m(\chi_1^+)-m(\chi_1^0)$

$c\tau$ for χ_2^0

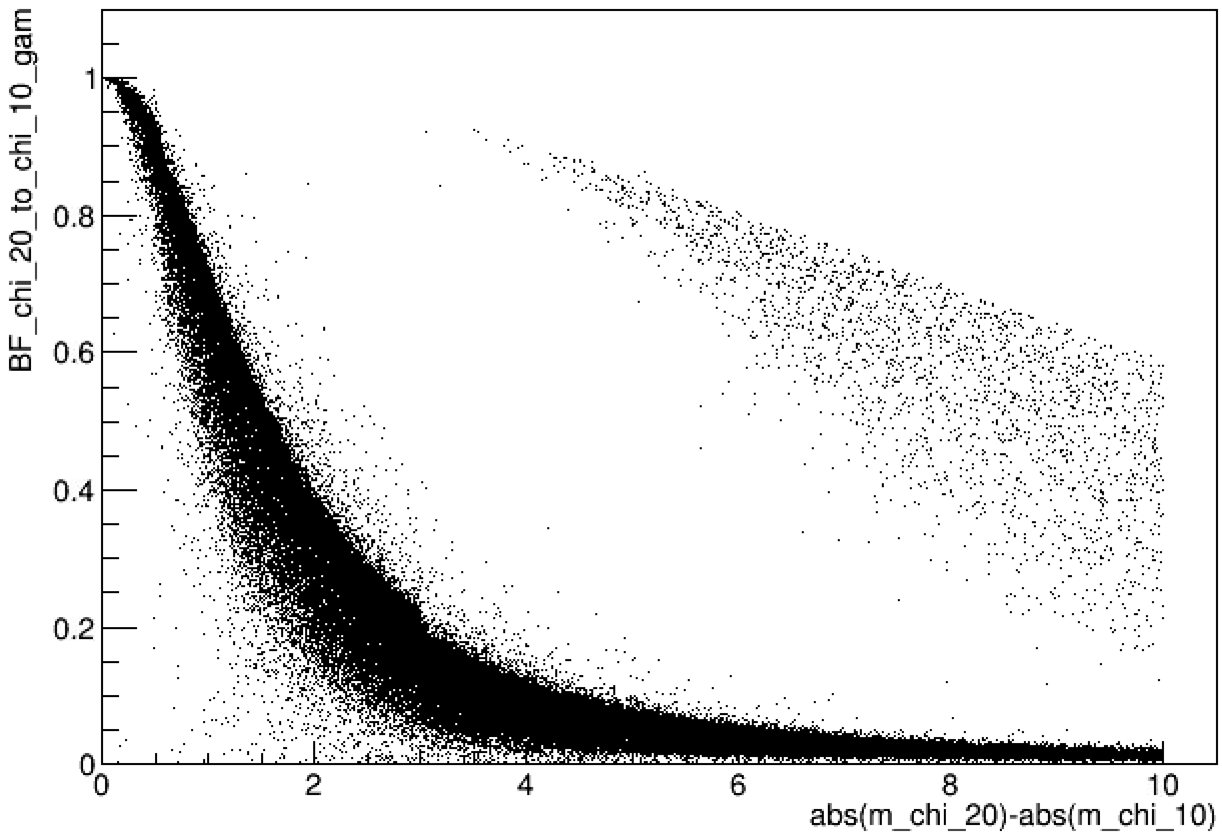


$m(\chi_2^0)-m(\chi_1^0)$

Decays of χ_2^0

For low Δm, χ_2^0 also mainly decays through γ instead of Z^* (so no leptons)

$BF(\chi_2^0 \rightarrow \chi_1^0 + \gamma)$



$m(\chi_2^0)-m(\chi_1^0)$

pMSSM Scan Parameters

- Using a 19 parameter pMSSM as basis model
  - No CP violating parameters
  - Minimal flavor violation
  - Degenerate 1st and 2nd generations sfermions
  - Lightest sparticle (LSP) is a neutralino
  - R-parity is exactly conserved (LSP is stable)

Flavor physics constraints

- Sample parameters uniformly over wide range (up to 4TeV)

Higgs sector parameters:

$1 < \tan\beta < 60$

$0.1 \text{ TeV} < M_A < 4 \text{ TeV}$

Neutralino/chargino mass parameters:

$-4 \text{ TeV} < \mu < 4 \text{ TeV}$, $|\mu|>80 \text{ GeV}$

$-4 \text{ TeV} < M_1 < 4 \text{ TeV}$

$-4 \text{ TeV} < M_2 < 4 \text{ TeV}$, $|M_2|>70 \text{ GeV}$

Slepton mass parameters:

$0.09 \text{ TeV} < m_{eL}=m_{\mu L} < 4 \text{ TeV}$

$0.09 \text{ TeV} < m_{eR}=m_{\mu R} < 4 \text{ TeV}$

$0.09 \text{ TeV} < m_{\tau L} < 4 \text{ TeV}$

$0.09 \text{ TeV} < m_{\tau R} < 4 \text{ TeV}$

Squark/gluino mass parameters:

$0.2 \text{ TeV} < M_3 < 4 \text{ TeV}$

$0.2 \text{ TeV} < m_{q1L}=m_{q2L} < 4 \text{ TeV}$

$0.2 \text{ TeV} < m_{uR}=m_{cR} < 4 \text{ TeV}$

$0.2 \text{ TeV} < m_{dR}=m_{sR} < 4 \text{ TeV}$

$0.1 \text{ TeV} < m_{q3L} < 4 \text{ TeV}$

$0.1 \text{ TeV} < m_{tR} < 4 \text{ TeV}$

$0.1 \text{ TeV} < m_{bR} < 4 \text{ TeV}$

Trilinear coupling parameters:

$-4 \text{ TeV} < A_b < 4 \text{ TeV}$

$-8 \text{ TeV} < A_t < 8 \text{ TeV}$

$-4 \text{ TeV} < A_\tau < 4 \text{ TeV}$

Non-ATLAS Search Constraints

- For each point evaluate whether it is a "viable" model
  - Model has to be theoretically "sound"
  - Model should not already be excluded by other measurements

Low energy constraints:

$g_\mu - 2$	$[-1.77 : 4.38] \times 10^{-9}$	±3σ union of theory and exp. meas.
$BF(b \to s\gamma)$	$[0.269 : 0.387] \times 10^{-3}$	±2σ union of theory and exp. meas.
$BF(B_s \to \mu\mu)$	$[1.6 : 4.2] \times 10^{-9}$	±2σ union of theory and exp. meas.
$BF(B^+ \to \tau\nu_\tau)$	$[64 : 161] \times 10^{-6}$	±2σ union of theory and exp. meas.

LEP constraints:

$\Gamma_{invis.}(Z)$	< 2 MeV	Invisible width in addition to neutrinos
$\Delta\rho$	$[-0.0005 : 0.0017]$	
Charged sparticles	> 100 GeV	Raised to 103 GeV for $\tilde{\chi}_1^+$ in most cases

Higgs mass constraints:

$m(h)$	124–128 GeV	Higgs mass range was set at end of 2013 Uncertainty is set by theory prediction

Dark matter constraints:

Relic density	$\Omega h^2 < 0.1221$
Direct SI	$< 4\times$ LUX
Direct SD, p	$< 4\times$ COUPP
Direct SD, n	$< 4\times$ Xenon

Relic dark matter density from Planck
only used as upper limit (use +2σ)
Allow other DM component than LSP

For direct detection use factor 4 looser limit
to account for nuclear form factor uncertainties
(also scale down by LSP relic density/DM density)

Sampling by LSP Type

- In total 500 million model points were generated and 311,209 viable models selected

LSP type	Definition	Sampled	Simulated Number	Simulated Fraction	Weight
'Bino-like'	$N_{11}^2 > \max(N_{12}^2, N_{13}^2 + N_{14}^2)$	480×10^6	104,201	35%	$1/24$
'Wino-like'	$N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2)$	20×10^6	80,239	26%	1
'Higgsino-like'	$(N_{13}^2 + N_{14}^2) > \max(N_{11}^2, N_{12}^2)$		126,769	39%	1
Total		500×10^6	311,209		

- Models split by the dominant component of LSP
- Bino-like LSP suppressed by relic density constraint as most models have low annihilation cross section
  - Oversampled by factor 24 to get similar samples of each
  - In combined plots later, the Bino-like LSP models are weighted down by 1/24 to restore uniform scan prior

Fraction of Models Excluded

Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2-6 jets + E_T^{Miss}	32.06%	35.56%	29.65%	33.46%
0-lepton + 7-10 jets + E_T^{Miss}	7.82%	5.59%	7.63%	8.01%
0/1-lepton + 3 b-jets + E_T^{Miss}	9.03%	5.98%	7.17%	10.30%
1-lepton + jets + E_T^{Miss}	7.99%	5.47%	7.47%	8.40%
Monojet	6.93%	14.61%	6.32%	7.06%
SS/3-leptons + jets + E_T^{Miss}	2.43%	1.65%	2.35%	2.51%
Taus + jets + E_T^{Miss}	3.04%	1.30%	2.96%	3.14%
0-lepton, stop	9.34%	7.58%	8.26%	10.08%
1-lepton, stop	6.06%	3.62%	5.23%	6.66%
2b-jets + E_T^{Miss}	3.69%	3.37%	2.95%	4.17%
2-leptons, stop	0.23%	0.38%	0.33%	0.17%
Monojet, stop	3.11%	11.27%	2.48%	3.23%
Stop with Z boson	0.32%	1.01%	0.23%	0.36%
tb+E_T^{Miss},stop	5.30%	1.86%	4.28%	6.06%
ℓh, electroweak	0.00%	0.00%	0.00%	0.00%
2-leptons, electroweak	0.47%	0.91%	0.17%	0.64%
2-taus, electroweak	0.05%	0.06%	0.00%	0.07%
3-leptons, electroweak	0.34%	2.02%	0.39%	0.25%
4-leptons	0.53%	1.13%	0.55%	0.49%
Disappearing Track	11.41%	0.39%	29.91%	0.08%
Long-lived sparticles	0.06%	0.09%	0.02%	0.08%
$H/A \to \tau^+\tau^-$	1.85%	2.17%	0.87%	2.46%
Total	40.60%	39.59%	45.43%	37.58%