# Constraints from LHC-data on Sleptons in scenarios with light $\nu_R$

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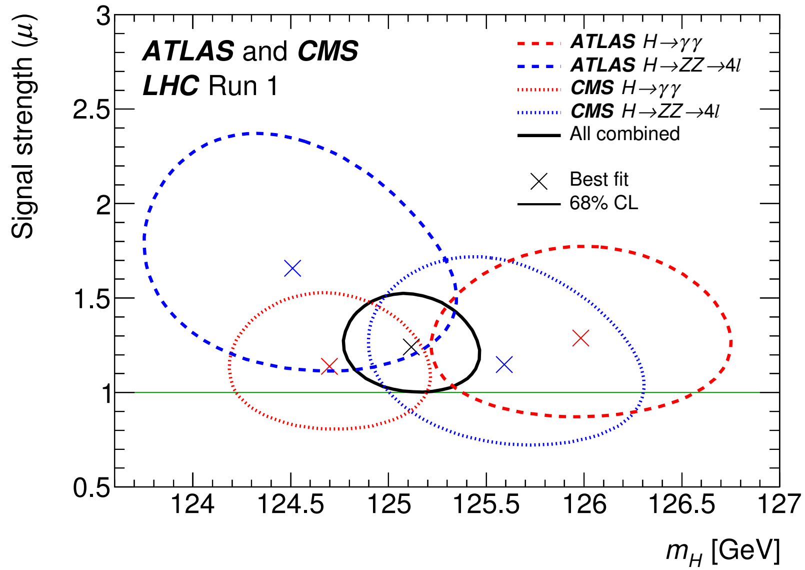
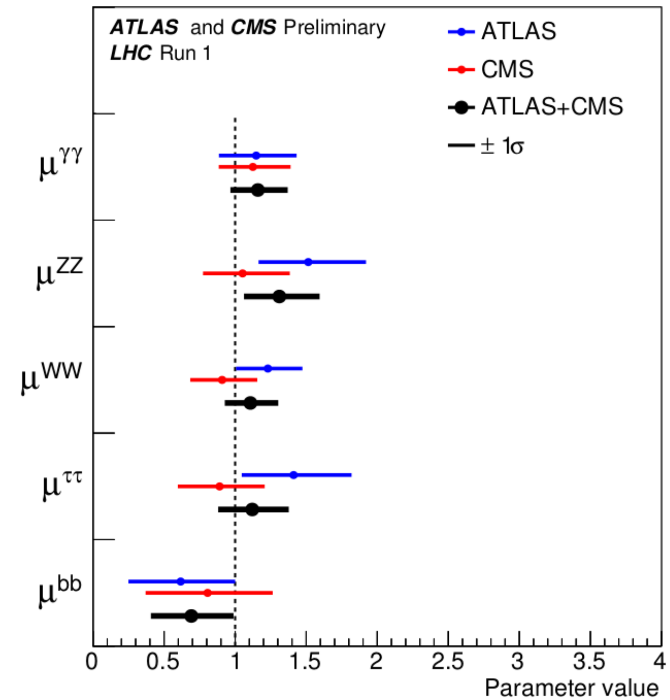
in coll. with N. Cerna-Velazco, T. Faber, J. Jones-Perez

# Higgs results in a nut-shell




$m_H = 125.09 \pm 0.21$ (stat) $\pm 0.11$ (sys) GeV

run 1, PRL **114** (2015) 191803

ATLAS: $m_H = 124.98 \pm 0.19$ (stat) $\pm 0.21$ (sys) GeV

CMS: $m_H = 125.26 \pm 0.20$ (stat) $\pm 0.08$ (sys) GeV

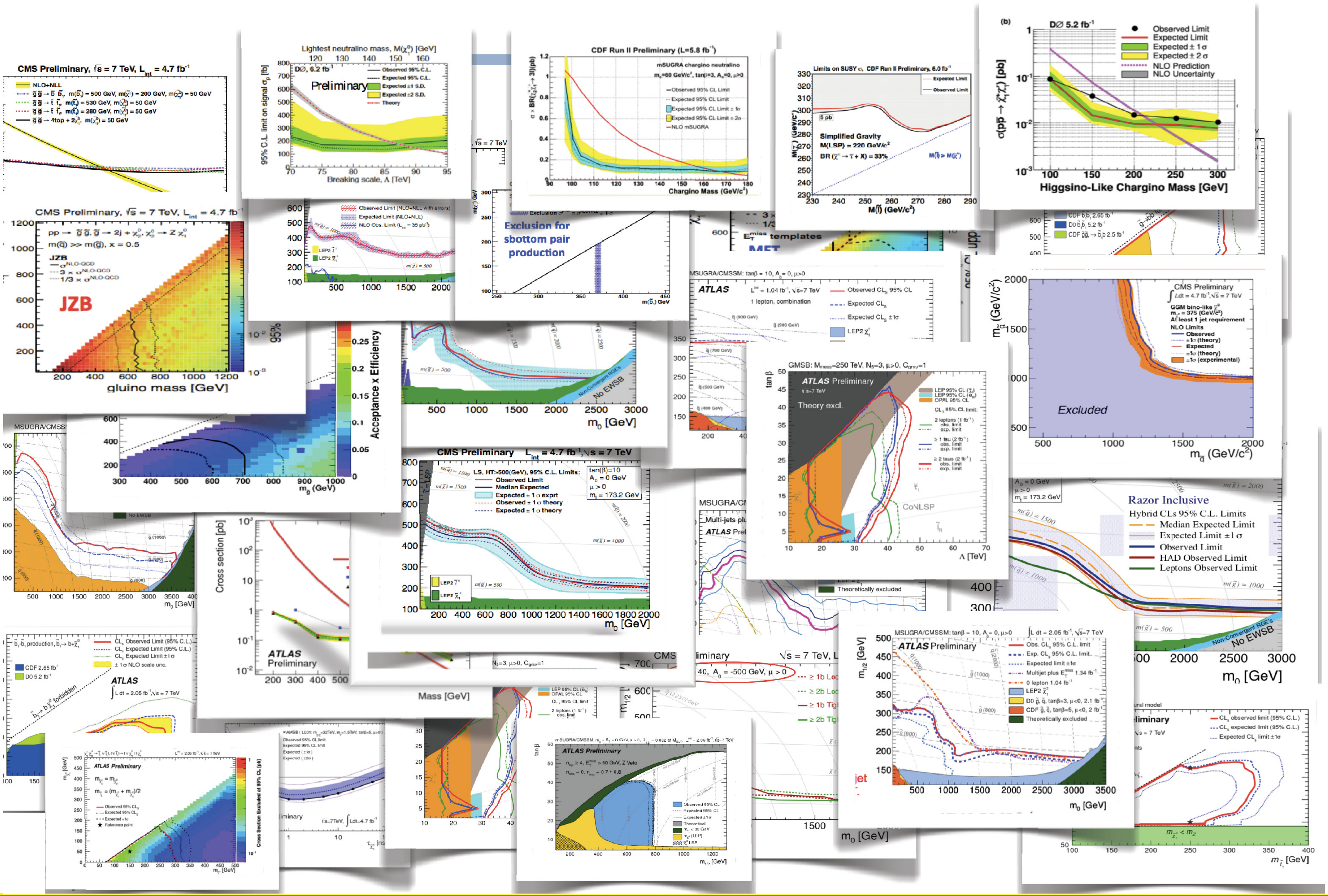
see e.g. talk by A.-M. Magnan, ALPS 2018

ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

$(125 \text{ GeV})^2 \simeq m_Z^2 + (86 \text{ GeV})^2 \Rightarrow$ large corrections within MSSM

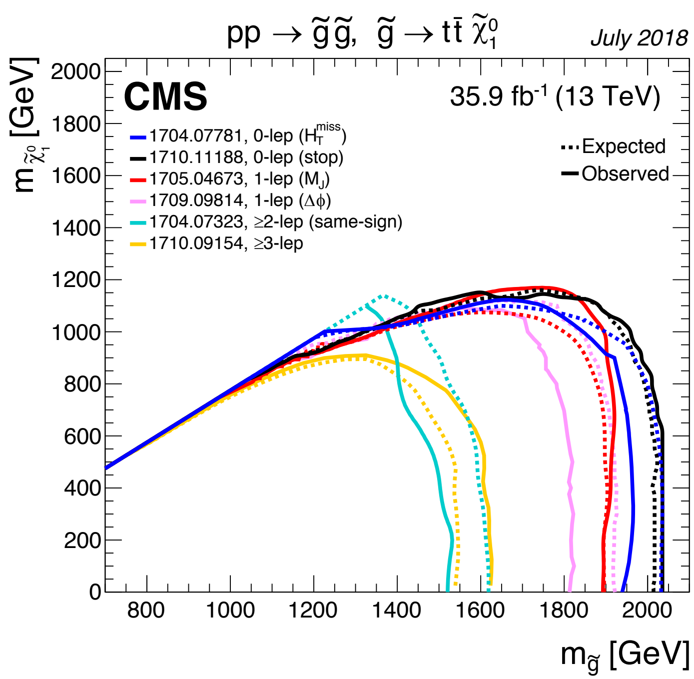
# BSM searches, so far hardly anything . . .

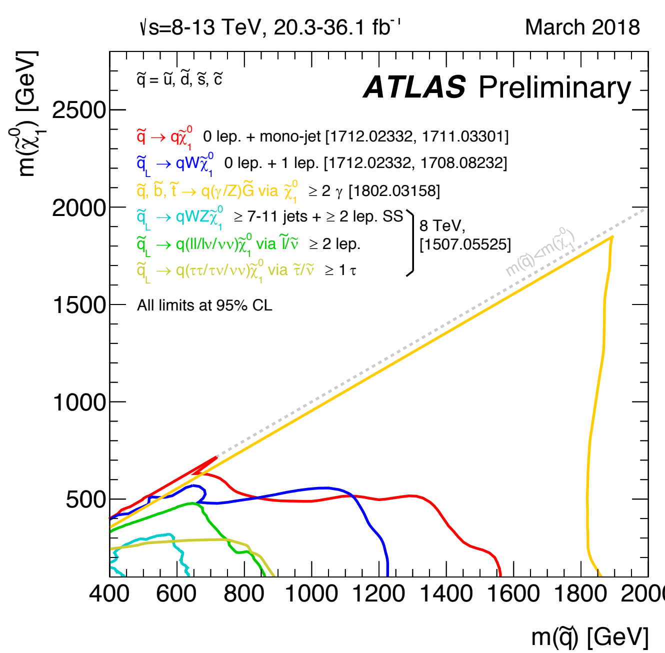


# Summary of generic RPC searches

- In simplified model approach (depending on decay mode and/or mass splittings):
  - $M_{\tilde{g}} \lesssim \mathcal{O}(1\text{ TeV}) - \mathcal{O}(2\text{ TeV})$ @ 95% CL
  - $M_{\tilde{q}} \lesssim \mathcal{O}(0.5\text{ TeV}) - \mathcal{O}(1.5\text{ TeV})$@ 95% CL
  - $M_{\tilde{t}} \lesssim \mathcal{O}(0.7\text{ TeV}) - \mathcal{O}(1.1\text{ TeV})$@ 95% CL

} Can be even worse in some corners of simplified model space.



# LHC data, in particular $m_h$, high scale models

$m_h = 125.2$ GeV $\Rightarrow$ large loop contributions

$\Rightarrow$ heavy stops and/or large left-right mixing for stops

- GMSB: $m_{\tilde{t}_1} \gtrsim 6$ TeV,
  M. A. Ajaib, I. Gogoladze, F. Nasir, Q. Shafi, arXiv:1204.2856

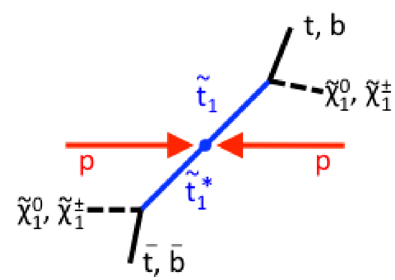
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXive:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV
- CMSSM, NUHM models: $|A_0| \simeq 2m_0$,
  H. Baer, V. Barger and A. Mustafayev, arXiv:1112.3017; M. Kadastik *et al.*, arXiv:1112.3647; O. Buchmueller *et al.*, arXiv:1112.3564; J. Cao, Z. Heng, D. Li, J. M. Yang, arXiv:1112.4391; L. Aparicio, D. G. Cerdeno, L. E. Ibanez, arXiv:1202.0822; J. Ellis, K. A. Olive, arXiv:1202.3262; . . .
  CMSSM fit to data P. Bechtle et al., arXiv:1508.05951: best fit point with $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2$ TeV, $m_{\tilde{l}_R} \simeq 600$ GeV, $m_{\tilde{\chi}_1^0} \simeq 450$ GeV
- general high scale models: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3}, m_{U_3})$ @ $M_{GUT}$
  among other cases, details in F. Brümmer, S. Kraml and S. Kulkarni, arXiv:1204.5977

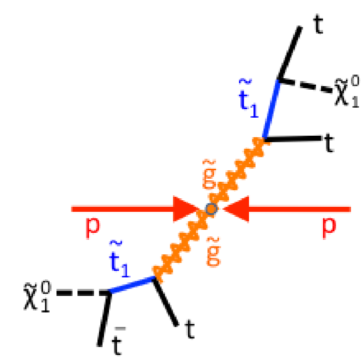
# General MSSM

several studies: S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail, T. Rizzo, arXiv:1308.0297 . . .

- generic signatures are well known: multi-lepton, multi-jets + missing $E_T$
- sub-class of general MSSM: ‘natural SUSY’
  see e.g. M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
  H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, arXiv:1207.3343
  keep only SUSY particles light needed for ’natural Higgs’:
  $$\tilde{t}_1, \tilde{b}_1, \tilde{g}, \tilde{\chi}^0_{1,2} \simeq \tilde{h}^0_{1,2}, \tilde{\chi}^+_1 \simeq \tilde{h}^+$$
  $\Rightarrow$ 100 MeV $\lesssim m_{\tilde{\chi}^+_1} - m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \lesssim 5 - 10$ GeV

$$\begin{aligned} \tilde{g} &\rightarrow \tilde{t}_1 t, \tilde{b}_1 b \\ \tilde{t}_1 &\rightarrow t\tilde{\chi}^0_{1,2}, b\tilde{\chi}^+_1, W^+\tilde{b}_1 \\ \tilde{b}_1 &\rightarrow b\tilde{\chi}^0_{1,2}, t\tilde{\chi}^-_1, W^-\tilde{t}_1 \end{aligned}$$




BRs depend on the nature of $\tilde{t}_1$ and $\tilde{b}_1$
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = -\mu' \tilde{H}_d \tilde{H}_u$
(G. G. Ross, K. Schmidt-Hoberg and F. Staub, arXiv:1701.03480)

# Natural SUSY + $\tilde{\nu}_R$: minimal inverse seesaw model

$$\mathcal{W}_{eff} = \mathcal{W}_{\rm MSSM} + \frac{1}{2}(M_R)_{ij}\,\hat{\nu}_{R,i}\,\hat{\nu}_{R,j} + (Y_\nu)_{ij}\,\widehat{L}_i \cdot \widehat{H}_u\,\hat{\nu}_{R,j}$$

$$(Y_\nu)_{\ell 5} = \pm (Z_\ell^{\rm NH})^* \sqrt{\frac{2 m_3 M_5}{v_u}}\cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\rm NH})^* \sqrt{\frac{2 m_3 M_6}{v_u}}\cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_{56} & \sin\phi_{56} \\ 0 & -\sin\phi_{56} & \cos\phi_{56} \end{pmatrix}$$

$\phi_{56} \in \mathbb{C}$

$m_{\nu_h,i} \simeq M_{i-3}$, $M_4 = O($keV$)$,
$M_5 \simeq M_6 = O($few - 100 GeV$)$

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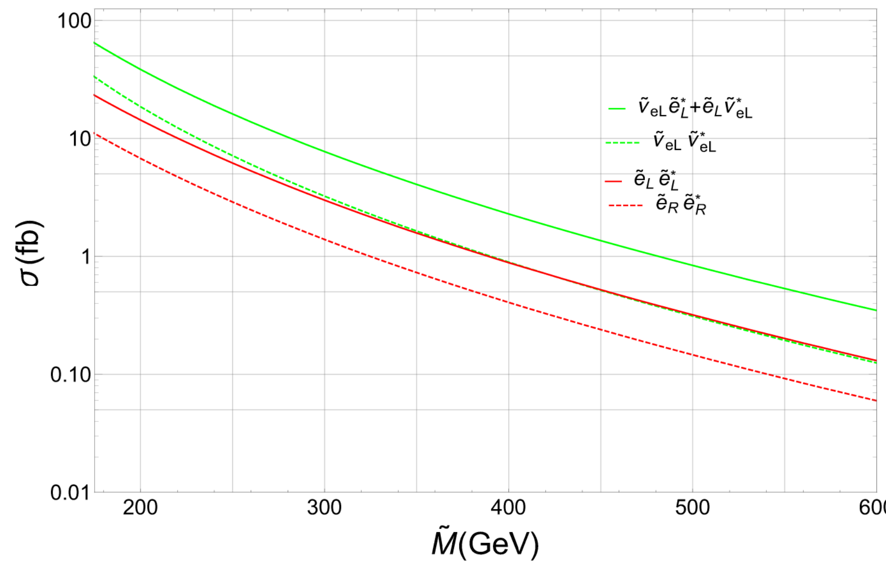
search for sleptons



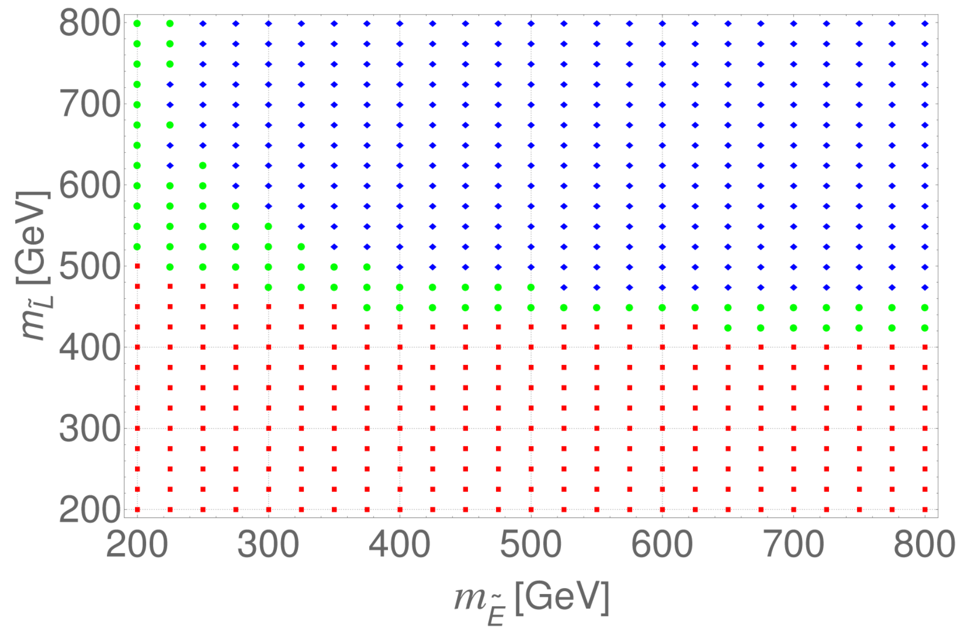

LHC, 13 TeV, tree-level
for searches: × K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

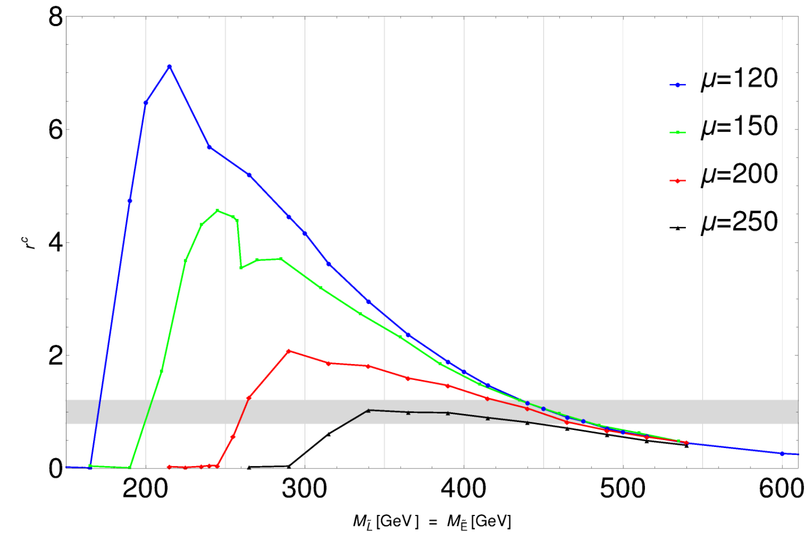
dominant decays:

$$\tilde{l}_L \to l\tilde{\chi}^0_1\ ,\ \nu\tilde{\chi}^-_1$$

$$\tilde{\nu}_L \to l^-\tilde{\chi}^+_1\ ,\ \nu\tilde{\chi}^0_1$$

# Natural SUSY + $\tilde{\nu}_R$: Higgsino LSP




$\mu = 120$ GeV, $\tan\beta = 10$

$m_{\tilde{L}} = m_{\tilde{E}}$, $\tan\beta = 10$

■ excluded, ● ambigous, ◇ allowed

8+13 TeV data (13.9 fb$^{-1}$)

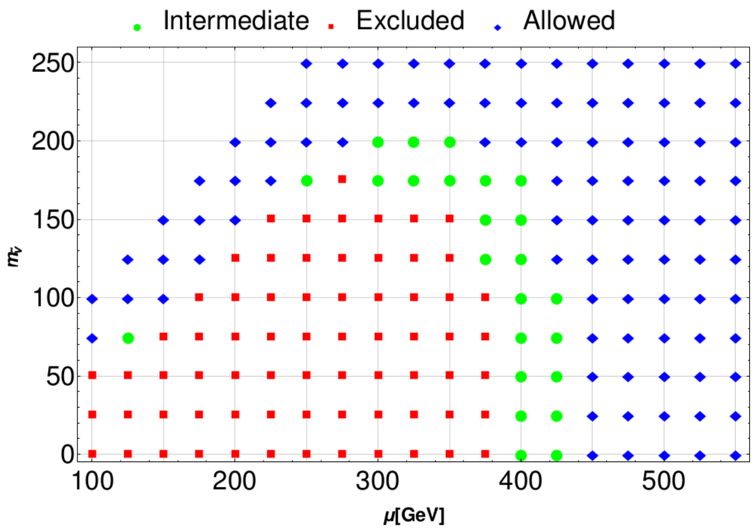
using `CheckMATE 2.0`

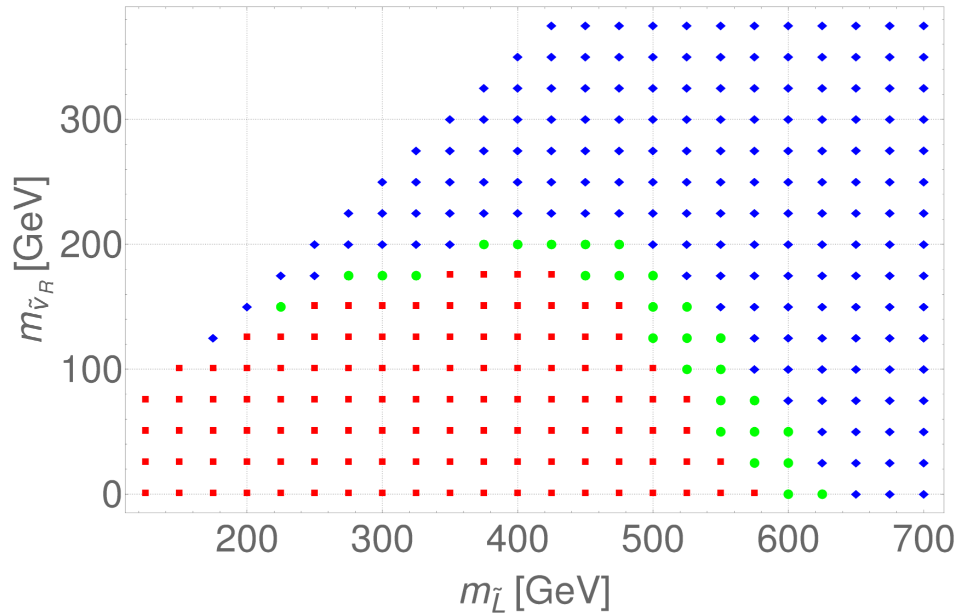
Nh. Cerna-Velazco, Th. Faber, J. Jones-Perez, WP
arXiv:1705.06583

# Natural SUSY + $\tilde{\nu}_R$: $\tilde{\nu}_R$-LSP

additional constraint

$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^+ \ell^- \tilde{\nu}_R \tilde{\nu}_R^*$$




8+13 TeV data (13.9 fb$^{-1}$)
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

Nh. Cerna-Velazco, Th. Faber, J. Jones-Perez, WP arXiv:1705.06583

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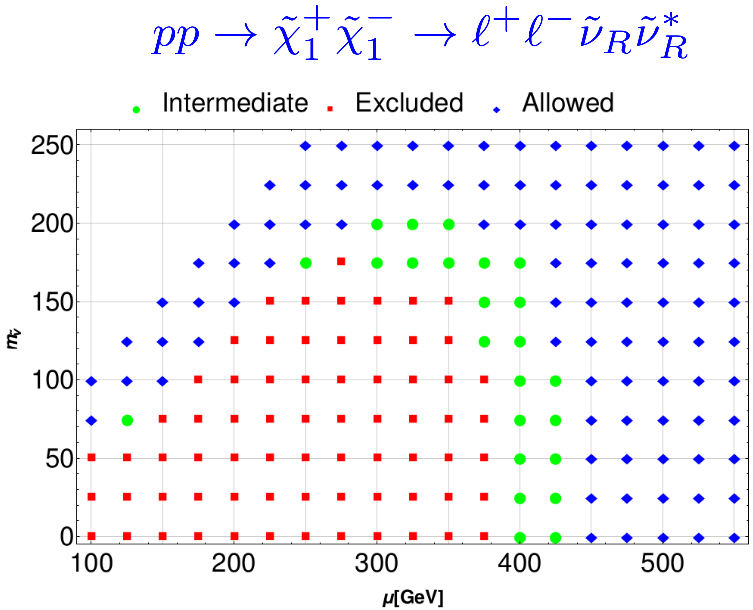
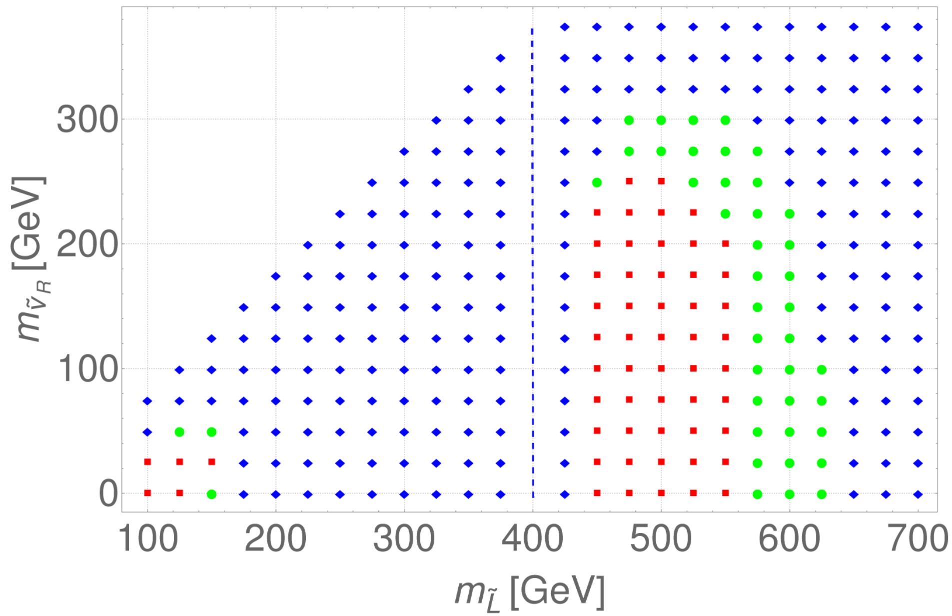


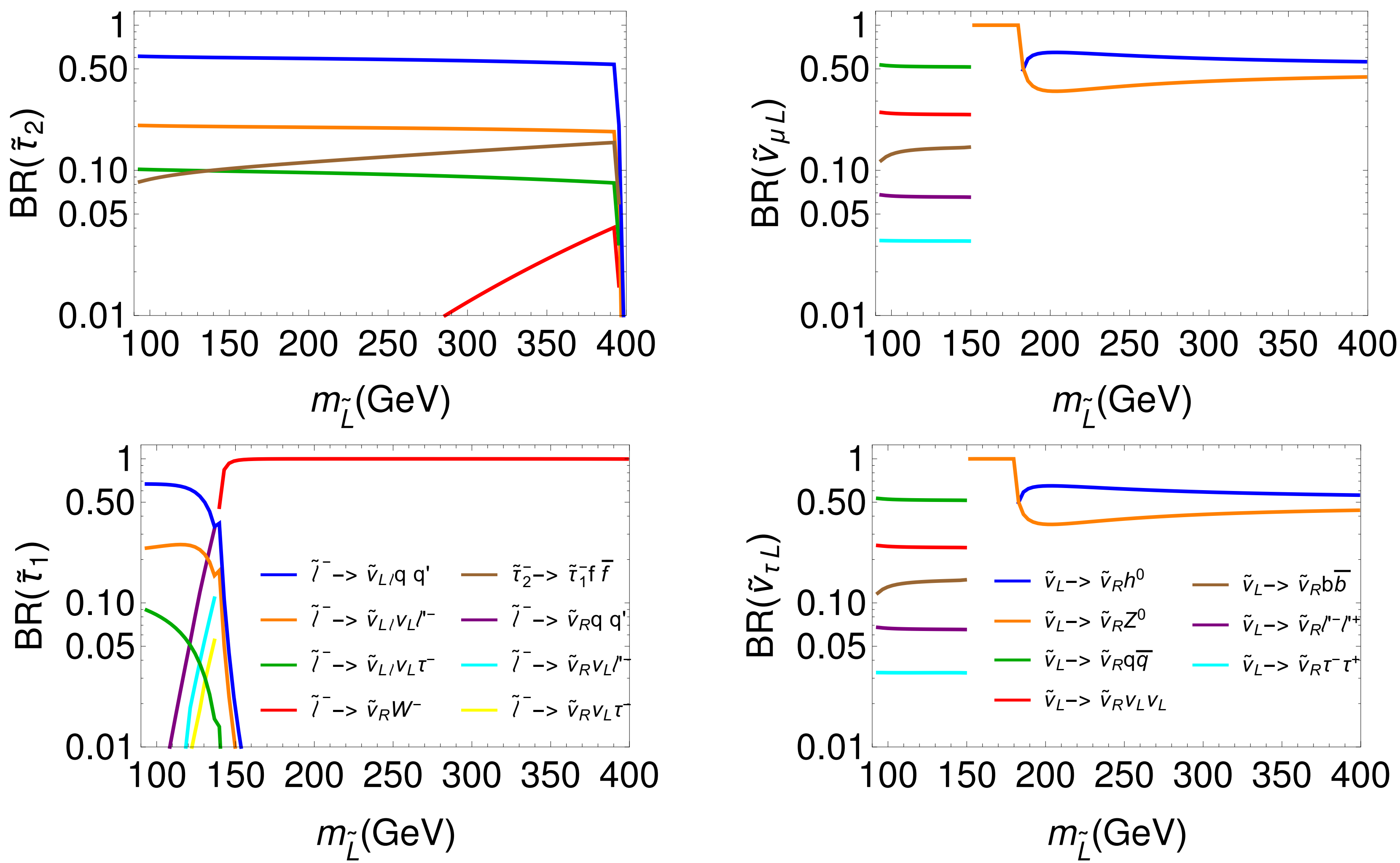

8+13 TeV data (13.9 fb$^{-1}$)
using CheckMATE 2.0
$m_{\nu_R} = 20$ GeV

$\mu = 400$ GeV, $m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

Nh. Cerna-Velazco, Th. Faber, J. Jones-Perez, WP arXiv:1705.06583

# $\tilde{\nu}_R$-LSP, 3-body decays

for $\mu = 400$ GeV $> m_{\tilde{L}} = m_{\tilde{E}}$, $\tan\beta = 6$, $M_1, M_2 \geq 500$ GeV




Nh. Cerna-Velazco, Th. Faber, J. Jones-Perez, WP arXiv:1705.06583

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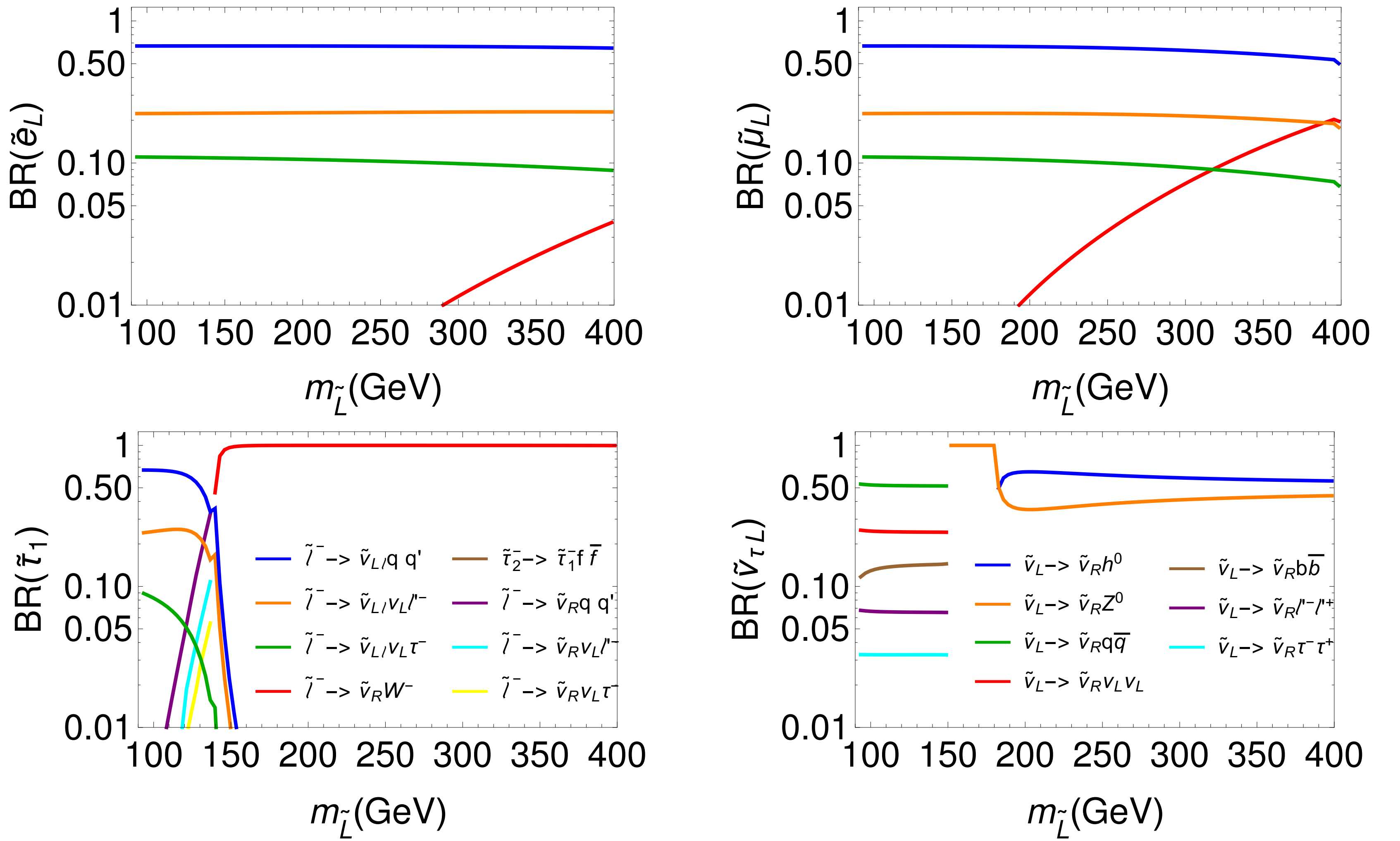
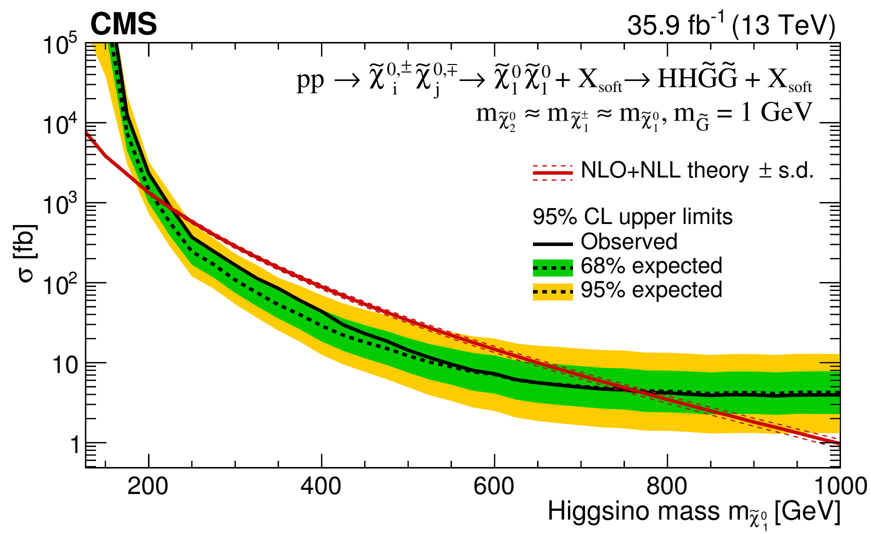
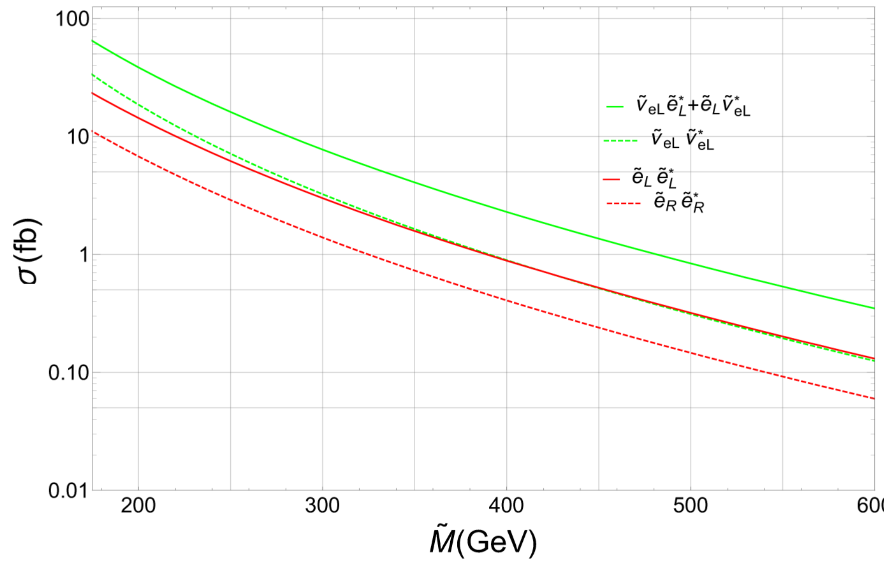



Nh. Cerna-Velazco, Th. Faber, J. Jones-Perez, WP arXiv:1705.06583

# Searches for Higgsinos decaying into $Z, W, H$




CMS arXiv:1709.04896

see also talk by Reina Camacho Toro

# Conclusions

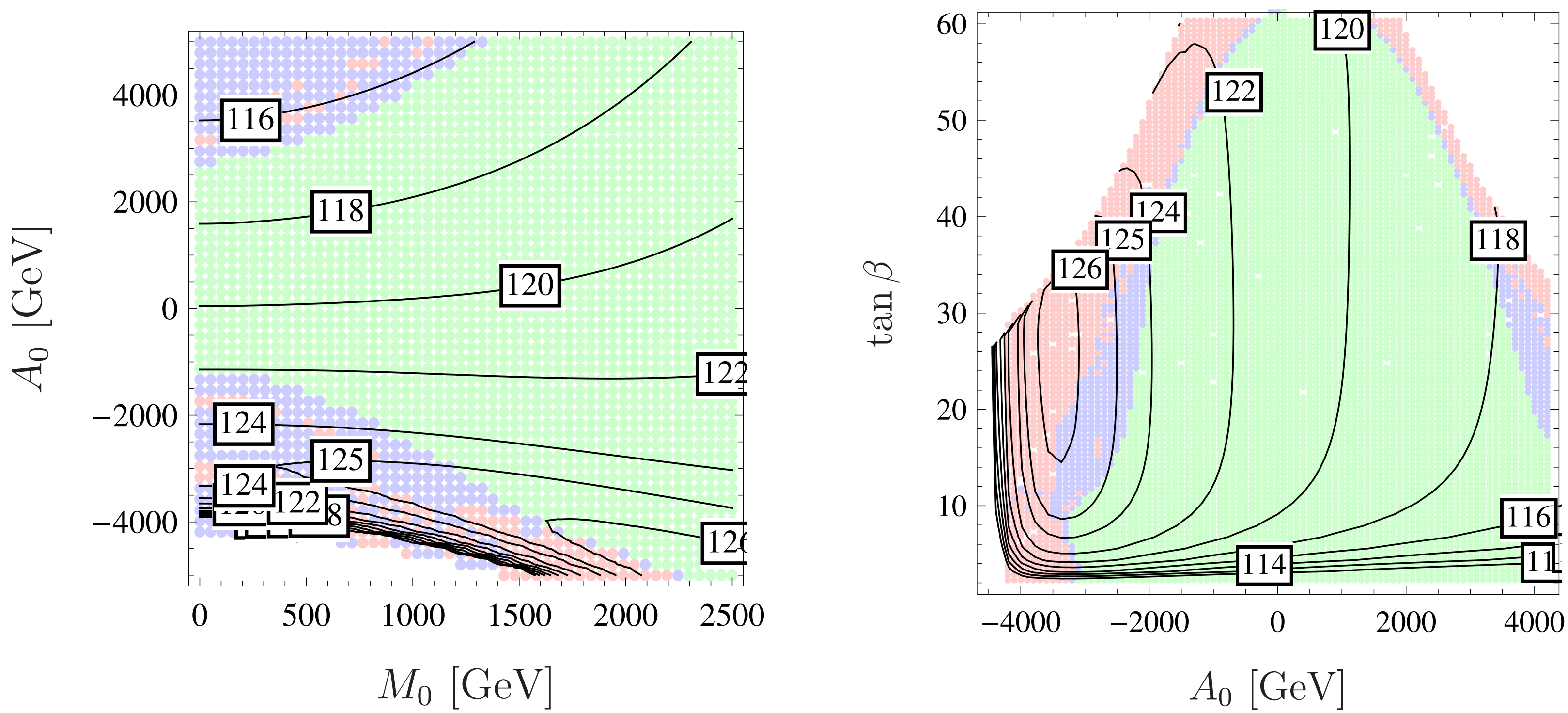
- 'Natural SUSY': take only those states light which contribute to EWSB: $\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_i$
  disadvantage: cannot explain dark matter relic density
- consider scenarios with light $\nu_R$ and a minimal inverse seesaw
  $\Rightarrow \tilde{\nu}_R$ LSP potential DM-candidate, no direct DM constraint apply
- $m_{\tilde{h}^+} \lesssim 400$ GeV excluded if $m_{\tilde{h}^+} - m_{\tilde{\nu}_R} \gtrsim 150$ GeV
- 2-body decays dominate: $m_{\tilde{E}} \gtrsim 200$ GeV & $m_{\tilde{L}} \gtrsim 600$ GeV if sufficiently hard leptons in the final state
- 3-body decays dominate: $\tilde{l}_L$ with masses of about 200 GeV still allowed

Outlook:

- include newer analyses, in particular those containing $b$-jets with somewhat compress spectra

# mSUGRA/CMSSM, charge/color breaking minima

- SUSY models contain many scalars $\Rightarrow$ complicated potential
- usually some parameters ($\mu$, $B$) are choosen to obtain correct EWSB
- does not exclude the existence of other minima breaking charge and/or color!




$M_{1/2} = 1$ TeV, $\tan\beta = 10$, $\mu > 0$ $\quad\quad$ $M_{1/2} = M_0 = 1$ TeV

J.E. Camargo-Molina, B. O'Leary, W.P., F. Staub, arXiv:1309.7212

# Heavy neutrinos

Constraints from $Z$-width, invisible width

$$\left| 1 - \sum_{ij=1, i\leq j}^{3} \left| \sum_{k=1}^{3} U^{\nu}_{ik} U^{\nu,*}_{jk} \right|^2 \right| < 0.009$$

dominant decays

$$\begin{aligned} \nu_j &\rightarrow W^{\pm} l^{\mp} \\ \nu_j &\rightarrow Z \nu_i \\ \nu_j &\rightarrow h_k \nu_i \end{aligned}$$

if $m_\nu > m_h$

$$BR(\nu_j \rightarrow W^{\pm} l^{\mp}) : BR(\nu_j \rightarrow Z\nu_i) : BR(\nu_j \rightarrow h_k \nu_i) \simeq 0.5 : 0.25 : 0.25$$