Introduction and Overview BSM

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Before Higgs discovery

- something must be at the TeV scale as electroweak symmetry is broken

After Higgs discovery and several searches for new physics

- data described very well by SM
- no hint where at which scale to expect new physics

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EFT vs full models

full models vs **EFT**

"maximum optimism"

- SM extension addresses a problem deemed "serious"
  - tuning
  - dark matter
  - baryogenesis
  - …
- "solution" induces correlation in data, e.g. "light top partners"

"maximum scepticism"

- deform SM in most general yet consistent way
  - only SM fields are light
  - SM symmetries
  - maybe extra simplifications to make things manageable
- "any" correlation in data that can be induced from non-resolved scales in principle

Ch. Englert
summary of last week

Why extending the SM?

Most of the data can be explained (extremely well) by the SM, but

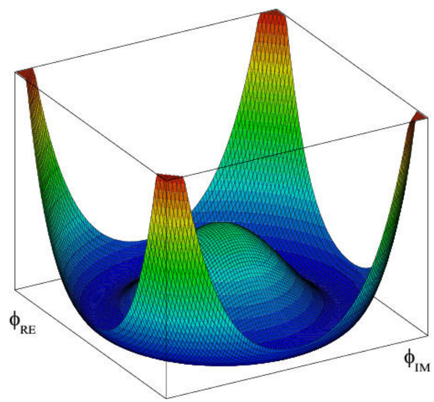
- Flavour
  - hierarchy of fermion masses, in particular ν
  - mixing pattern: small mixing for q versus large mixing for ν
- Anomalies
  - $(g-2)_\mu$
  - b-physics:

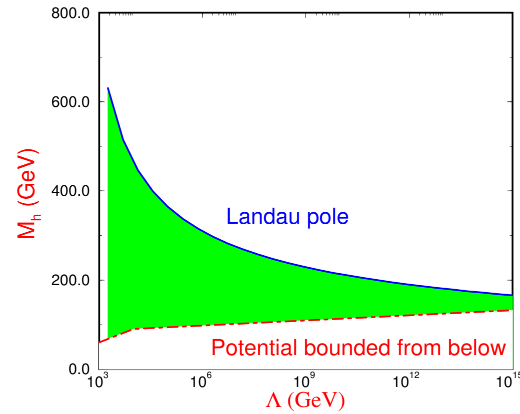
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)} \tau \bar{\nu})}{\Gamma(\bar{B} \to D^{(*)} l \bar{\nu})} \; (l = e, \mu) \qquad , \; R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)} e^+ e^-)}$$

  - ...
- Cosmology
  - Dark matter
  - Baryon asymmetry of the Universe

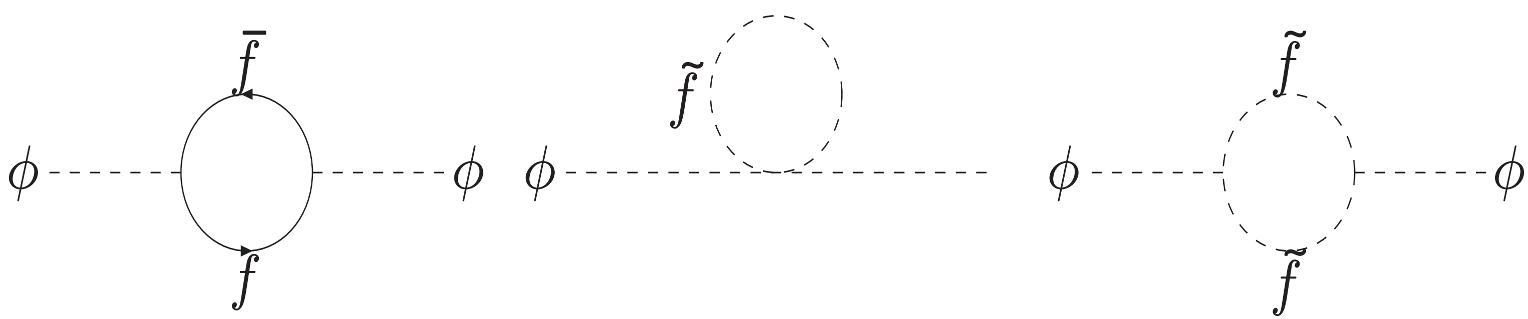
Why extending the SM?

- SM & $m_h = 125.1$ GeV: potentially meta-stable (G. Degrassi *et al.*, arXiv:1205.6497)



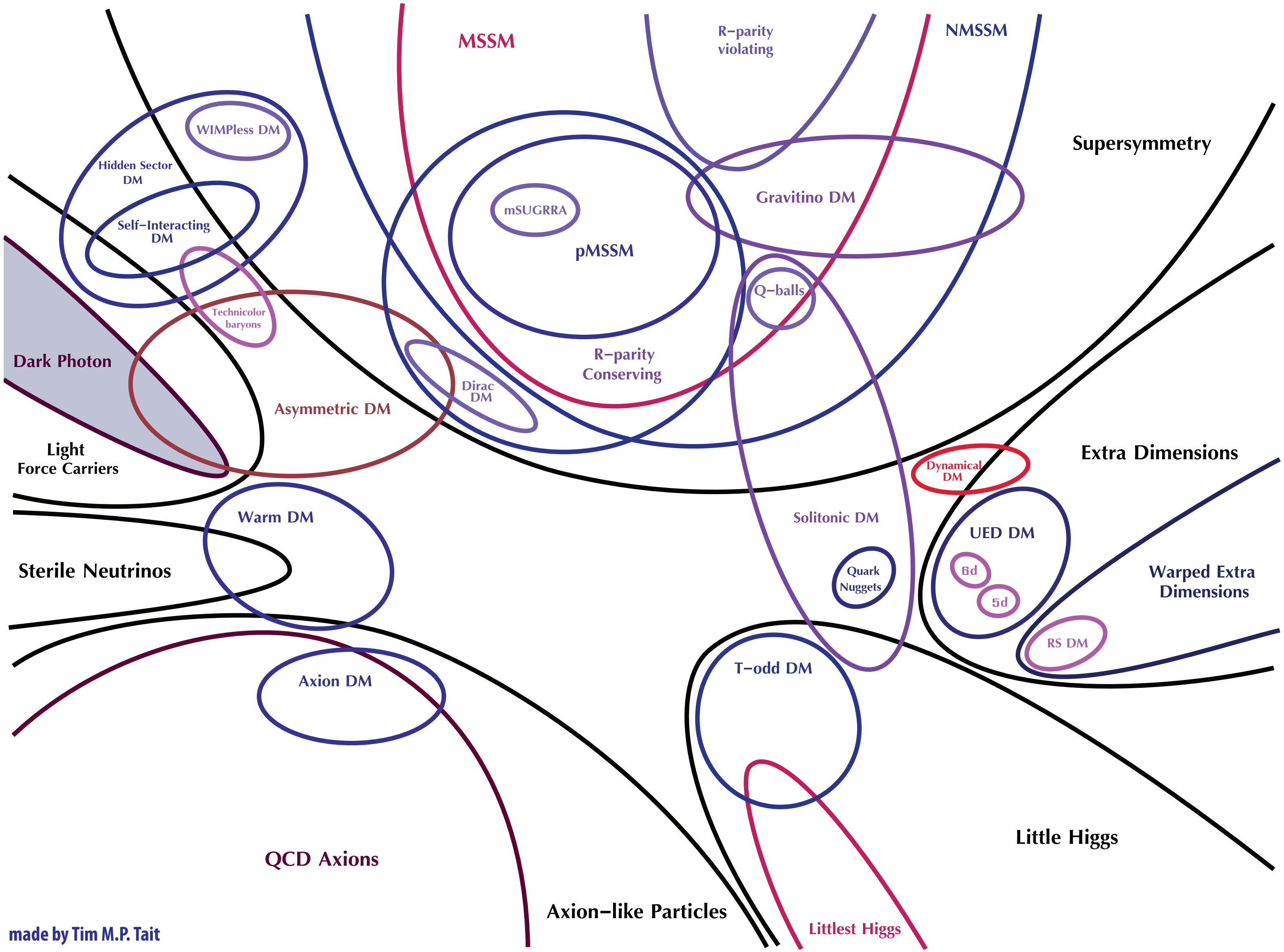


- "Why does electroweak symmetry break?" or "Why is $\mu^2 < 0$ in the SM?"
- Hierarchy problem (?)

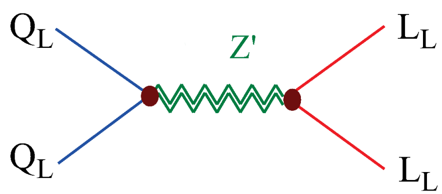


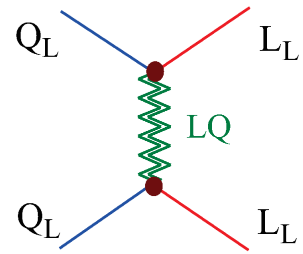
$\delta m_h^2 \propto \Lambda^2$: Sensitivity to highest mass scale of unknown physics

Model space & dark matter



J.L. Feng et al., arXiv:1401.6085





Roads to UV completions

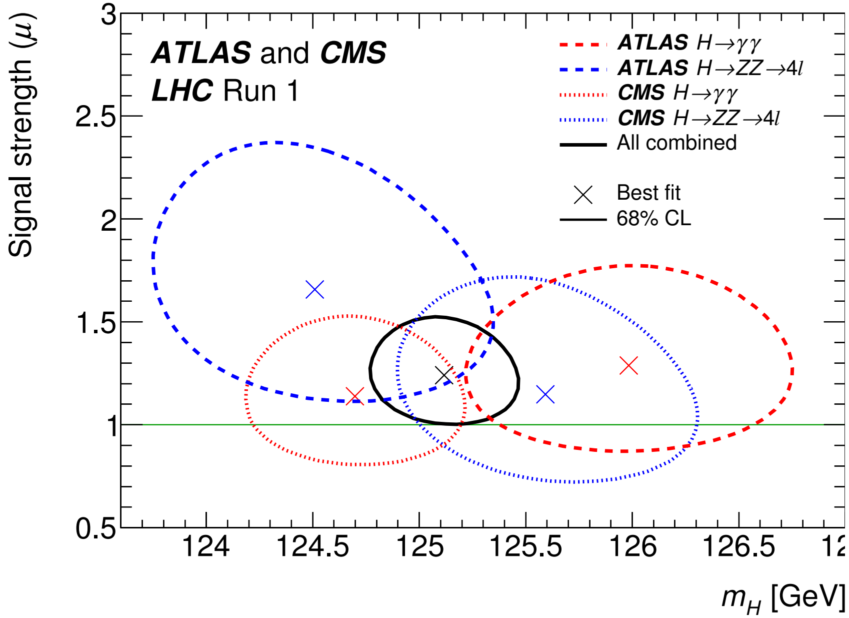
Non-perturbative TeV-scale dynamics (non-renormalizable models)

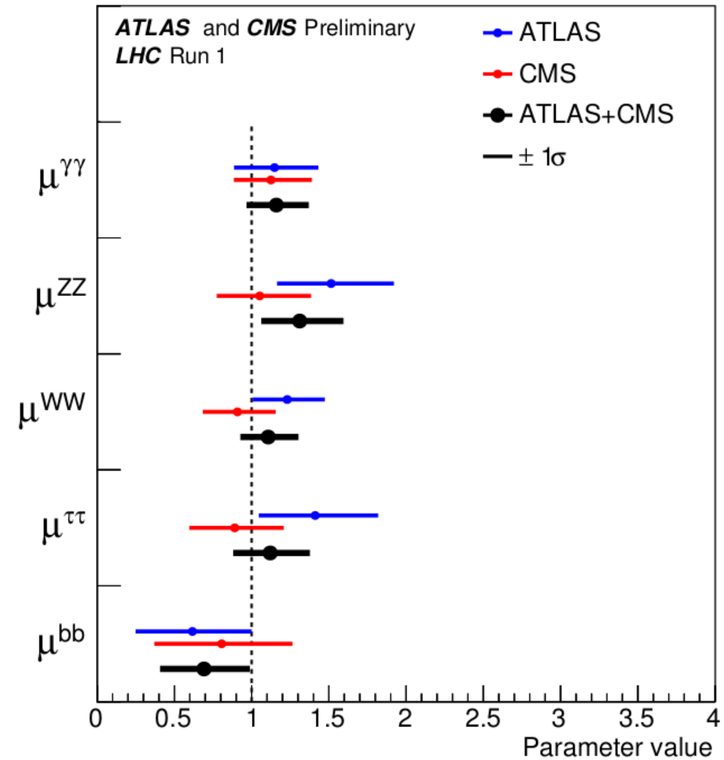
- Scalar LQ as PNG: Gripaios, ’10; Gripaios, Nardecchia, Renner, ’14
- Vector LQ (or W',Z') as technifermion resonances: Barbieri et al. ’15; Buttazzo et al. ’16; Barbieri et al. ’17
- W', Z' as Kaluza-Klein excitations (e.g. from warped extra dim.): Megias, Quiros, Salas ’17; Megias, Panico, Pujolas, Quiros ’17

Perturbative TeV-scale dynamics (renormalizable models)

- Renormalizable models with scalar mediators (LQ, but also RPV-SUSY): Hiller, Schmaltz, ’14; Becirevic et al. ’16; Fajfer et al. ’15-’17; Dorsner et al. ’17; Crivellin, Müller, Ota ’17; Altmannshofer, Dev, Soni, ’17
- Gauge models: Cline, Camalich ’17; Calibbi, Crivellin, Li, ’17; Assad, Fornal, Grinstein, ’17; Di Luzio, Greljo, Nardecchia, ’17

Higgs results in a nut-shell





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

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

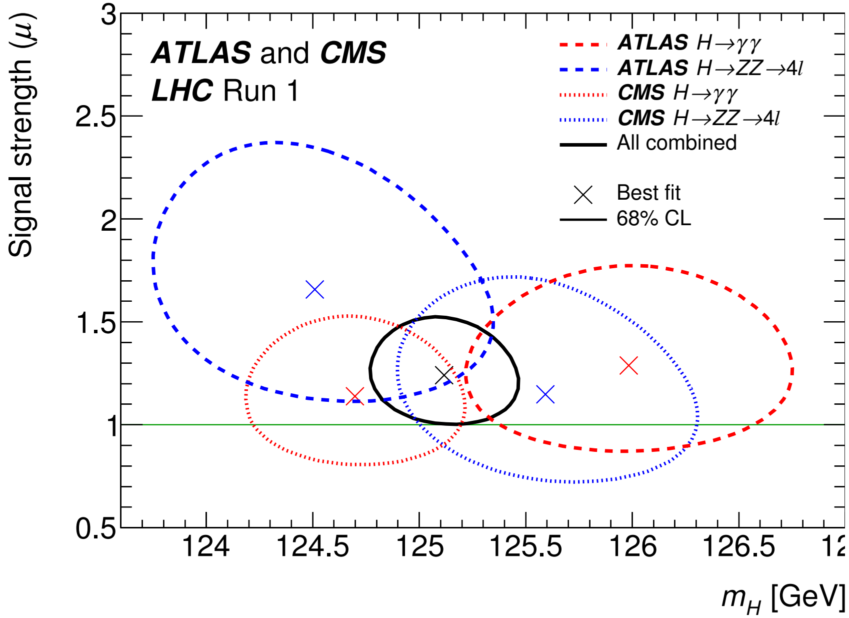
$m_H = 125.25 \pm 0.20$ (stat) ± 0.08 (sys) GeV

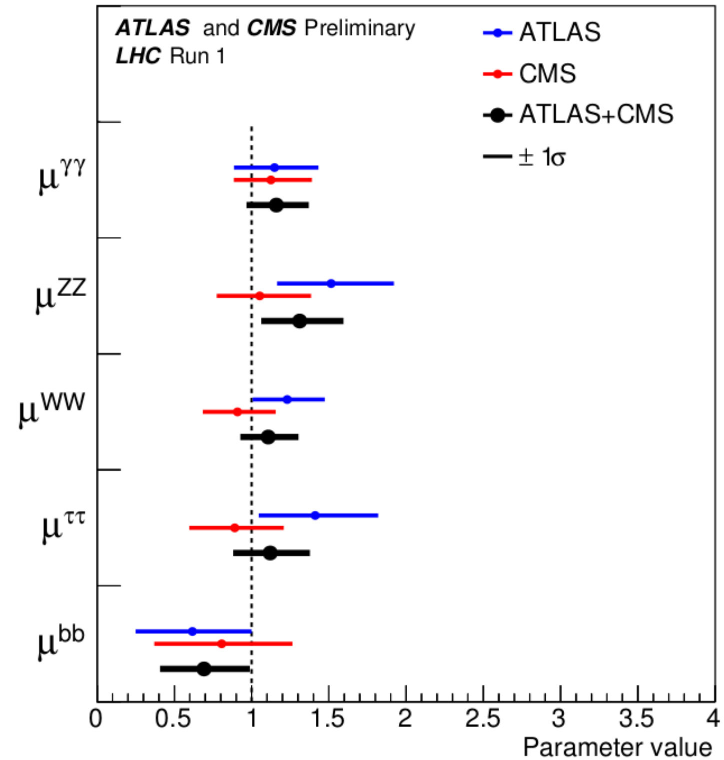
run 2, talk by R. Nicolaidou @ Moriond'17, QCD

ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

Higgs results in a nut-shell





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run 2, talk by R. Nicolaidou @ Moriond'17, QCD

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

MSSM, Higgs sector

- after EWSB:
  neutral CP-even: h, H neutral CP-odd: A charged: H^+, H^-
- Higgs masses:
  at tree level
  $m_A, \tan\beta = v_u/v_d$
  $m_h \le m_Z$

  Ellis et al; Okada et al; Haber,Hempfling; Hoang et al; Carena et al; Heinemeyer et al; Zhang et al; Brignole et al; Harlander et al; Kant,Harlander,Mihaila,Steinhauser;...

  at higher order:

$$
\begin{aligned}
m_h^2 &\simeq m_Z^2 \cos^2(2\beta) + \frac{3 m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right] \\
M_S^2 &= m_{\tilde{t}_1} m_{\tilde{t}_2} \quad , \quad X_t = A_t - \mu \cot\beta \\
m_H, m_A, m_{H+} &: O(v) \ldots O(TeV) \\
m_{H+}^2 &= m_A^2 + m_W^2 \\
v^2 &= v_u^2 + v_d^2 = 4 m_W^2 / g^2
\end{aligned}
$$

decoupling limit: $m_A \gg v$, $\tan\beta \gg 1$;
current precision including leading 3-loop effects: O(GeV)

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

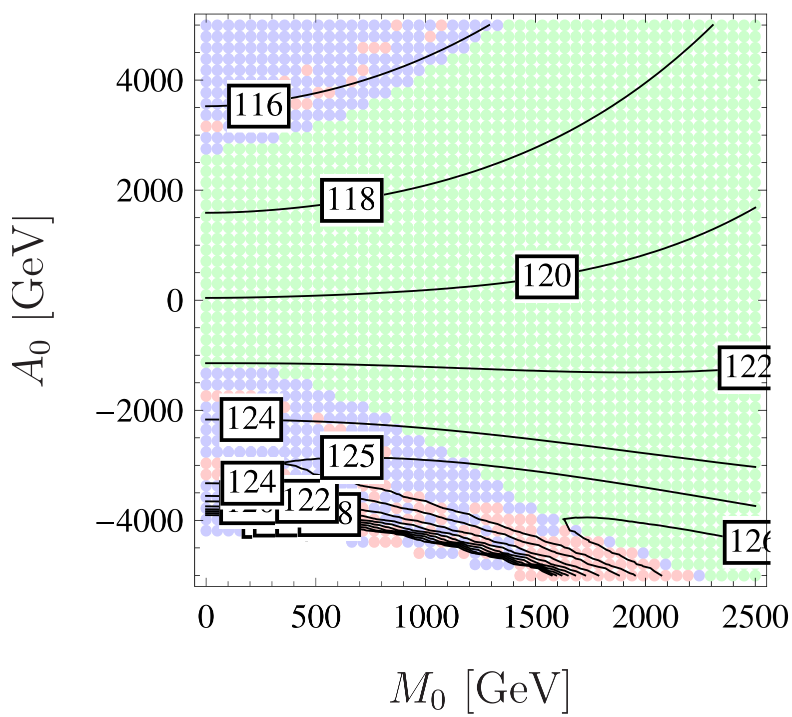
  more complicated models based on P. Meade, N. Seiberg and D. Shih, arXiv:0801.3278 $\Rightarrow$ allow additional terms
  e.g. S. Knappen, D. Redigolo, arXiv:1606.07501 $m_{\tilde{t}_1} \simeq m_{\tilde{b}_1} \gtrsim 1$ TeV if $M_{\text{mess}} \gtrsim 10^{15}$ GeV

- 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

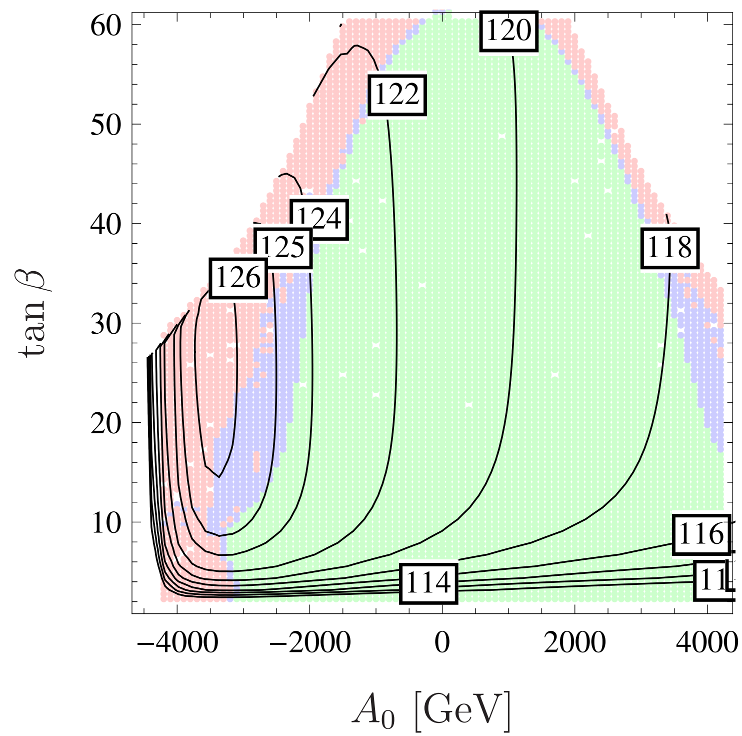
- general high scale models: $A_0 \simeq -(1-3)\max(M_{1/2}, m_{Q_3}, m_{U_3})$ @ M_{GUT}
  among other cases, details in F. Brümmer, S. Kraml and S. Kulkarni, arXiv:1204.5977

mSUGRA/CMSSM, charge/color breaking minima

- SUSY models contain many scalars $\Rightarrow$ complicated potential
- usually some parameters (μ, 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, $\tan\beta = 10$, $\mu > 0$



$M_{1/2} = M_0 = 1$ TeV

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

The electroweak measure of fine-tuning

$$\mathcal{L}_{MSSM} = \mu \tilde{H}_u \tilde{H}_d + \text{ h.c. } + (m^2_{H_u} + |\mu|^2)|H_u|^2 + (m^2_{H_d} + |\mu|^2)|H_d|^2 + \dots$$

basic idea: contributions to m_Z should not contain large cancellations among each other

$$\frac{m_Z^2}{2} = \frac{m^2_{H_d} + \Sigma_d - (m^2_{H_u} + \Sigma_u) \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \simeq -(m^2_{H_u} + \Sigma_u) - |\mu|^2$$

'standard fine-tuning measure'†

$$\Delta_{FT} = \max[c_i] \ , \quad c_i = \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right| = \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|$$

requiring at most a tuning at the per-cent level one finds

$$|\mu|^2 \simeq m_Z^2 \simeq |m^2_{H_u}| \ , \quad m_{\tilde{t}_1} \lesssim \text{ 1 TeV } , \quad m_{\tilde{g}} \lesssim \text{ 1-2 TeV}$$

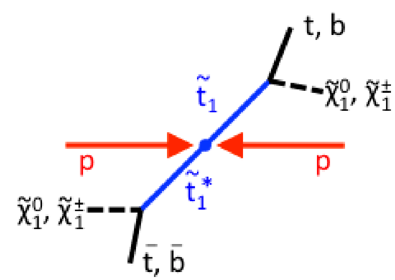
† Ellis, Enqvist, Nanopoulos, Zwirner 1986; Barbieri, Guidice 1988

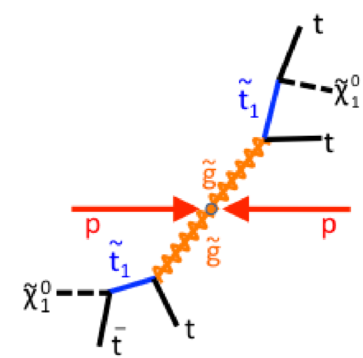
General MSSM

several studies, see e.g. S. Sekmen et al., arXiv:1109.5119; A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, arXiv:1211.4004; M. Cahill-Rowley, J. Hewett, A. Ismail and 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

$$\begin{aligned} \tilde g &\rightarrow \tilde t_1 t, \tilde b_1 b \\ \tilde t_1 &\rightarrow t\tilde\chi^0_{1,2}, b\tilde\chi^+_1, W^+\tilde b_1 \\ \tilde b_1 &\rightarrow b\tilde\chi^0_{1,2}, t\tilde\chi^-_1, W^-\tilde t_1 \end{aligned}$$

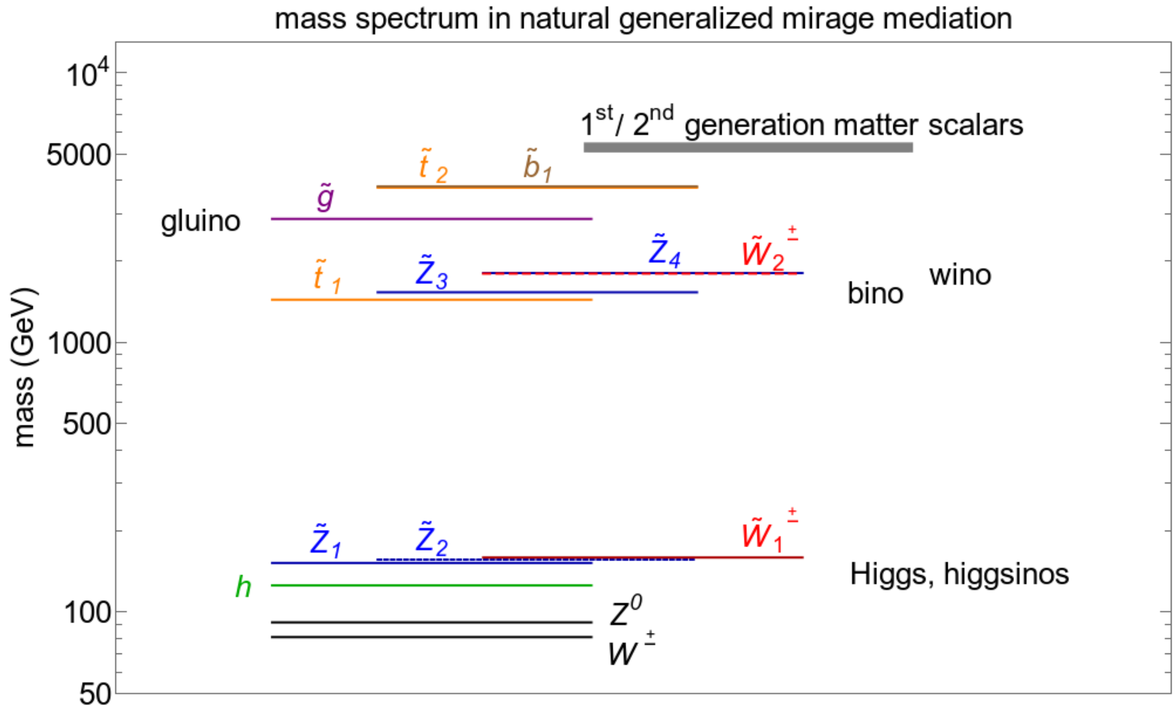




BRs depend on the nature of $\tilde t_1$ and $\tilde b_1$
Higgsino mass: $\mu + \mu'$ with soft SUSY breaking parameter: $\mathcal{L} = \mu' \tilde H_u \tilde H_d$

General Mirrage Mediation

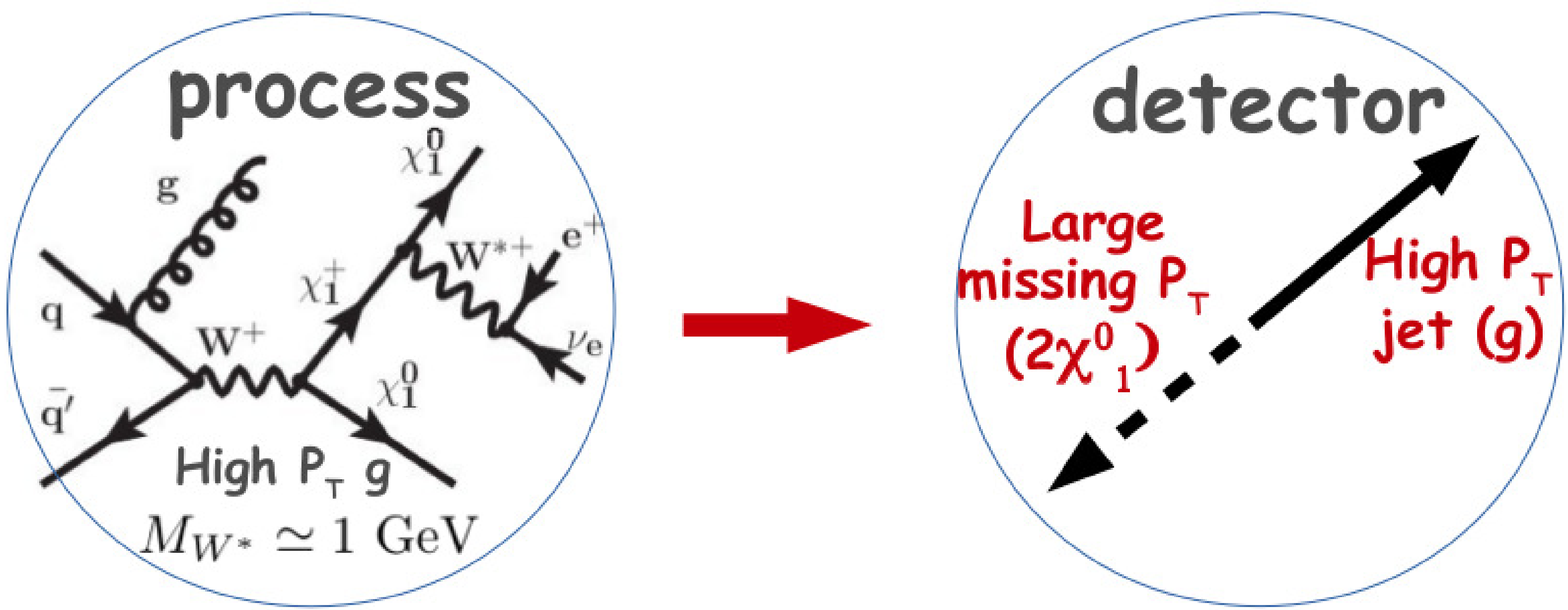
Different sources for soft SUSY breaking: moduli & AMSB
main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



H. Baer, V. Barger, H. Serce and X. Tata, arXiv:1610.06205

Higgsino LSP: Challenge for LHC

Most challenging case: only higgsinos accessible but nothing else and ΔM to small for any leptonic signature



The only way to probe compressed higgsinos is a mono-jet signature:
'Where the Sidewalk Ends? ...' Alves, Izaguirre, Wacker 2011

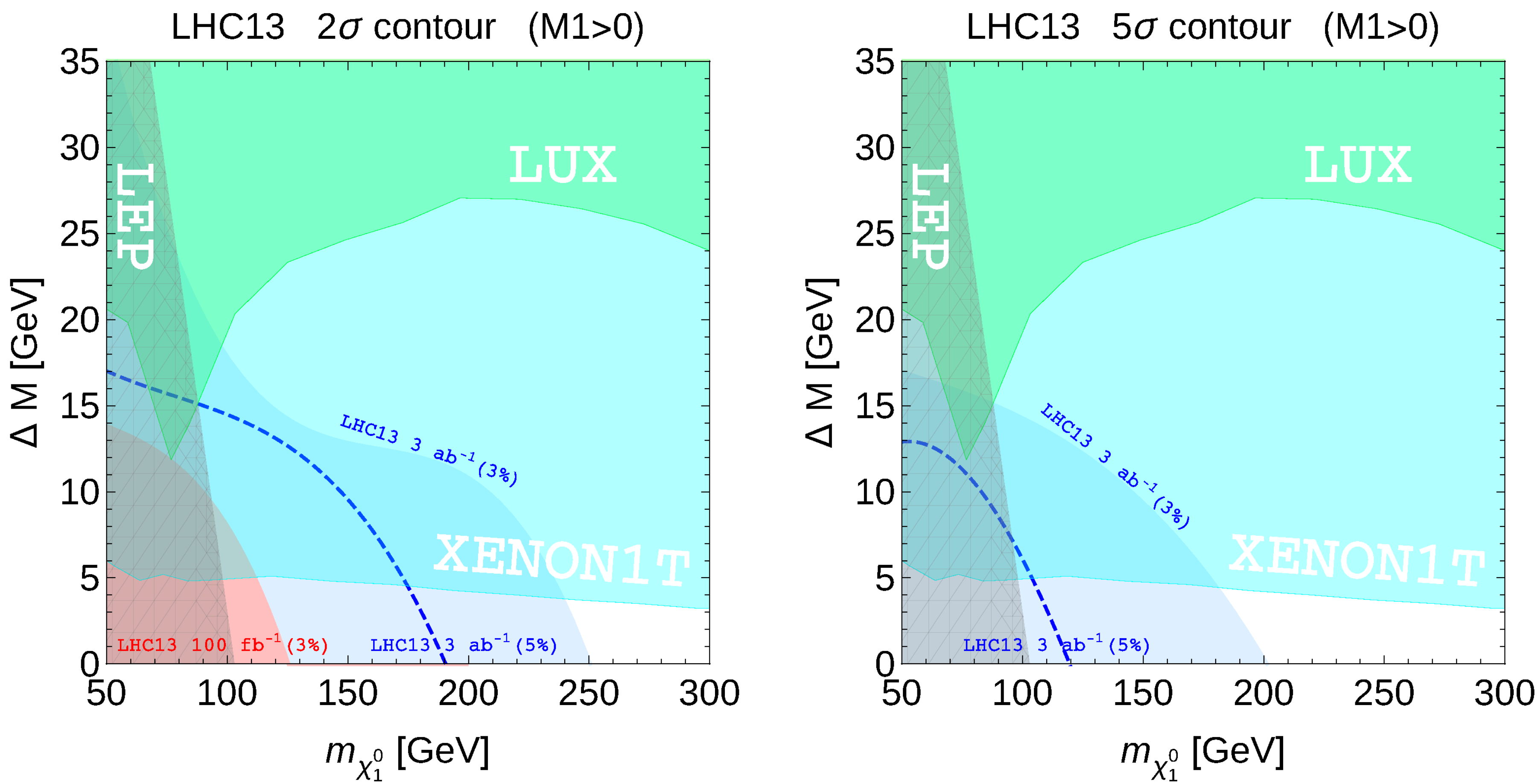
related work C. Han et al., arXiv:1310.4274; P. Schwaller, J. Zurita, arXiv:1312.7350; Z. Han et al, arXiv:1401.1235; H. Baer et al., arXiv:1401.1162, ...

Background suppression

	$Z(\nu\bar{\nu})j$	$W(l\nu)j$	$\mu =$ 100 GeV	$\mu =$ 200 GeV
Initial # of events	3.15$\cdot 10^6$	1.25$\cdot 10^7$	3.63$\cdot 10^5$	6.45$\cdot 10^3$
$p_T^j >$ 200 GeV $\lvert\eta^j\rvert < 2.4$	1.05$\cdot 10^6$	4.11$\cdot 10^6$	1.73$\cdot 10^5$	3528
Jet veto ($n \geq 3$)	8.7$\cdot 10^5$	3.13$\cdot 10^6$	1.33$\cdot 10^5$	2691
$\Delta\phi(j_1, j_2) < 2.5$	7.2$\cdot 10^5$	2.3 $\cdot 10^6$	1.10$\cdot 10^5$	2320
Veto $e^\pm, \mu^\pm, \tau^\pm$	7.2$\cdot 10^5$	6.8 $\cdot 10^5$	1.08$\cdot 10^5$	2301
$E_T^{\mathrm{miss}} > 200$ GeV	6.4$\cdot 10^5$	4.3$\cdot 10^5$	9846	2188
$E_T^{\mathrm{miss}} > 600$ GeV	4353	1002	171	93
$E_T^{\mathrm{miss}} > 800$ GeV	694	0	37	22

Complementarity: LHC @ 13 TeV versus DM direct detection

exclusion reach | discovery reach



D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

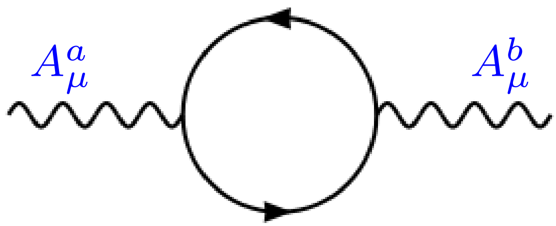
Extended gauge groups, motivation

- additional D-term contributions to m_h at tree-level
  extra $U(1)_\chi$: $m^2_{h,tree} \leq m^2_Z + \frac{1}{4} g^2_\chi v^2$
- Origin of R-parity $R_P = (-1)^{2s+3(B-L)}$
  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Neutrino masses
  $B - L$ anomaly free $\Rightarrow \nu_R$
  usual seesaw, inverse seesaw

Gauge kinetic mixing

$U(1)_a \times U(1)_b$ models allow for (B. Holdom, PLB **166** (1986) 196)

$$\mathcal{L} \supset -\chi_{ab} \hat{F}^{a,\mu\nu} \hat{F}^b_{\mu\nu}$$



$$\Longleftrightarrow \qquad \gamma_{ab} = \frac{1}{16\pi^2} \mathrm{Tr}(Q_a Q_b)$$

equivalent

$$D_\mu = \partial_\mu - i \begin{pmatrix} Q_a \\ Q_b \end{pmatrix} \begin{pmatrix} g_{aa} & g_{ab} \\ g_{ba} & g_{bb} \end{pmatrix} \begin{pmatrix} A^a_\mu \\ A^b_\mu \end{pmatrix}$$

both $U(1)$ unbroken $\Rightarrow$ chose basis with e.g. $g_{ba} = 0$

affects also RGE running of soft SUSY parameters:
R. Fonseca, M. Malinsky, W.P., F. Staub, arXiv:1107.2670

A SUSY Z'-model

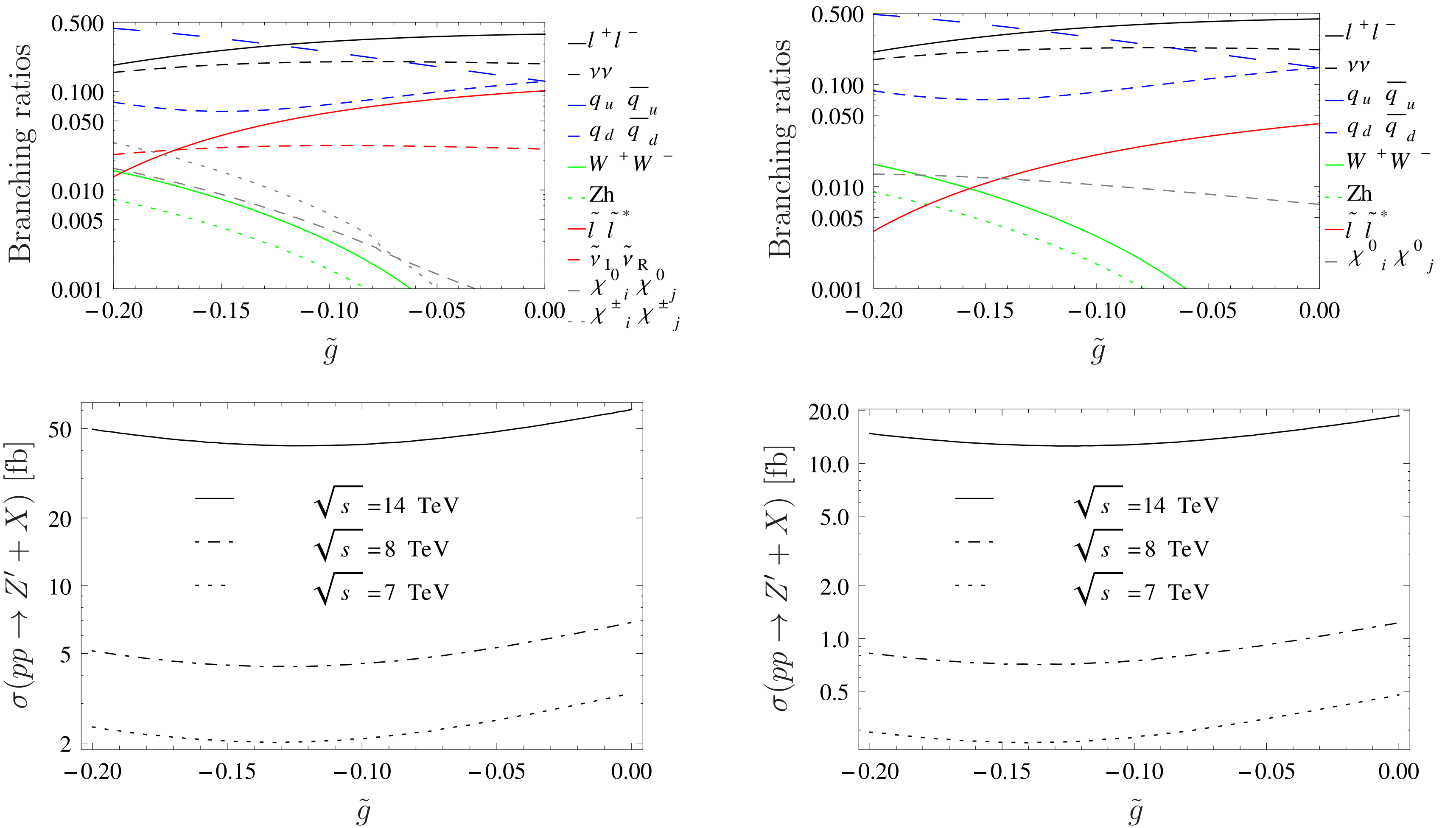
Superfield	Generations	$U(1)_Y \times SU(2)_L \times SU(3)_C \times U(1)_{B-L}$
$\hat{Q}$	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

$$W = Y_u^{ij}\,\hat{U}_i\,\hat{Q}_j\,\hat{H}_u\, - Y_d^{ij}\,\hat{D}_i\,\hat{Q}_j\,\hat{H}_d\, - Y_e^{ij}\,\hat{E}_i\,\hat{L}_j\,\hat{H}_d\, + \mu\,\hat{H}_u\,\hat{H}_d\, + Y_\nu^{ij}\,\hat{L}_i\,\hat{H}_u\,\hat{\nu}_j$$
$$-\,\mu'\,\hat{\eta}\,\hat{\bar{\eta}}\, + Y_x^{ij}\,\hat{\nu}_i\,\hat{\eta}\,\hat{\nu}_j$$

based on B. O'Leary, W.P., F. Staub, arXiv:1112.4600

K-factor for leptonic channels: ~ 1.2

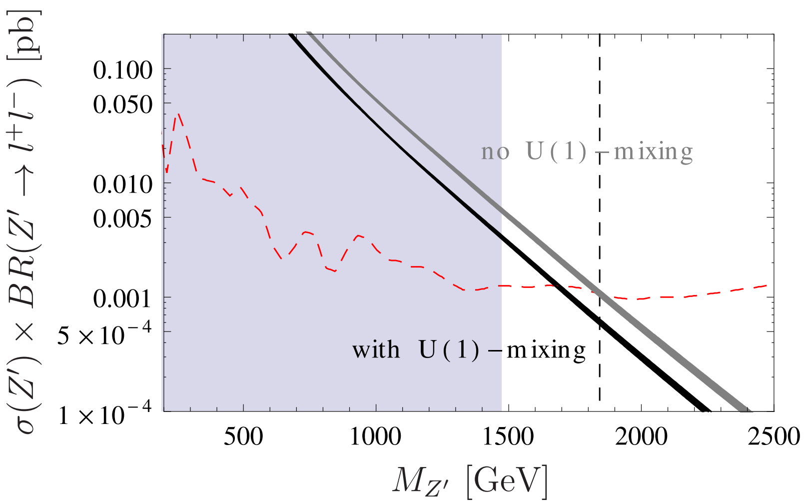
BL1 BL2



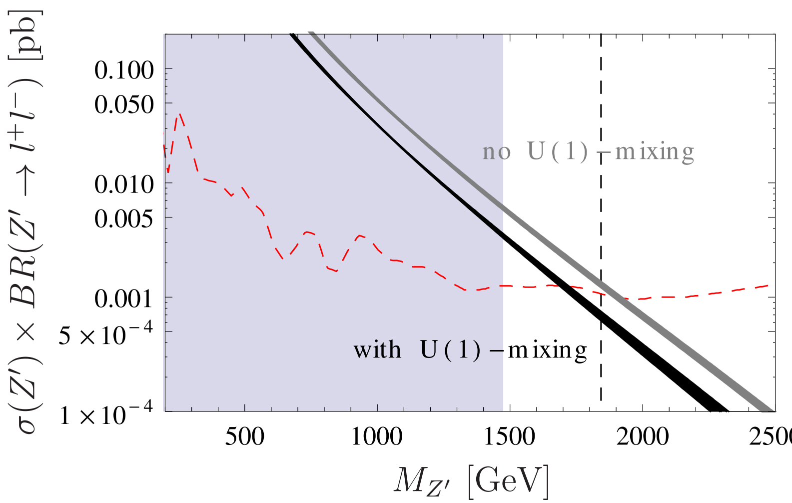
M. Krauss, B. O'Leary, W.P., F. Staub, arXiv:1206.3513

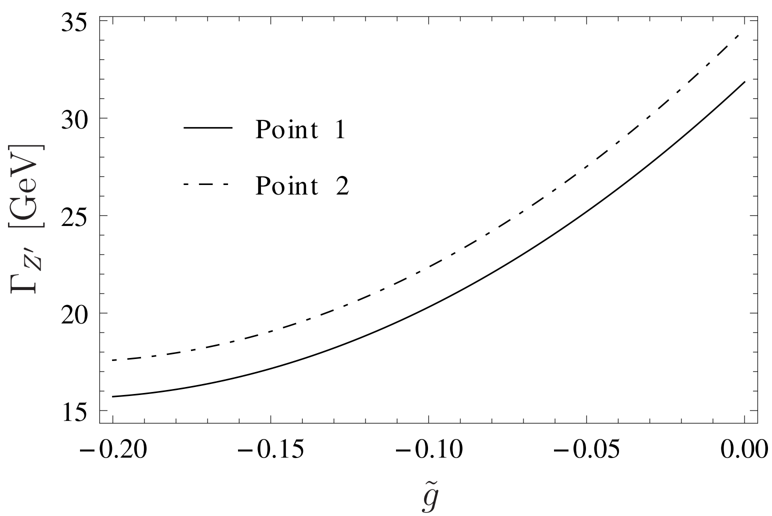
Z' physics, II

BL1



BL2





No.	$\tilde{g} = -0.11$	$\tilde{g} = 0$
BL1	1680 GeV	1840 GeV
BL2	1700 GeV	1910 GeV

Reinterpretation of LHC data

Several programs with partially different philosophies

- CheckMATE, M. Drees et al., arXiv:1312.2591
- Fastlim, M. Papucci et al., arXiv:1402.0492
- MadAnalysis 5, E. Conte et al., arXiv:1206.1599
- Rivet, A. Buckley et al.,arXiv:1003.0694
- SModelS, S. Kraml et al., arXiv:1312.4175

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

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

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

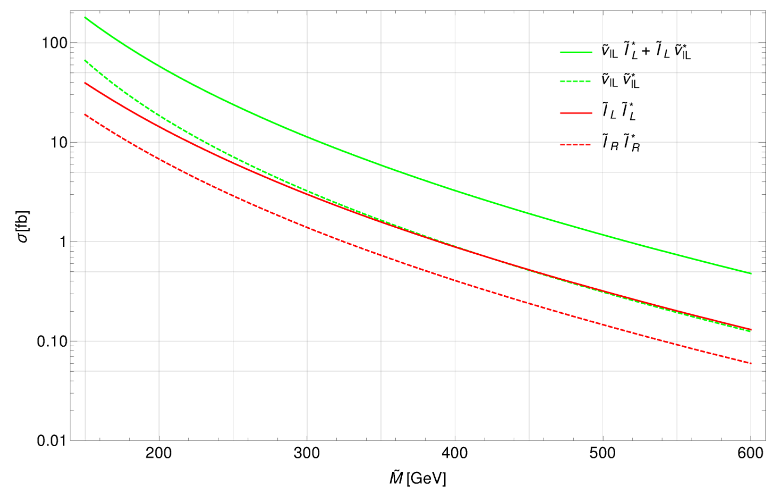
$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\text{NH}})^* \sqrt{\frac{2 m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

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

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

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

search for sleptons

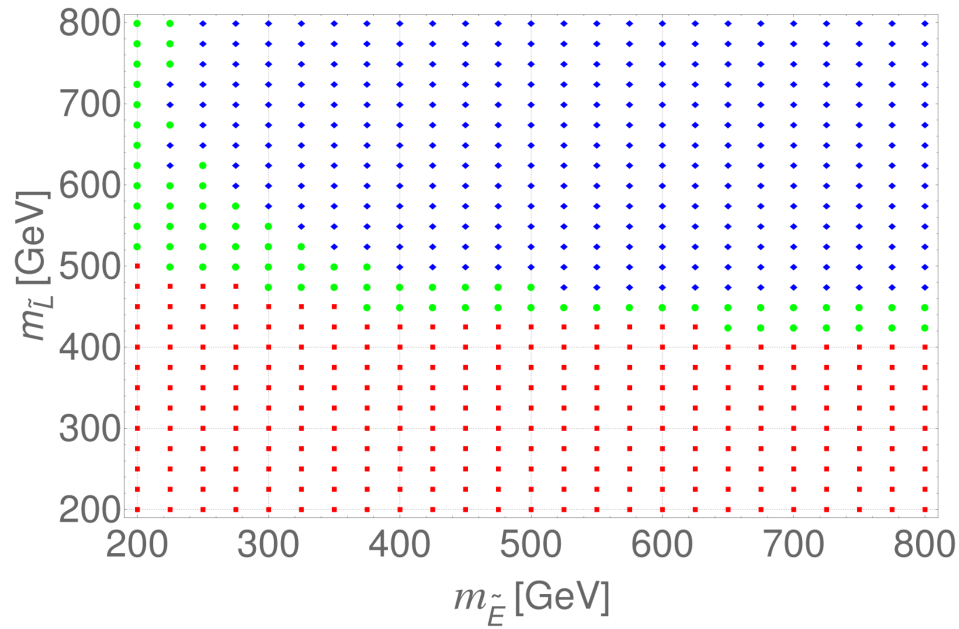


LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

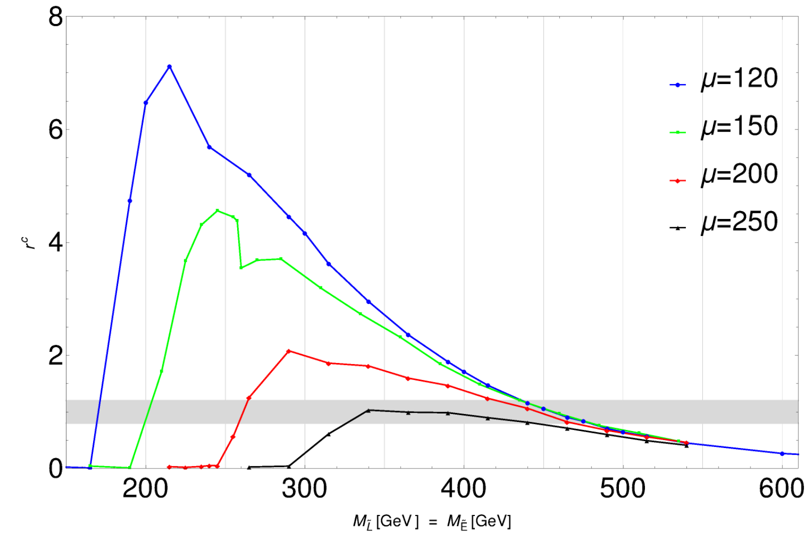
dominant decays:

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

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 , via

$$r = \frac{S - 1.96\Delta S}{S_{obs}}$$

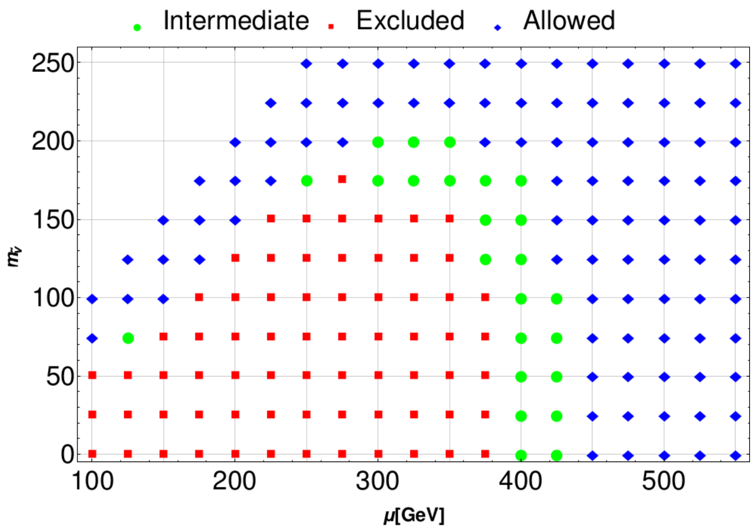
8+13 TeV data (13.9 fb^{-1})

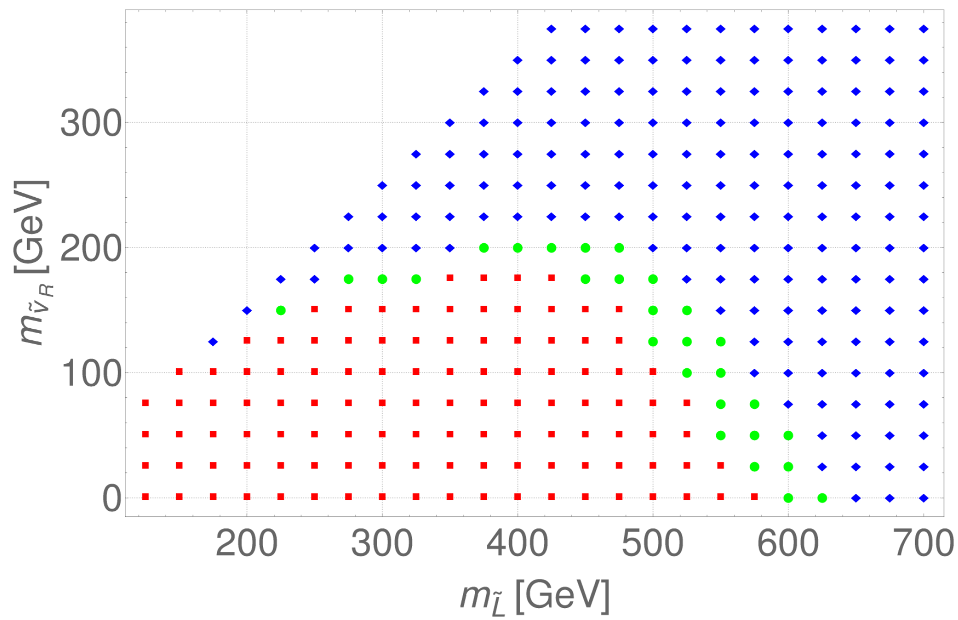
using `CheckMATE 2.0` Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

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

additional constraint

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





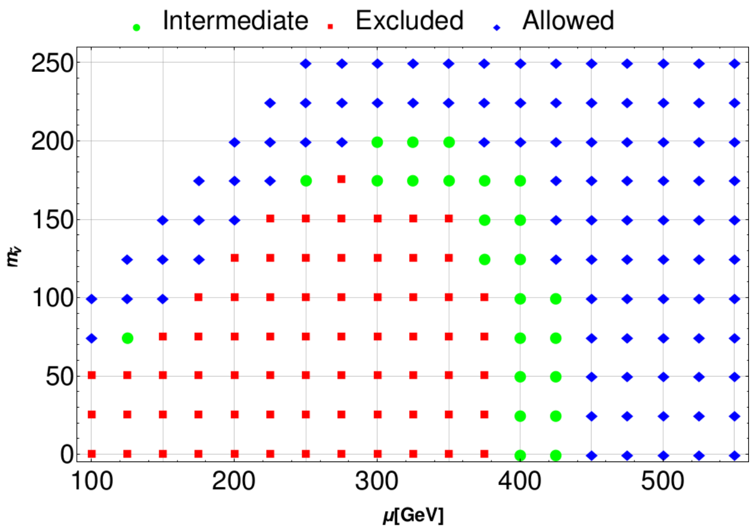
8+13 TeV data (13.9 fb^{-1})
using `CheckMATE 2.0`
$m_{\nu_R} = 20$ GeV

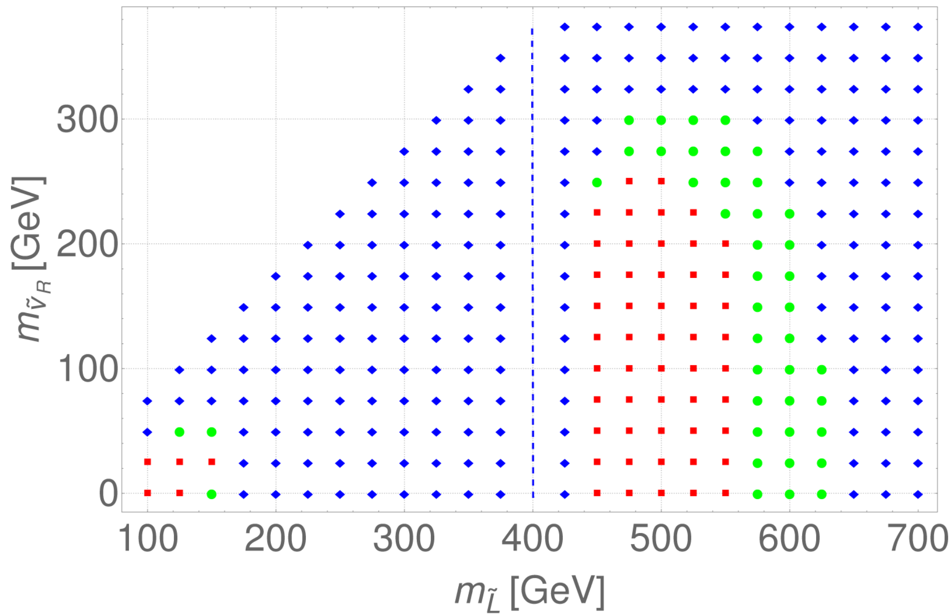
$\mu = 25 + m_{\tilde{\nu}} < m_{\tilde{l}} \simeq m_{\tilde{L}} = m_{\tilde{E}}$
$M_1 = M_2 = 2$ TeV, $\tan\beta = 6$

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

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

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

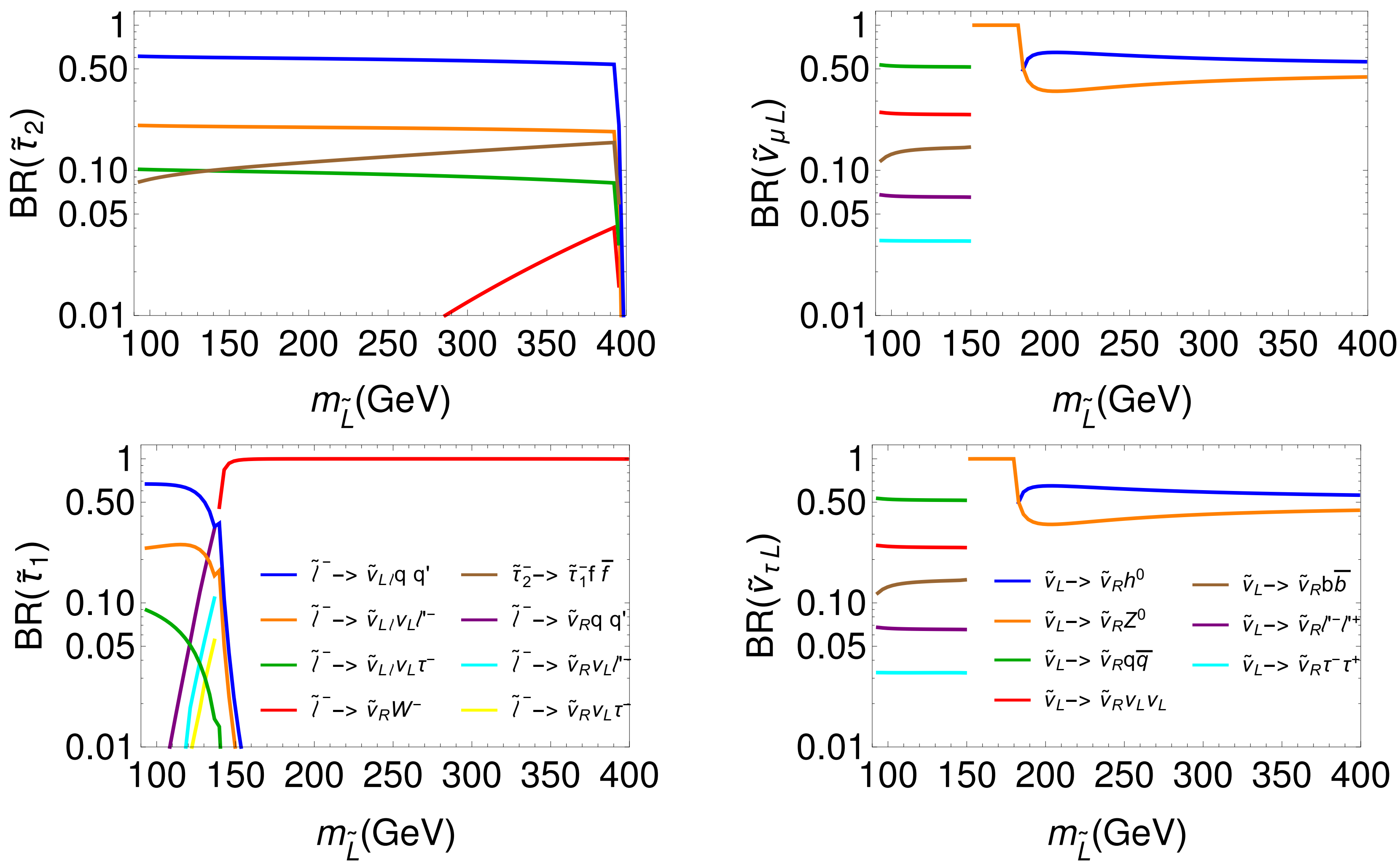
Nh. Cerna-Velazco, Th. Faber, J. Jones, WP arXiv:1705.06583

Concluding remarks

- no conclusive BSM signal so far: need good knowledge of tails of distributions
- QCD corrections (and partially EW corrections) are know for production and decays of several BSM particles
  - strongely interacting SUSY particles
  - electroweak SUSY particles
  - leptoquarks
  - $pp \to Z' \to l^+l^-$, $pp \to W' \to l\nu$
  - extended Higgs sectors
  - ...

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

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



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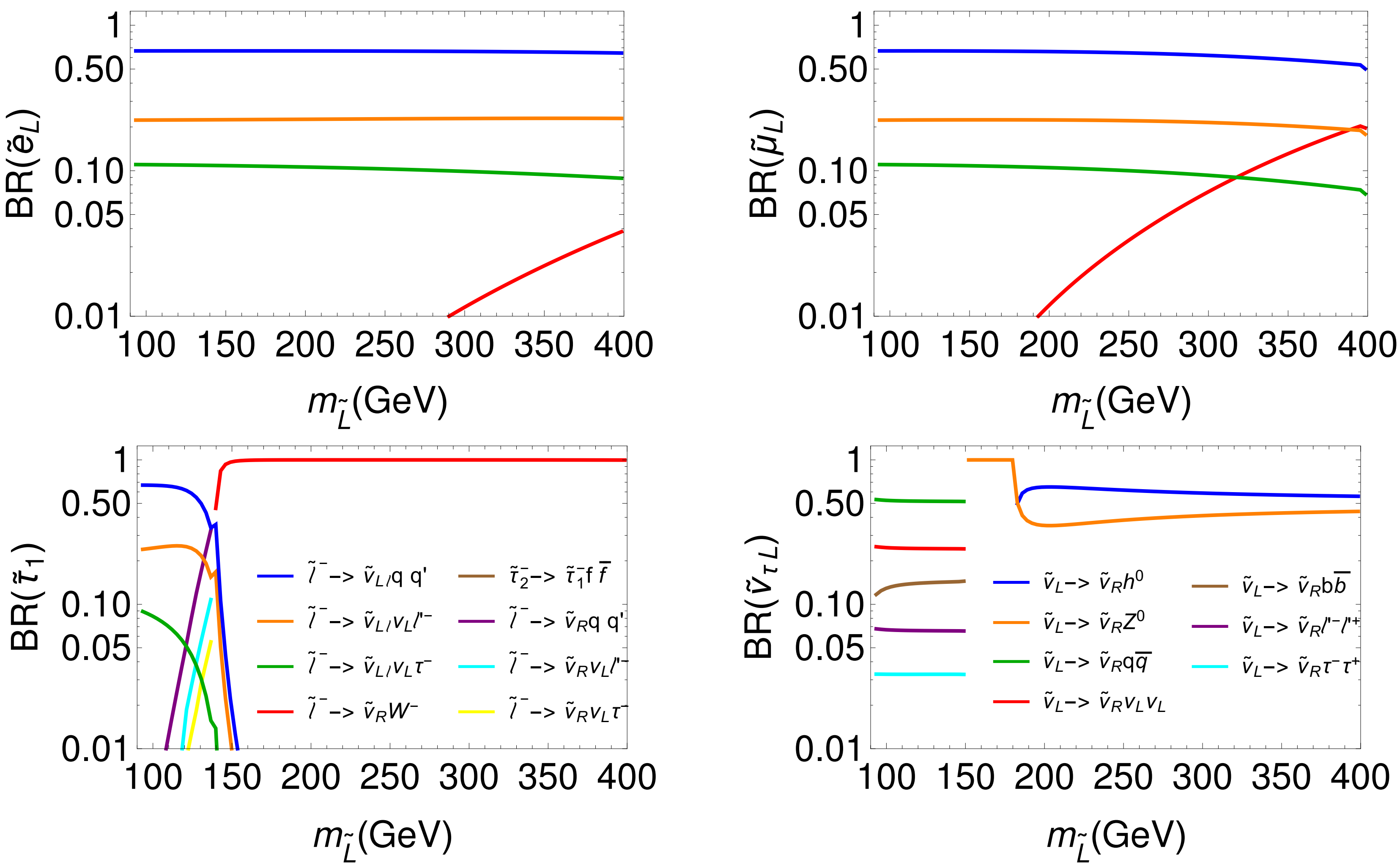
$\tilde{\nu}_R$-LSP, 3-body decays

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



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