TRIUMF THEORY

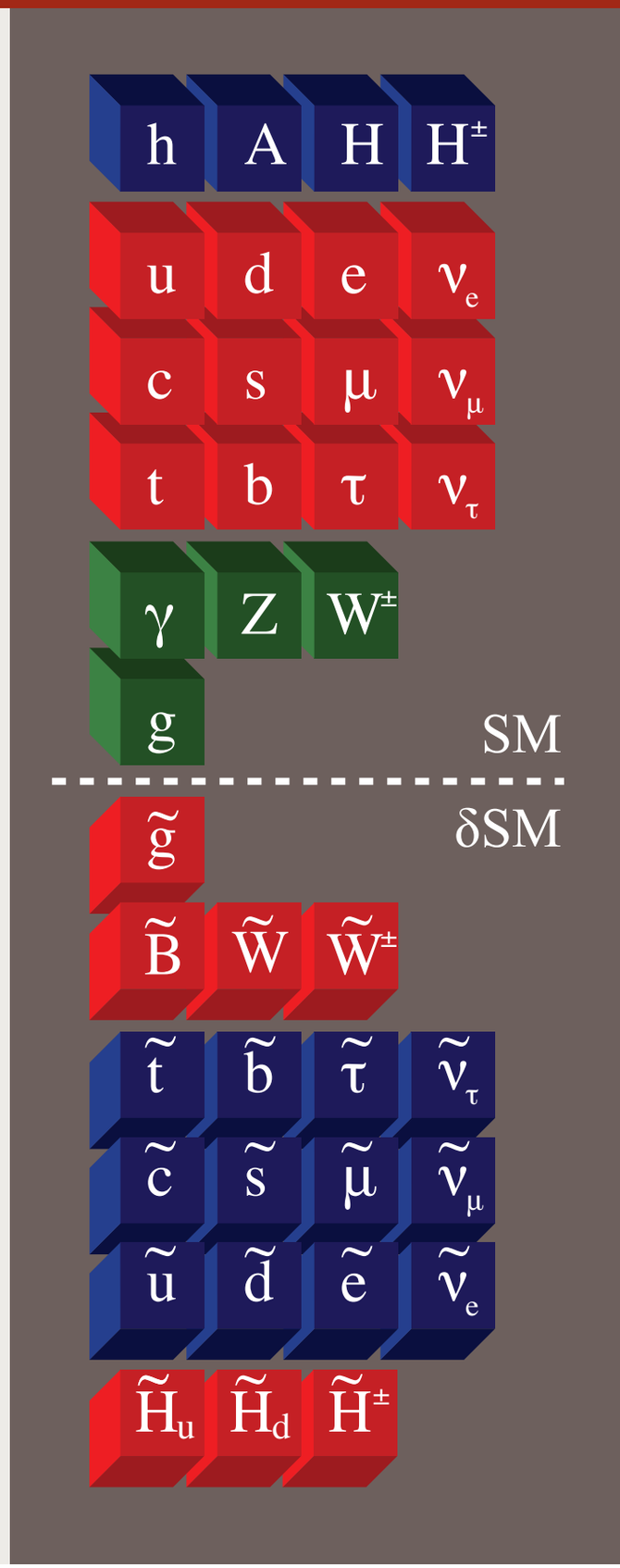
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

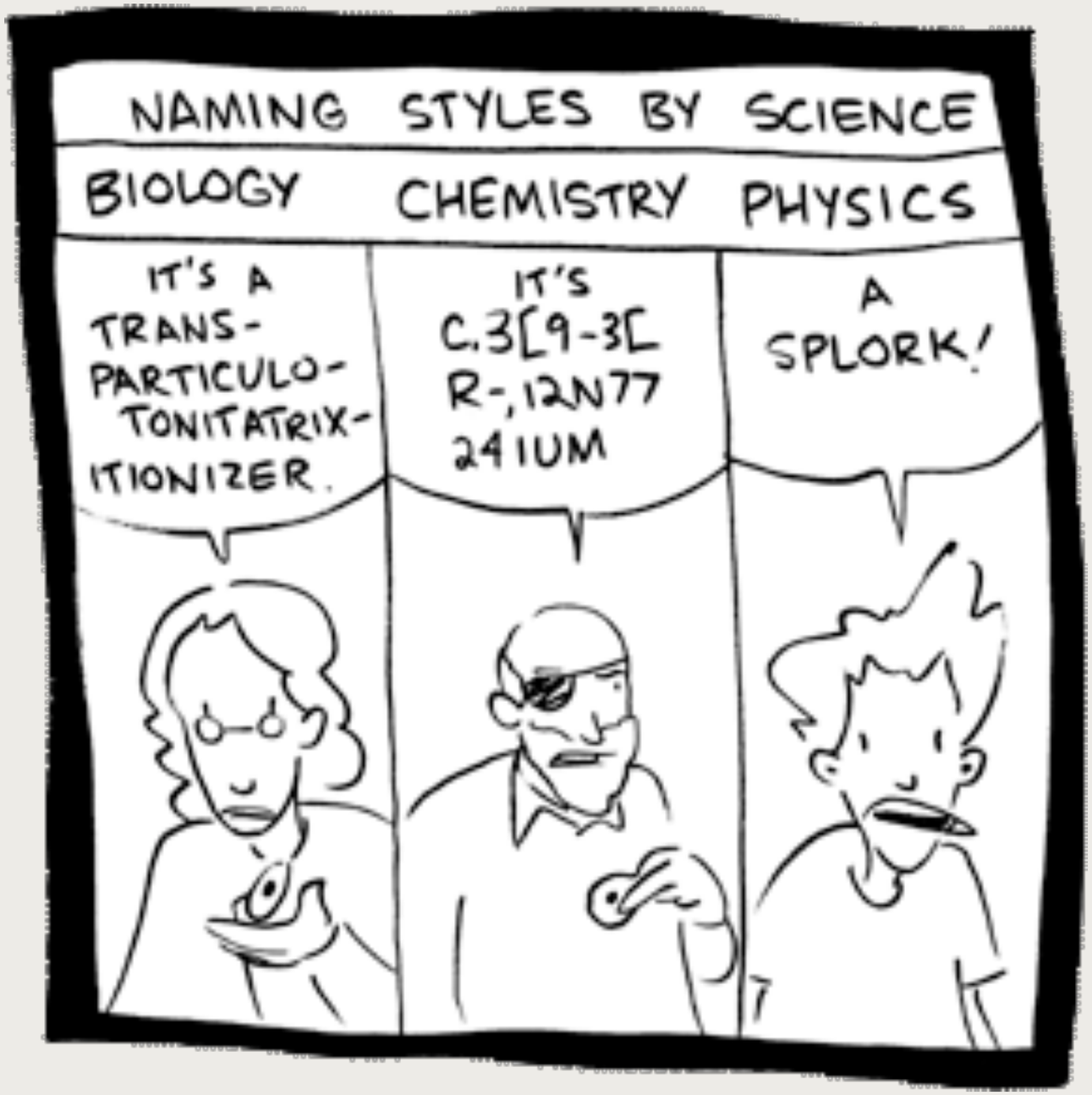
Electroweakino Constraints from LHC8

Travis Martin, TRIUMF
with David Morrissey, TRIUMF

Fermilab

Based on arXiv:1409.6322





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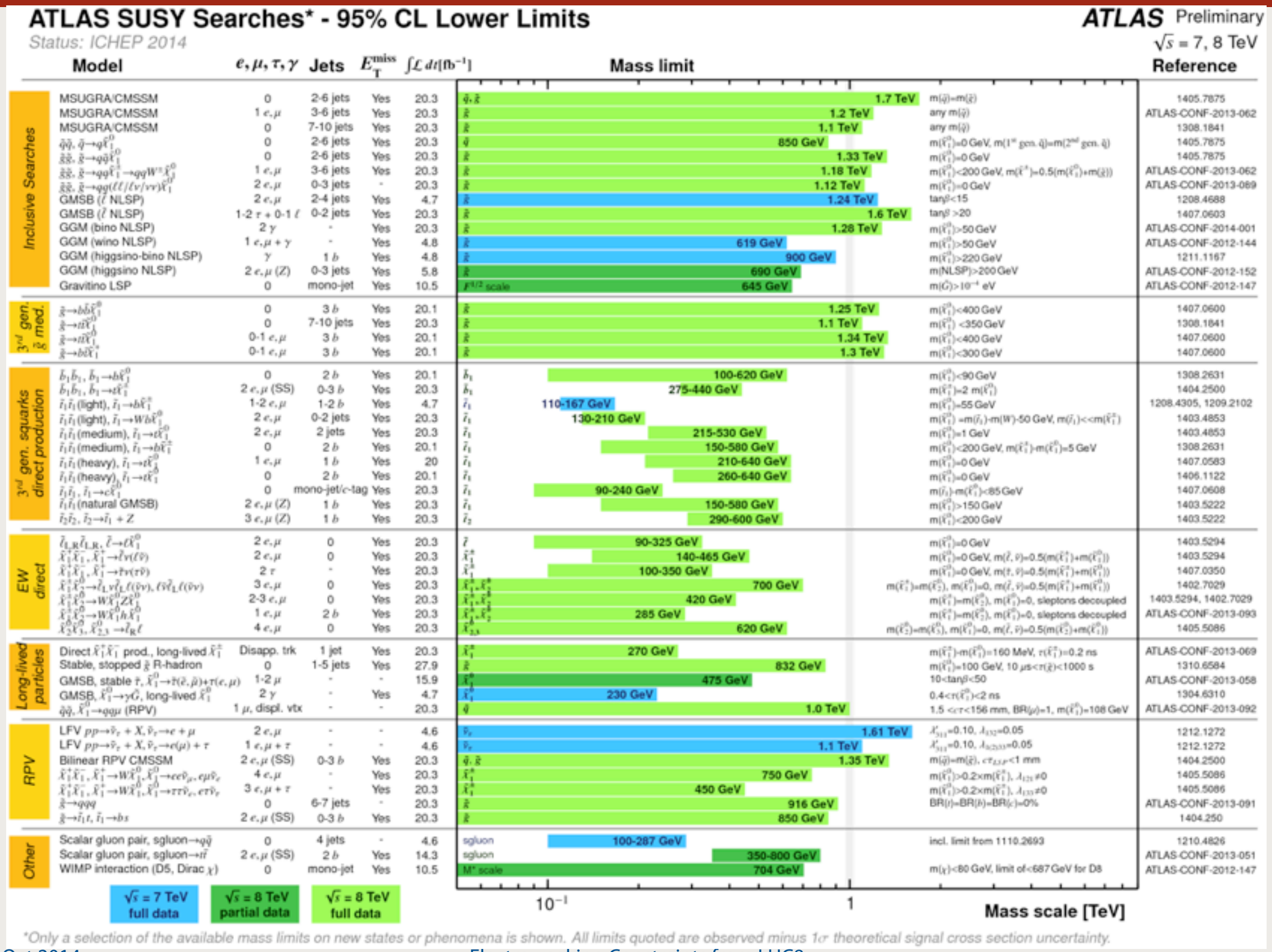
Overview

- SUSY/MSSM
- Properties of Electroweakinos
- Methodology for recasting measurements
- Results

Current Limits



Standard Model

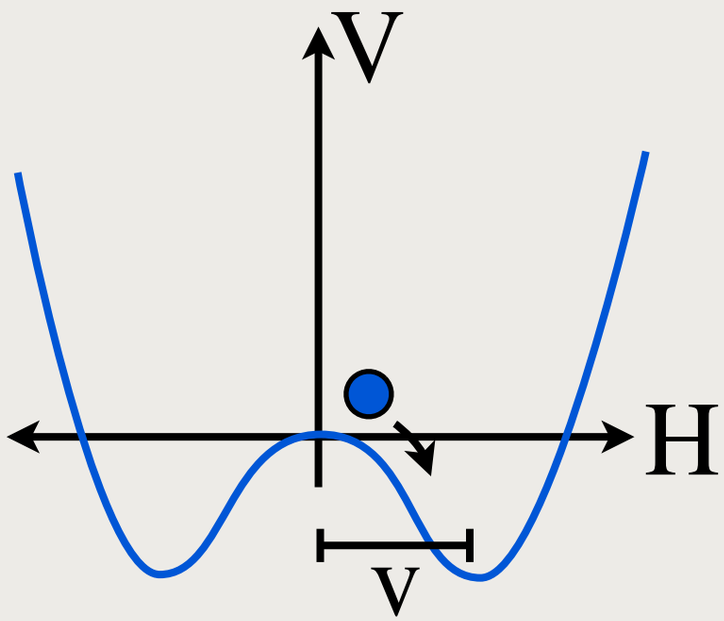
- Bare mass breaks gauge invariance

$$L = \cancel{-m\bar{\psi}_L\psi_R} \qquad L = -y\, H\cdot\bar{\psi}_L\psi_R$$

- SM Spontaneous Symmetry Breaking

$$V = -\mu^2 H^2 + \lambda H^4$$

$$H \rightarrow H + v$$

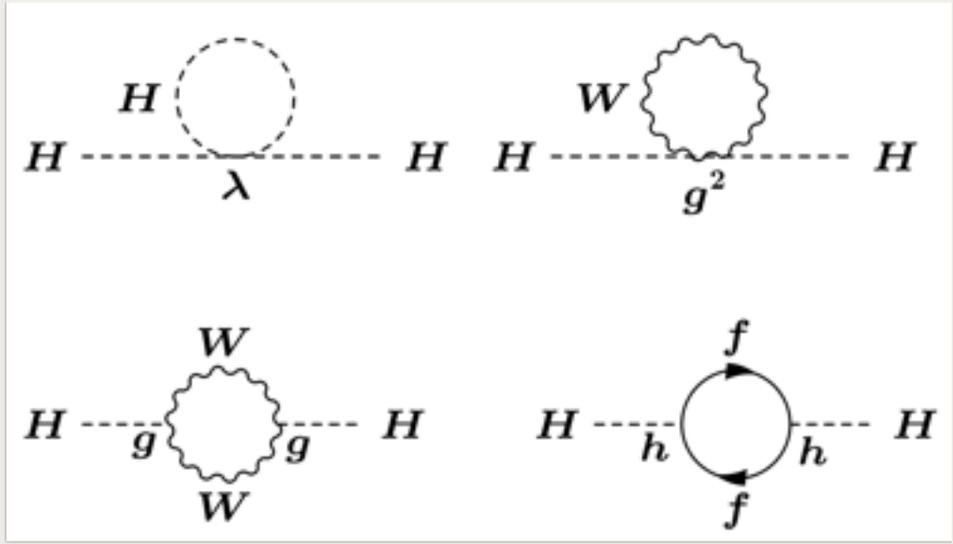


Higgs Mass Dilemma

- Corrections to Higgs mass

$$M_H^2 = (M_H^2)_{bare} + \mathcal{O}(\lambda, g^2, h^2)\Lambda^2$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots.$$



- But...

$$\Delta m_H^2 = \frac{1}{8\pi^2}(\lambda_S - |\lambda_f|^2)\Lambda_{\rm UV}^2 + \ldots.$$

Supersymmetry

- Propose a new symmetry

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle.$$

Bonus: R-parity

- Minimal Supersymmetric Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L \;\; \tilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu} \;\; \tilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\tilde{H}_u^+ \;\; \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\tilde{H}_d^0 \;\; \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm \;\; \tilde{W}^0$	$W^\pm \;\; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Details of MSSM

- Exact Supersymmetry? $\cancel{M_S = M_F}$
  - Soft SUSY breaking

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right) \\
& -\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\tilde{L}H_d + \text{c.c.}\right) \\
& -\tilde{Q}^\dagger\,\mathbf{m_Q^2}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m_L^2}\,\tilde{L} - \tilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\tilde{\bar{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}
$$

- Can reduce number of parameters by making assumptions, e.g. about behaviour at high energies

- pMSSM: 19 Parameters

Coloured Object Constraints

$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)
$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV

Electroweakino Constraints

EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3

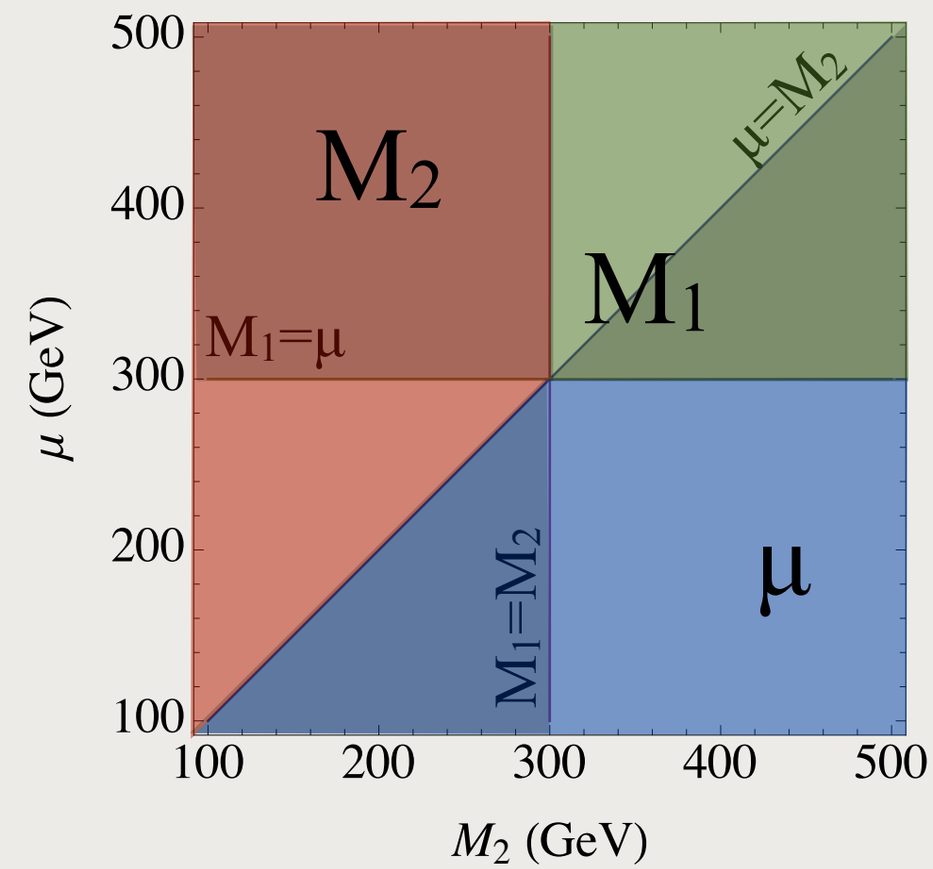
- Simplified models assume
  - intermediate sleptons
  - simplified hierarchy ($M_1 < M_2 << \mu$)
  - $M_1 \sim$ 0-50 GeV

pMSSM

- Electroweakinos
  - Neutralinos & Charginos

- pMSSM
  - $(M_1,M_2,\mu) \sim$ 20-500 GeV
  - $\tan\beta = 10$
  - $M_{other} = 2000$ GeV

- Six hierarchies
  - Region 1: $M_1<M_2,\mu$
  - Region 2: $M_2<M_1,\mu$
  - Region 3: $\mu<M_2,M_1$



Mass Eigenstates

- Charginos ($H^{\pm}$, $W^{\pm}$)

$$\chi_i^+ = \boxed{V_{ij}}\psi_j^+$$

$$\chi_i^- = \boxed{U_{ij}}\psi_j^-$$

$$-\mathcal{L}_{\pm} \supset (\psi^-)^t X \psi^+ + (h.c.)$$

$$X = \begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix}$$

- Neutralinos (B, W, H_u, H_d)

$$\chi_i^0 = \boxed{N_{ij}}\psi_j^0$$

$$-\mathcal{L} \supset \frac{1}{2}(\psi^0)^t Y \psi^0 + (h.c.)$$

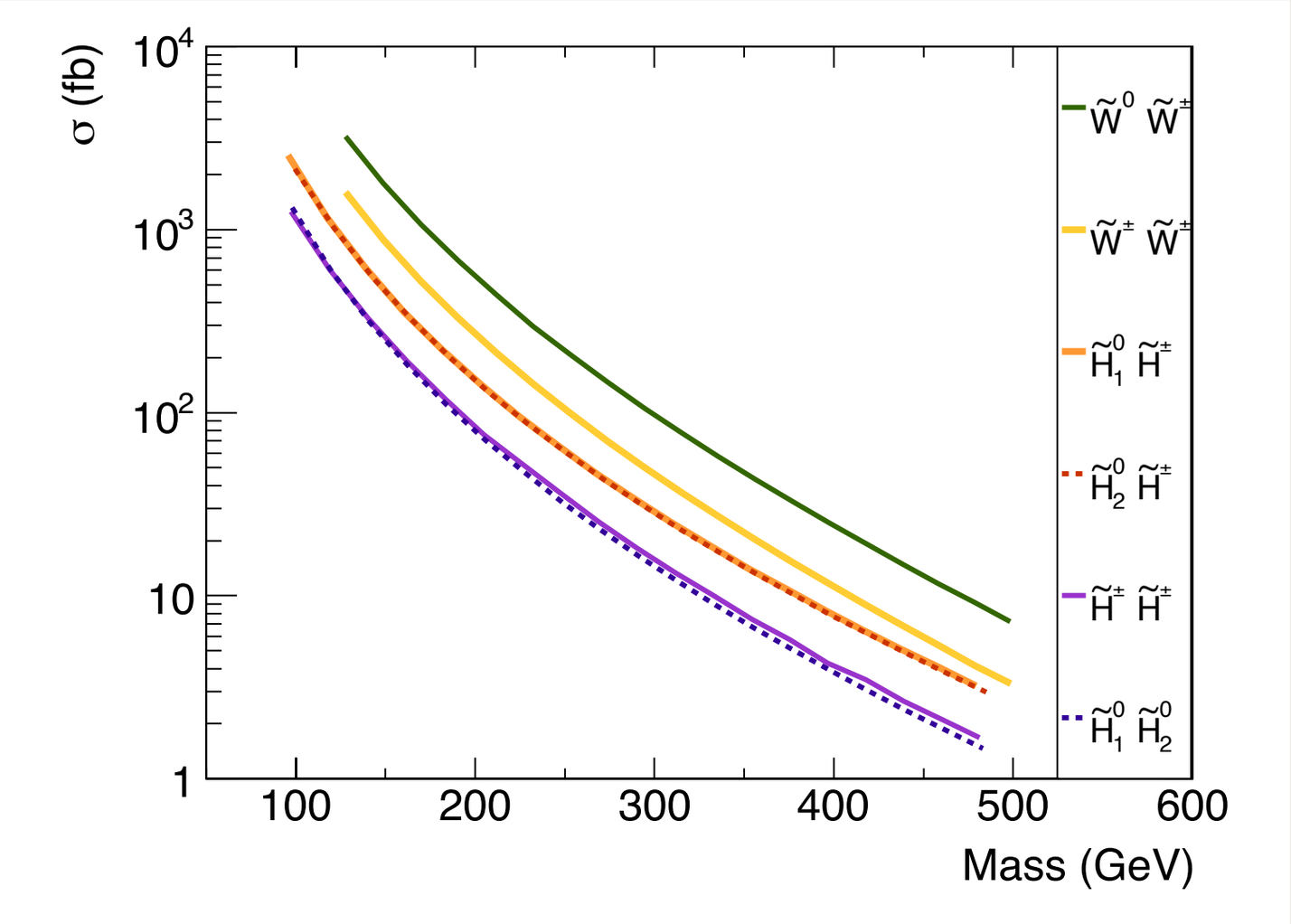
$$Y = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

$H_{\pm}=(H_u \pm H_d)/\sqrt{2}$

Production Rates

- "Pure" state limit
  - $pp \rightarrow \gamma^*/Z^* \rightarrow \chi^\pm\chi^\pm$
  - $pp \rightarrow W^{\pm *} \rightarrow \chi^0\chi^\pm$
  - $pp \rightarrow Z^* \rightarrow \chi^0\chi^0$

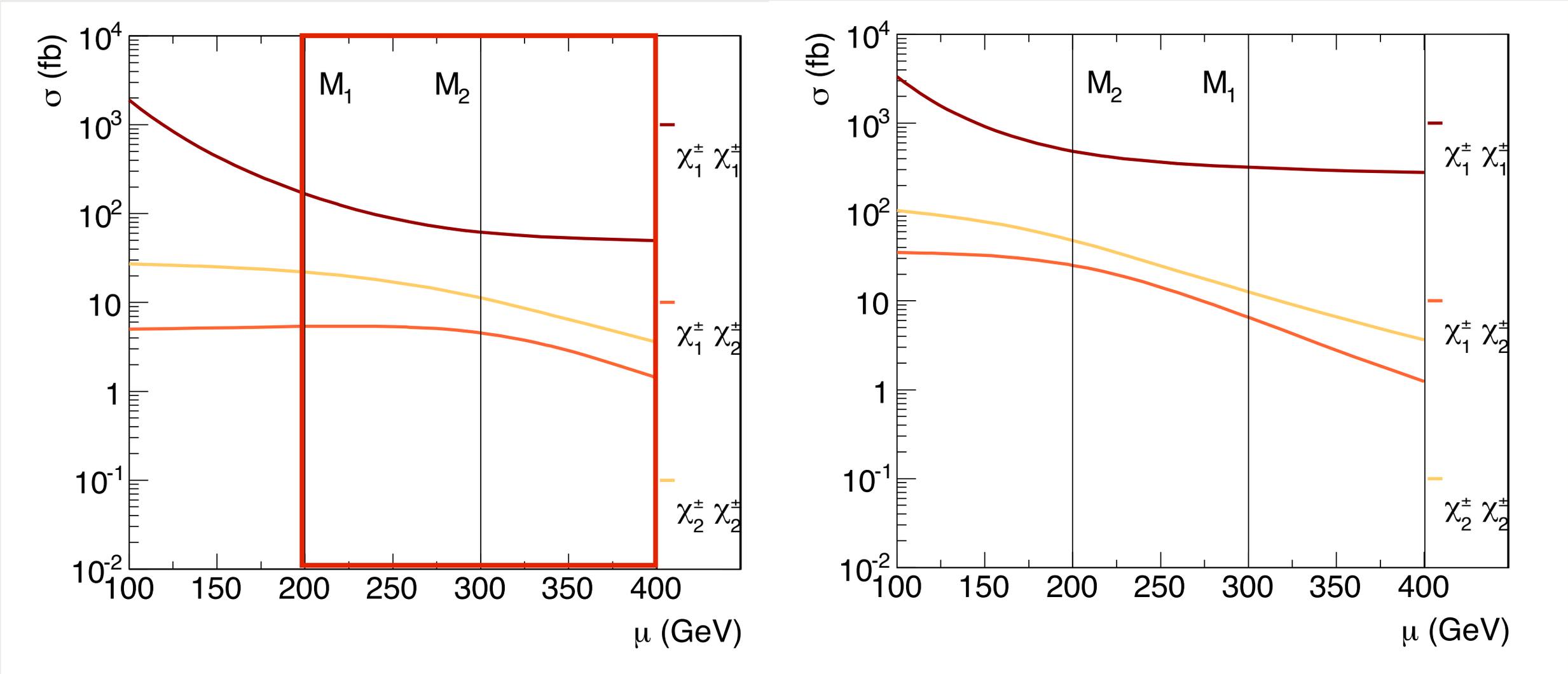
LHC8



- $H_1 = H_+$ & $H_2 = H_-$ $\quad H_\pm = (H_u \pm H_d)/\sqrt{2}$
- Neglect Higgs production

Hierarchies $M_1<M_2$

$\chi_i^\pm \chi_j^\pm$

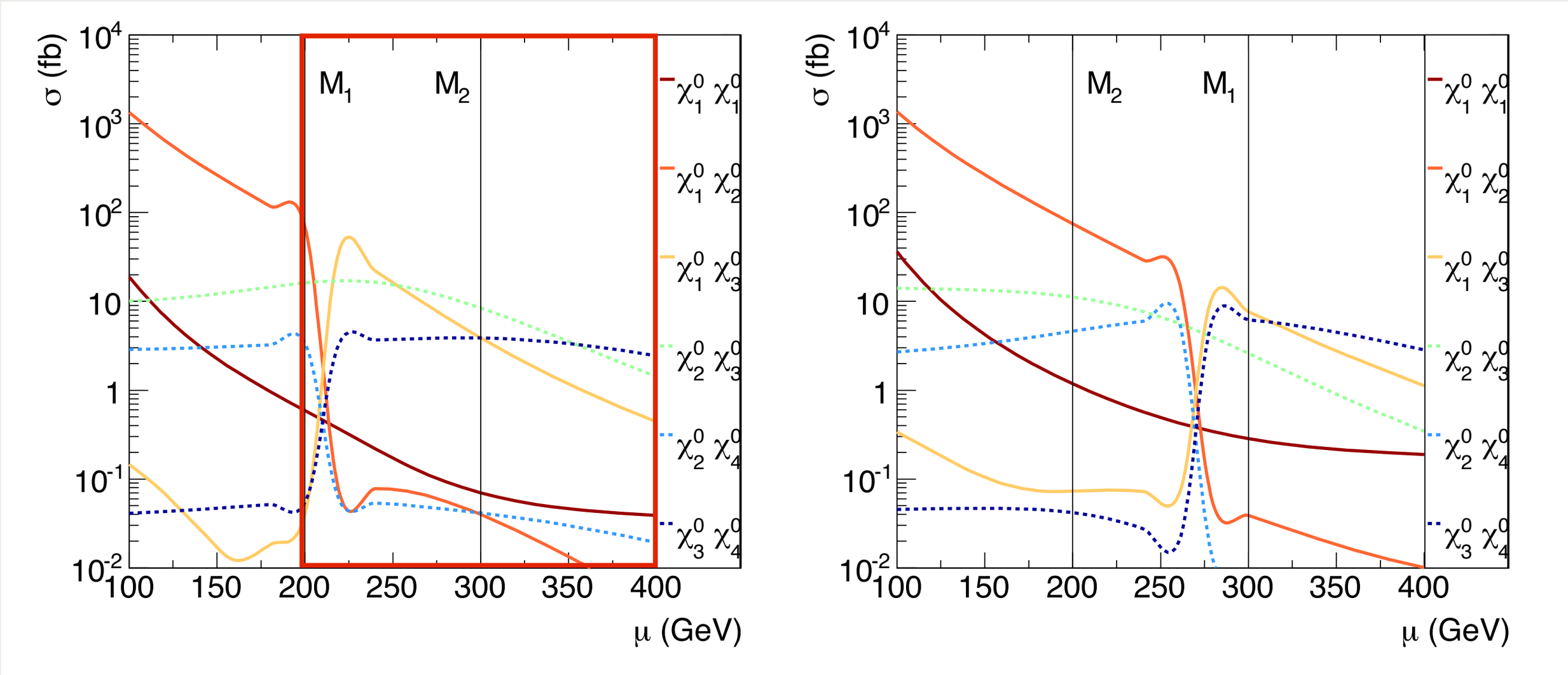


$$g_L/g = V_{iW} V_{jW}^* + 1/2 V_{iH} V_{jH}^* - \delta_{ij} s_W^2$$

$$g_R/g = U_{iW}^* U_{jW} + 1/2 U_{iH}^* U_{jH} - \delta_{ij} s_W^2$$

Hierarchies $M_1 < M_2$

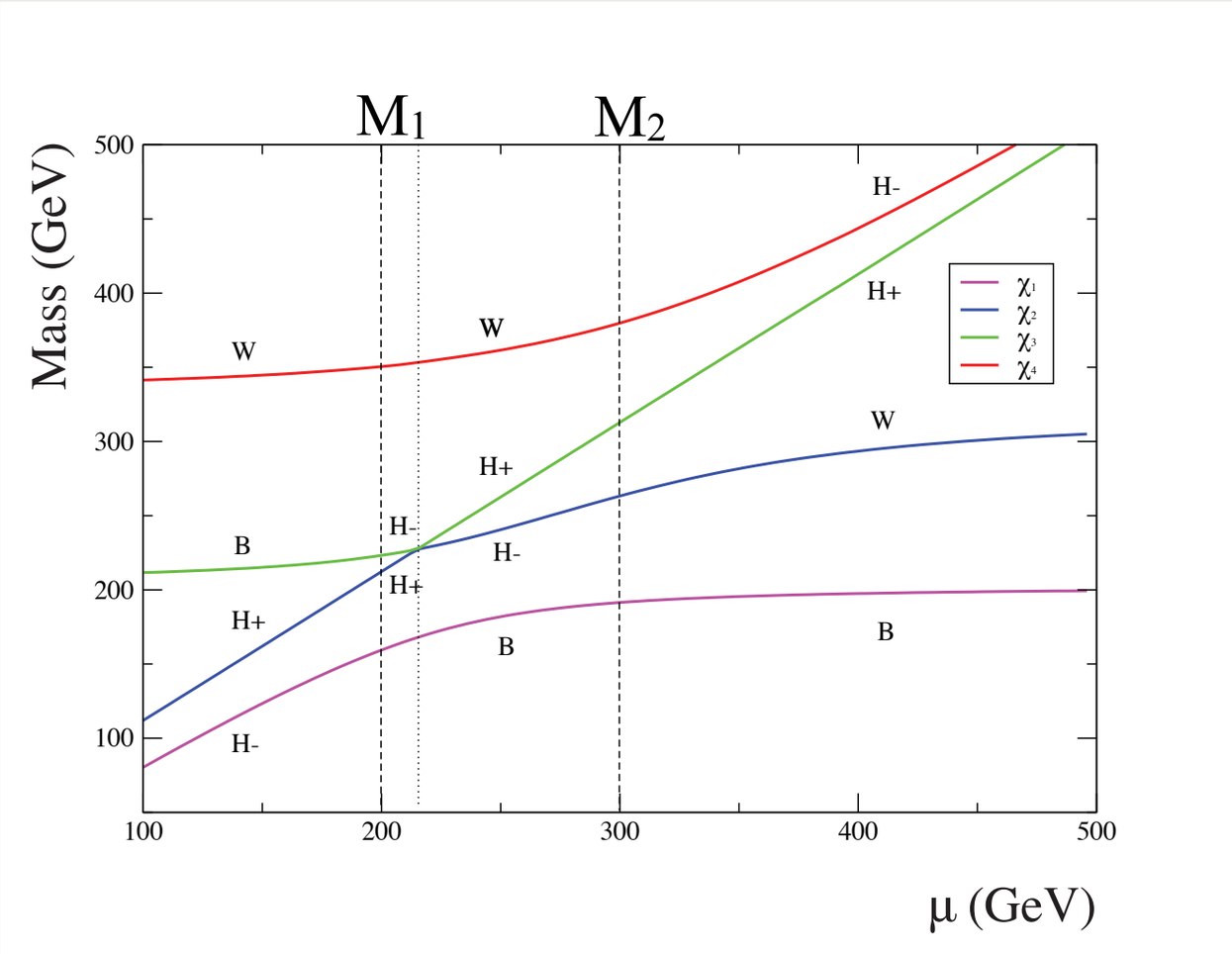
$\chi_i^0 \chi_j^0$

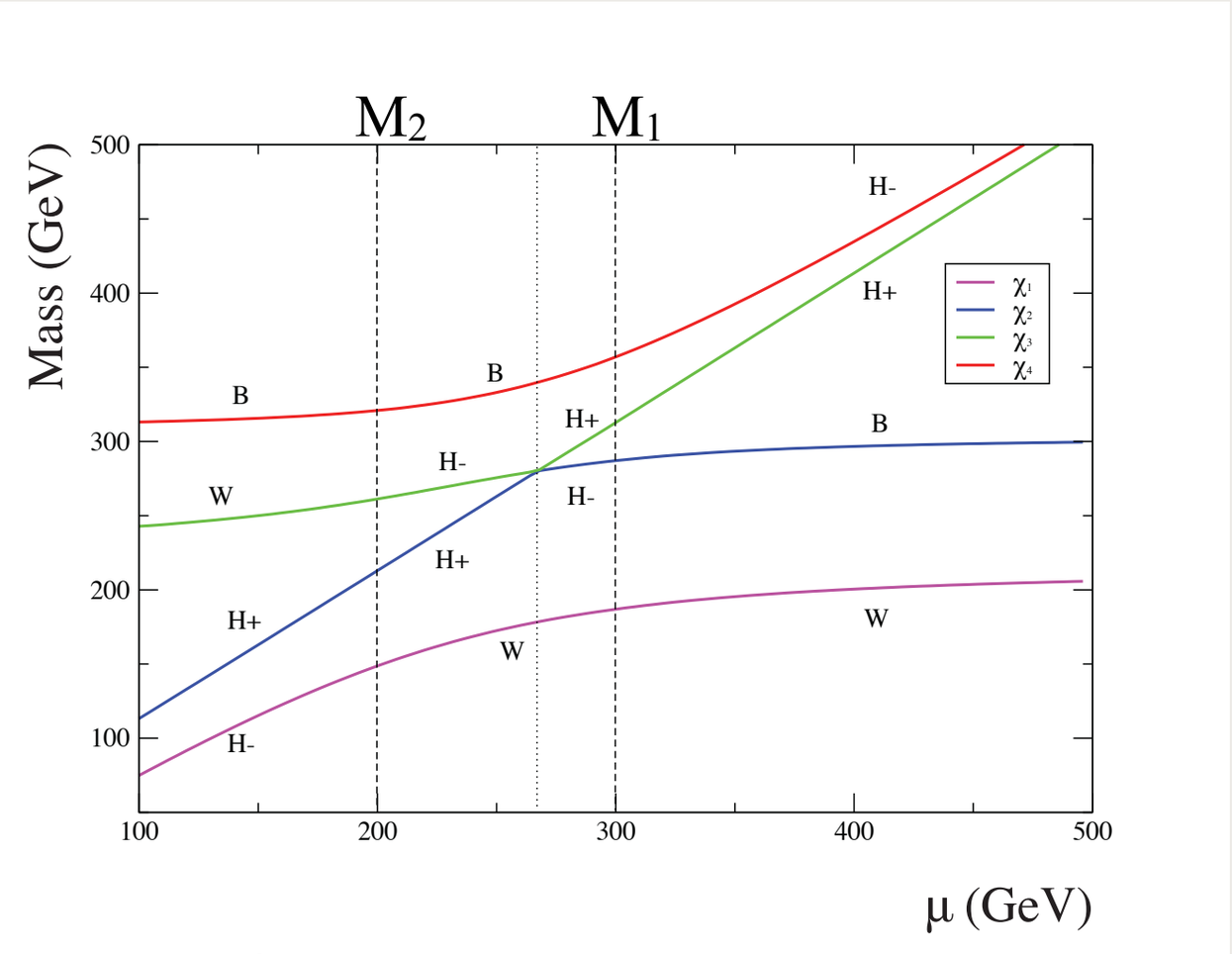


$$g_L/g_Z = N_{iH1} N_{jH1}^* + N_{iH2} N_{jH2}^*$$

$$g_R/g_Z = N_{iH1}^* N_{jH1} + N_{iH2}^* N_{jH2}$$

Neutral Mixing





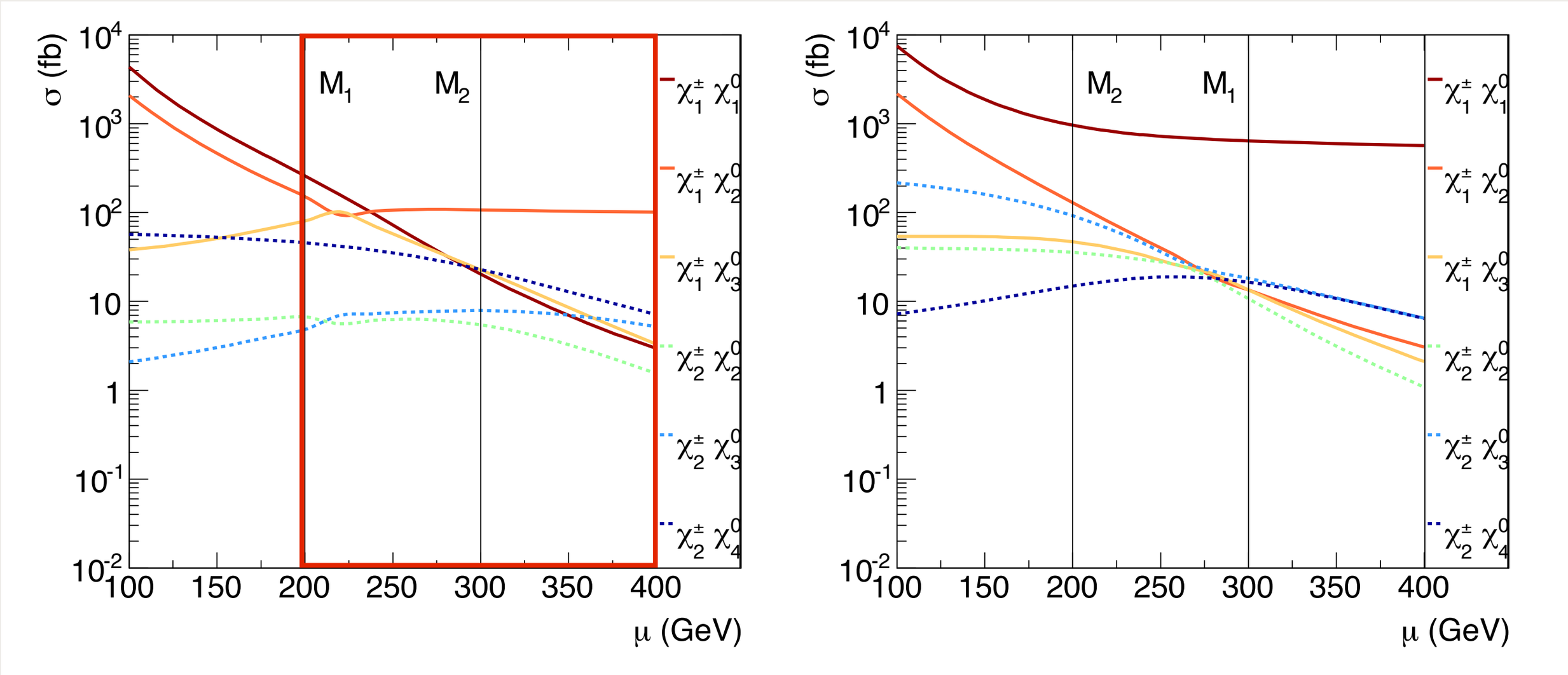
$$H_{\pm}=(H_u \pm H_d)/\sqrt{2}$$

$$\text{Mixing} \sim m_Z/|\mu \pm M_{1,2}|$$

(In region where μ & $M_{1,2}$ positive)

Hierarchies $M_1<M_2$

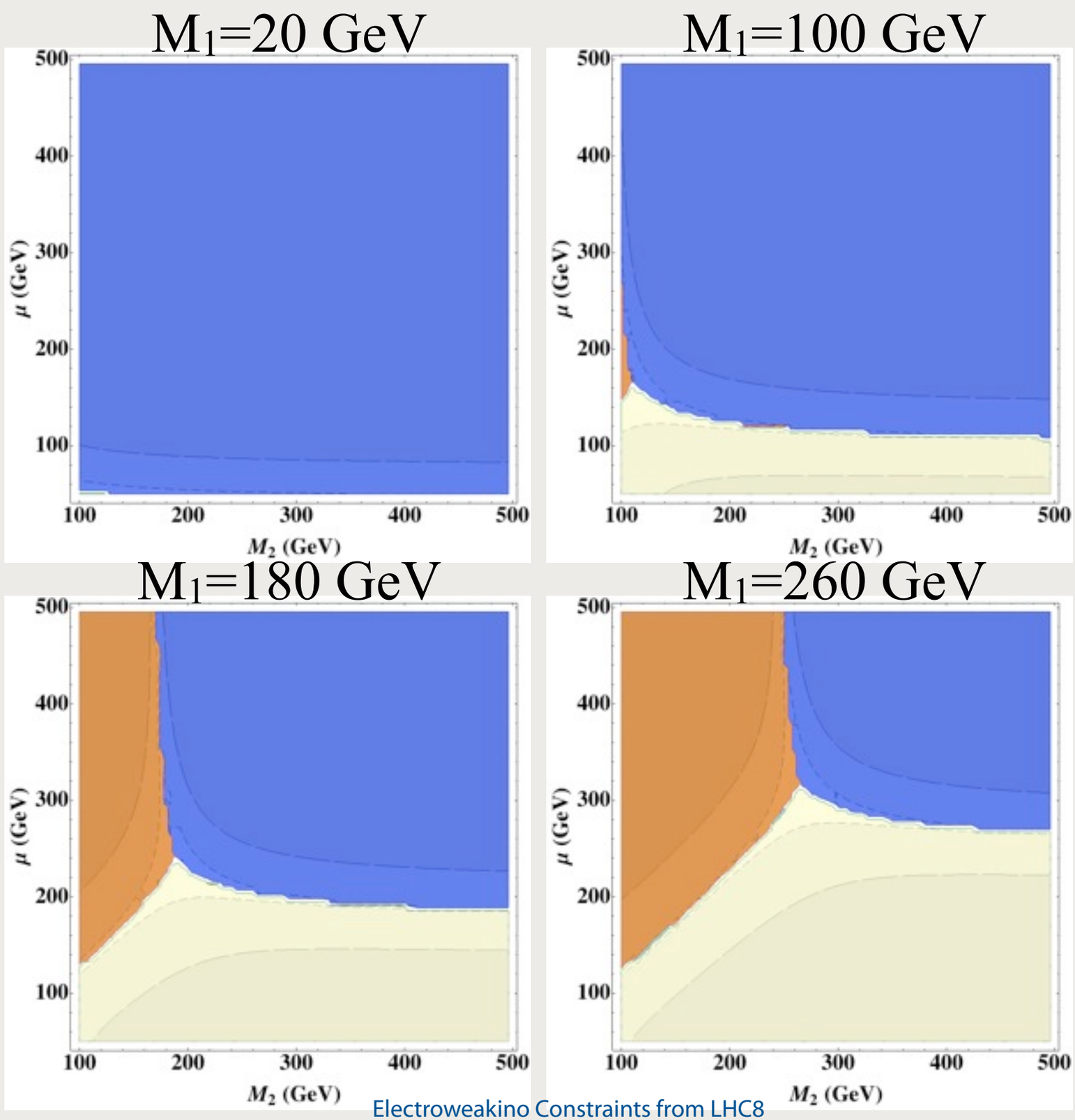
$\chi_i^0\ \chi_j^\pm$



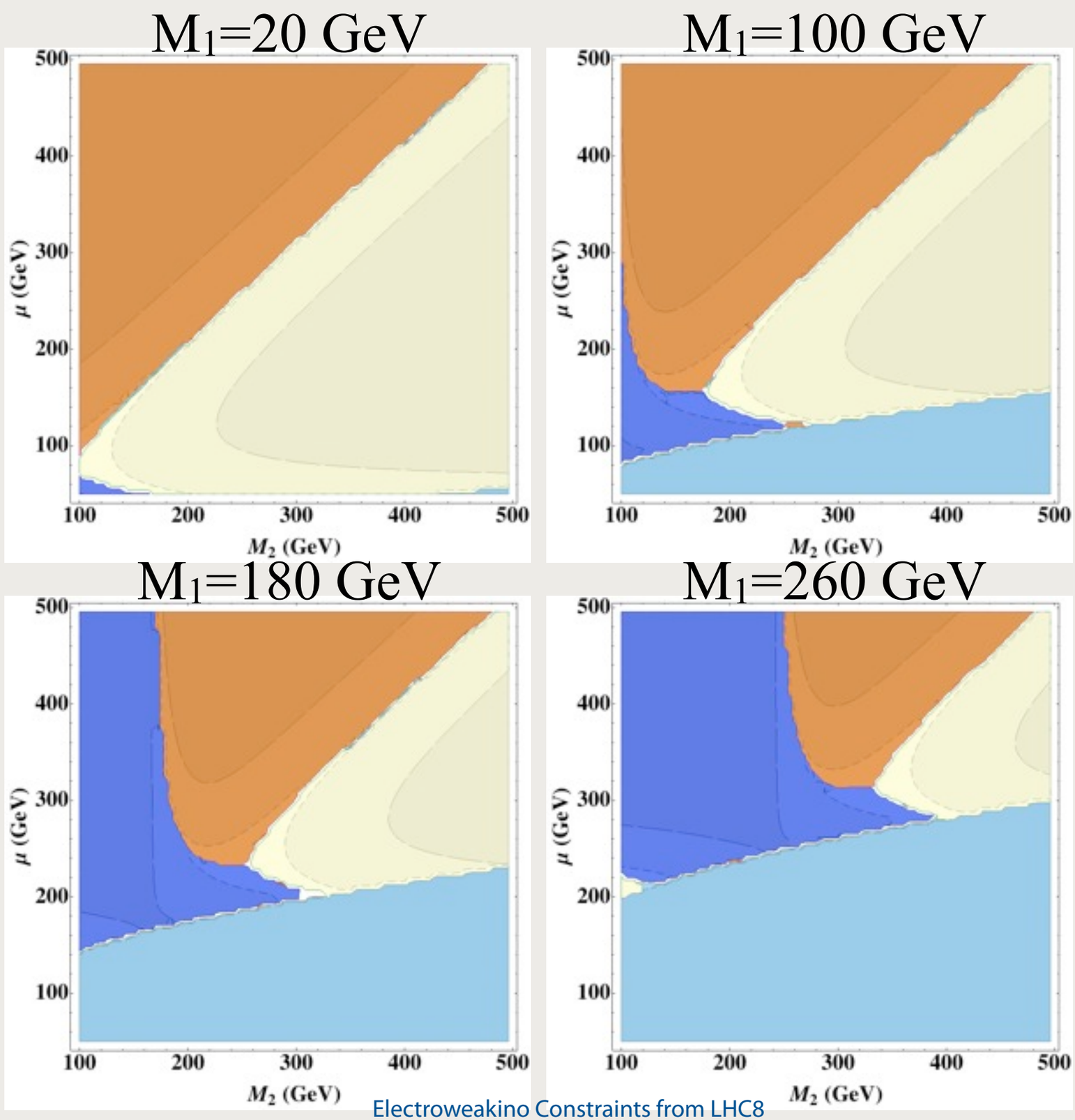
$$g_L/g = N_{iW} V_{jW}^* + N_{iH1} V_{jH}^* / \sqrt{2}$$

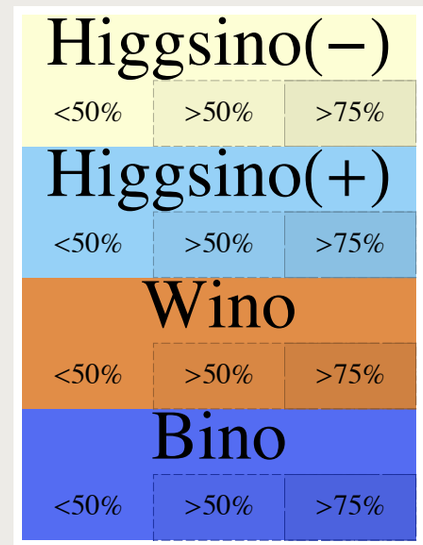
$$g_R/g = N_{iW}^* U_{jW} + N_{iH2}^* U_{jH} / \sqrt{2}$$

Composition - χ_1^0

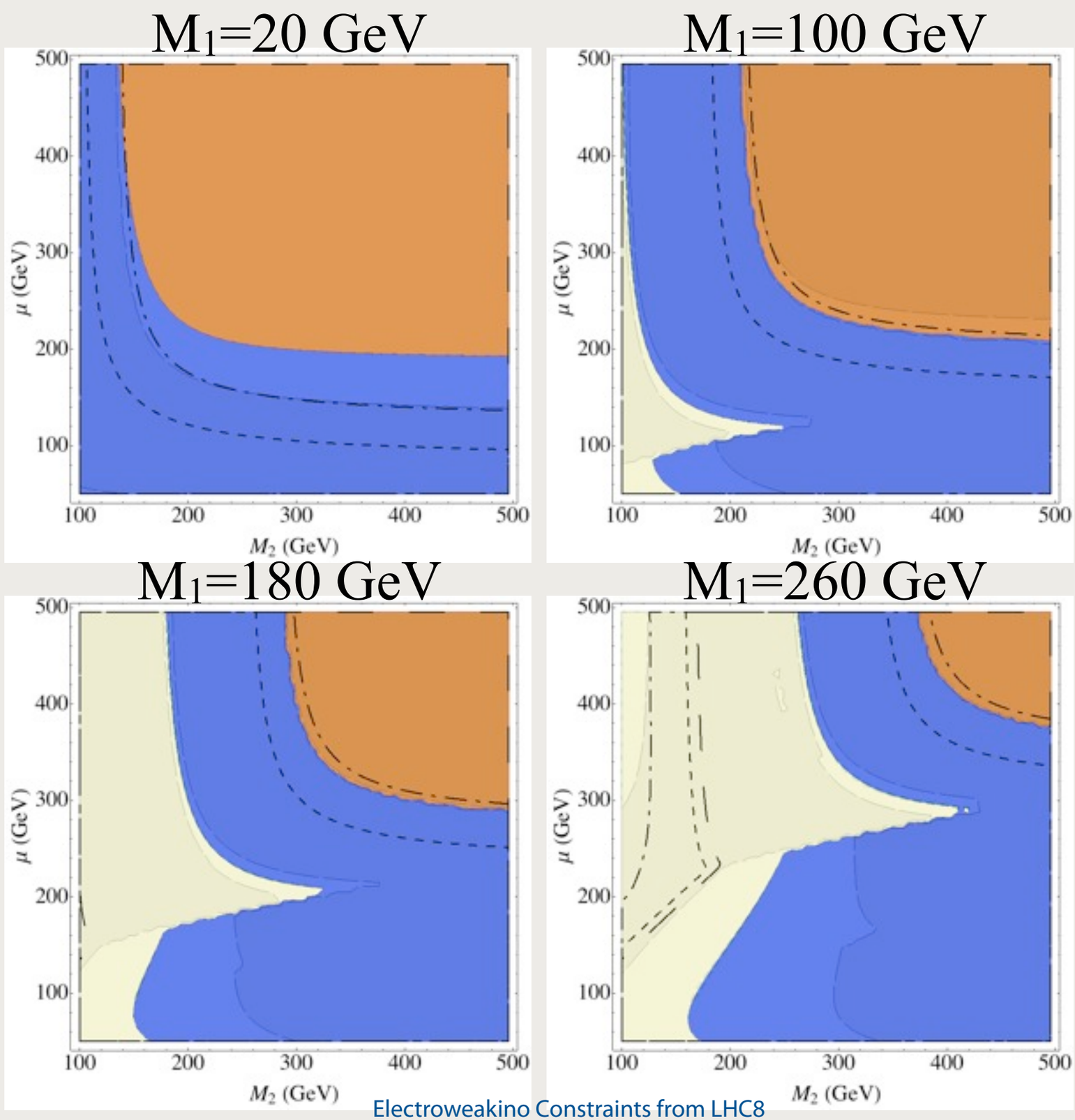


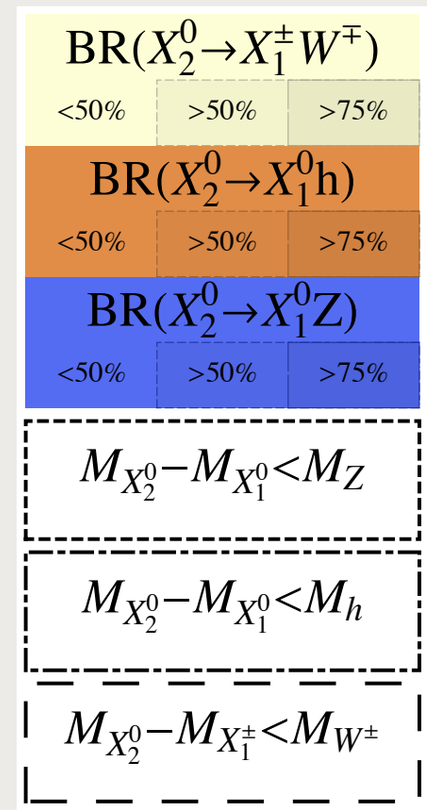
Composition - χ_2^0



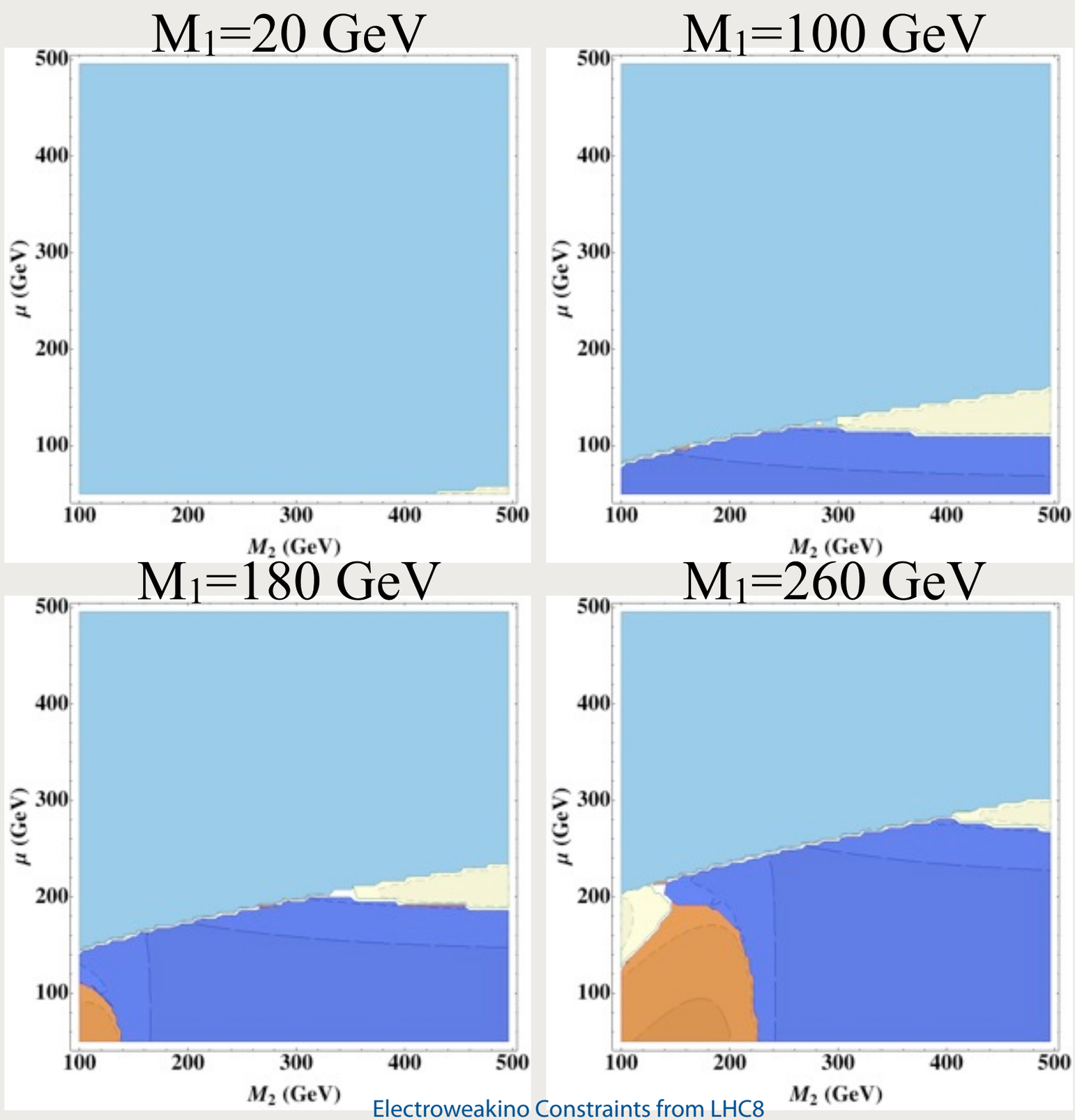


Primary Decay Modes - χ_2^0

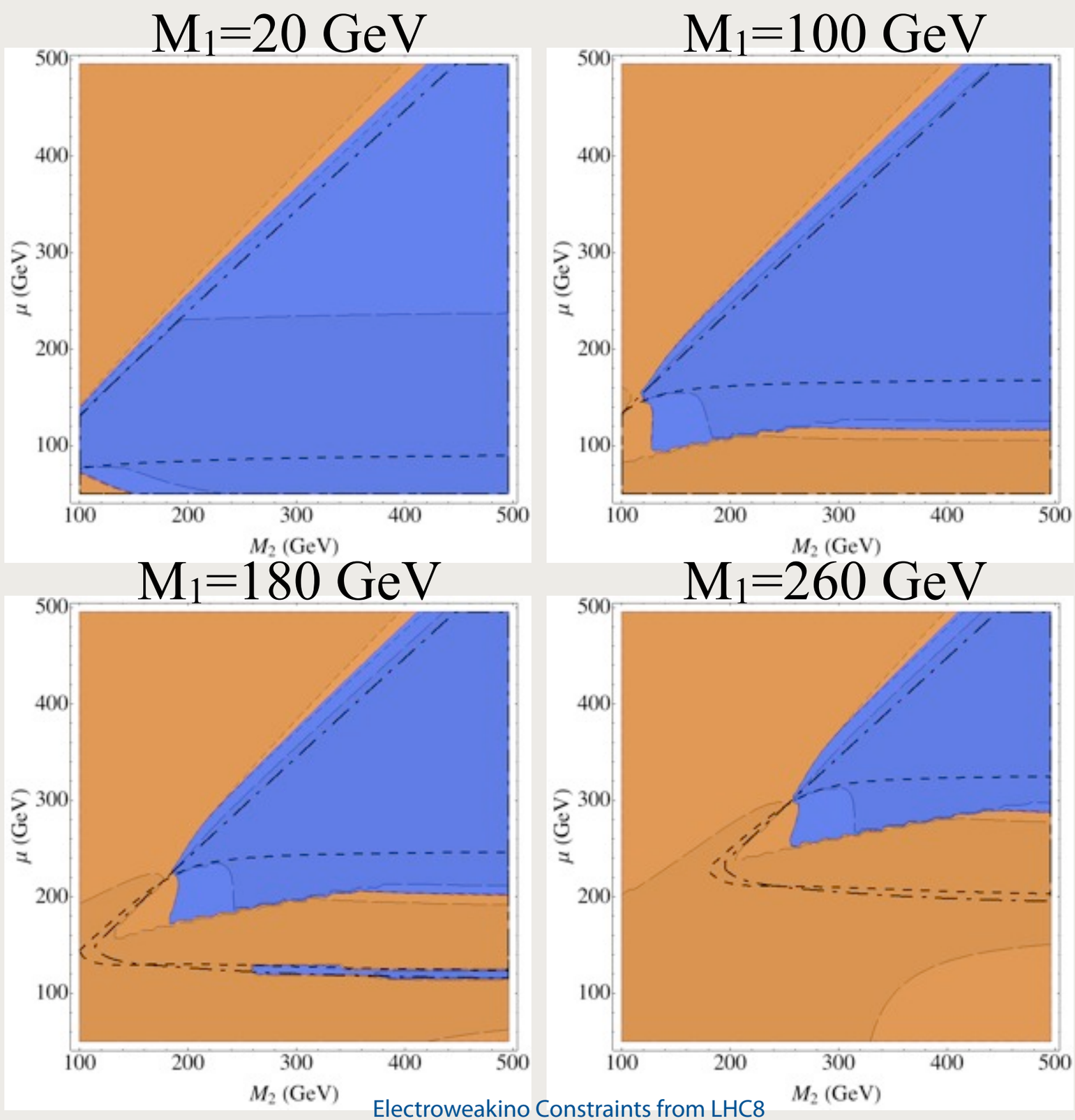


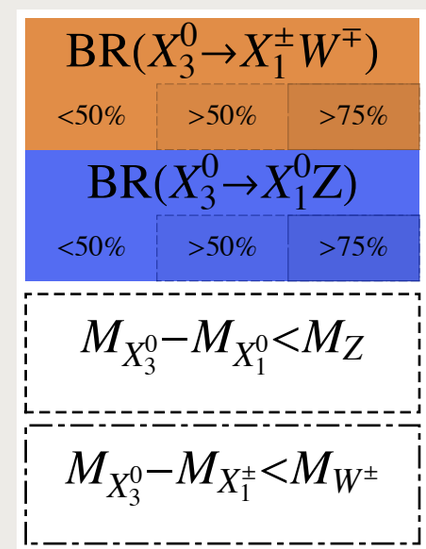


Composition - χ_3^0



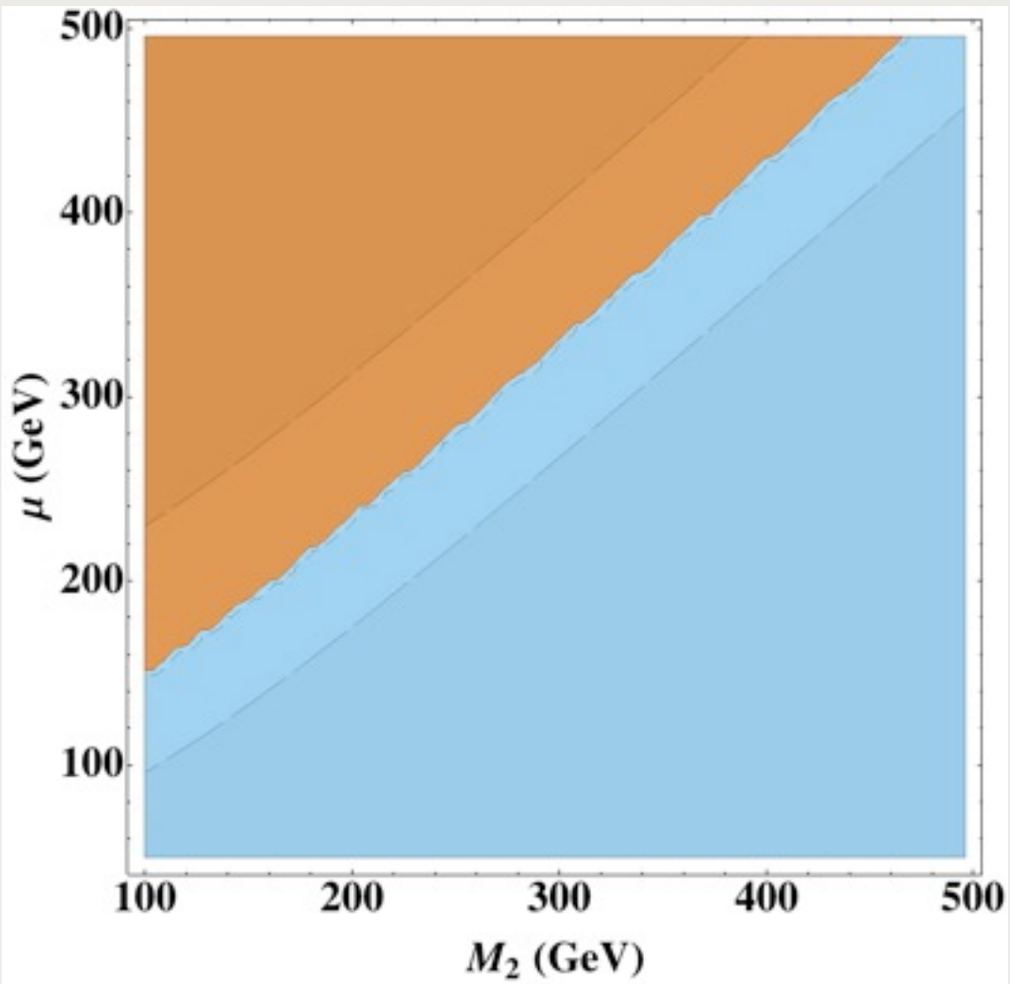
Primary Decay Modes - χ_3^0



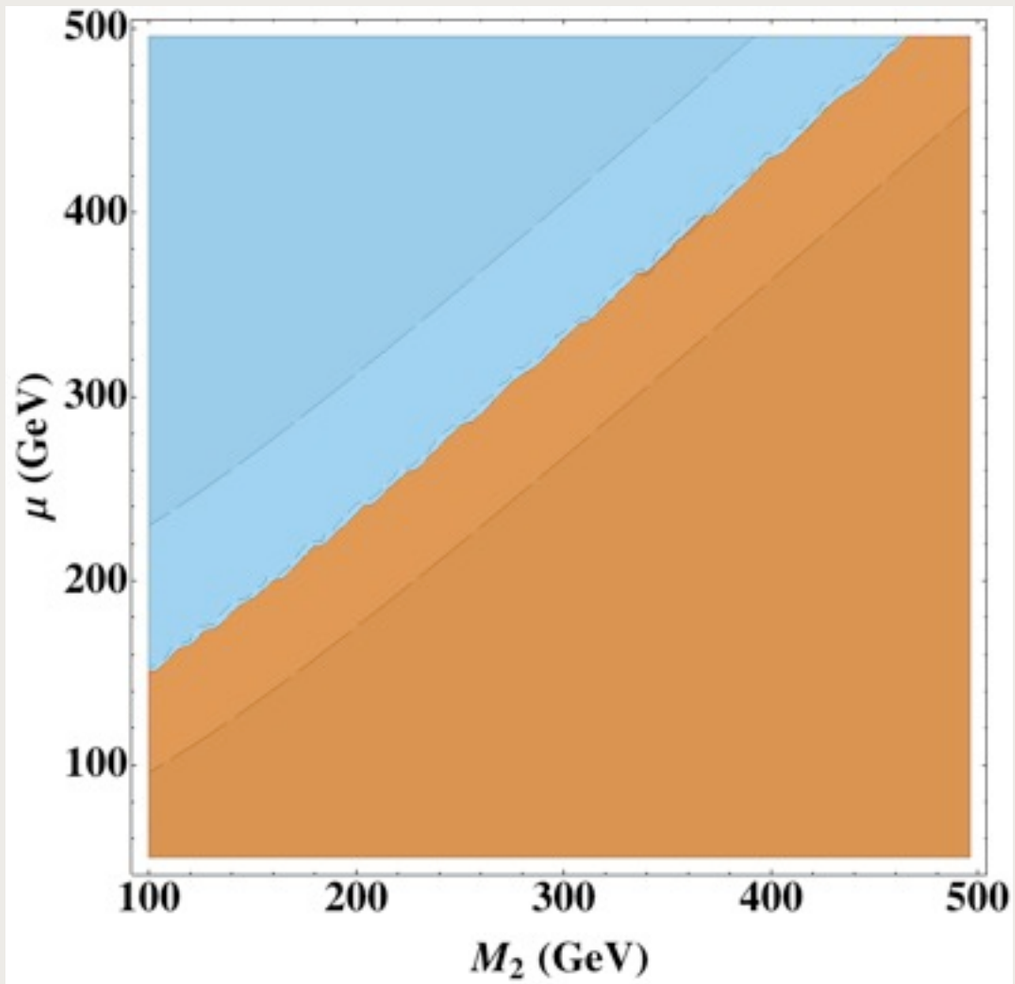


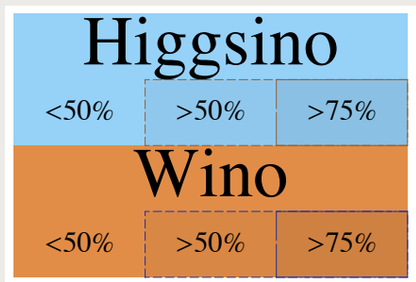
Composition - $\chi_1^{\pm}$, $\chi_2^{\pm}$

$\chi_1^{\pm}$

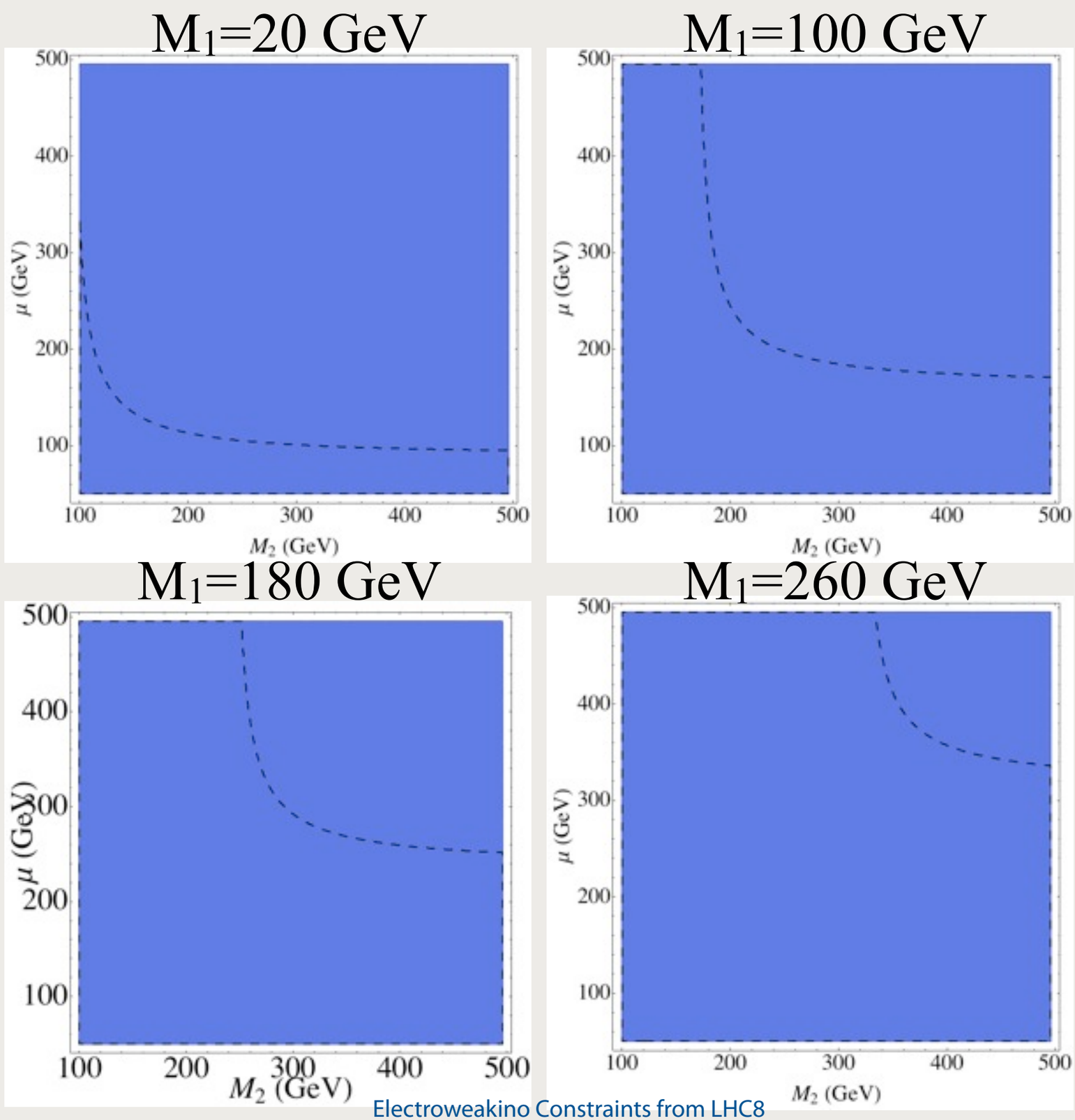


$\chi_2^{\pm}$





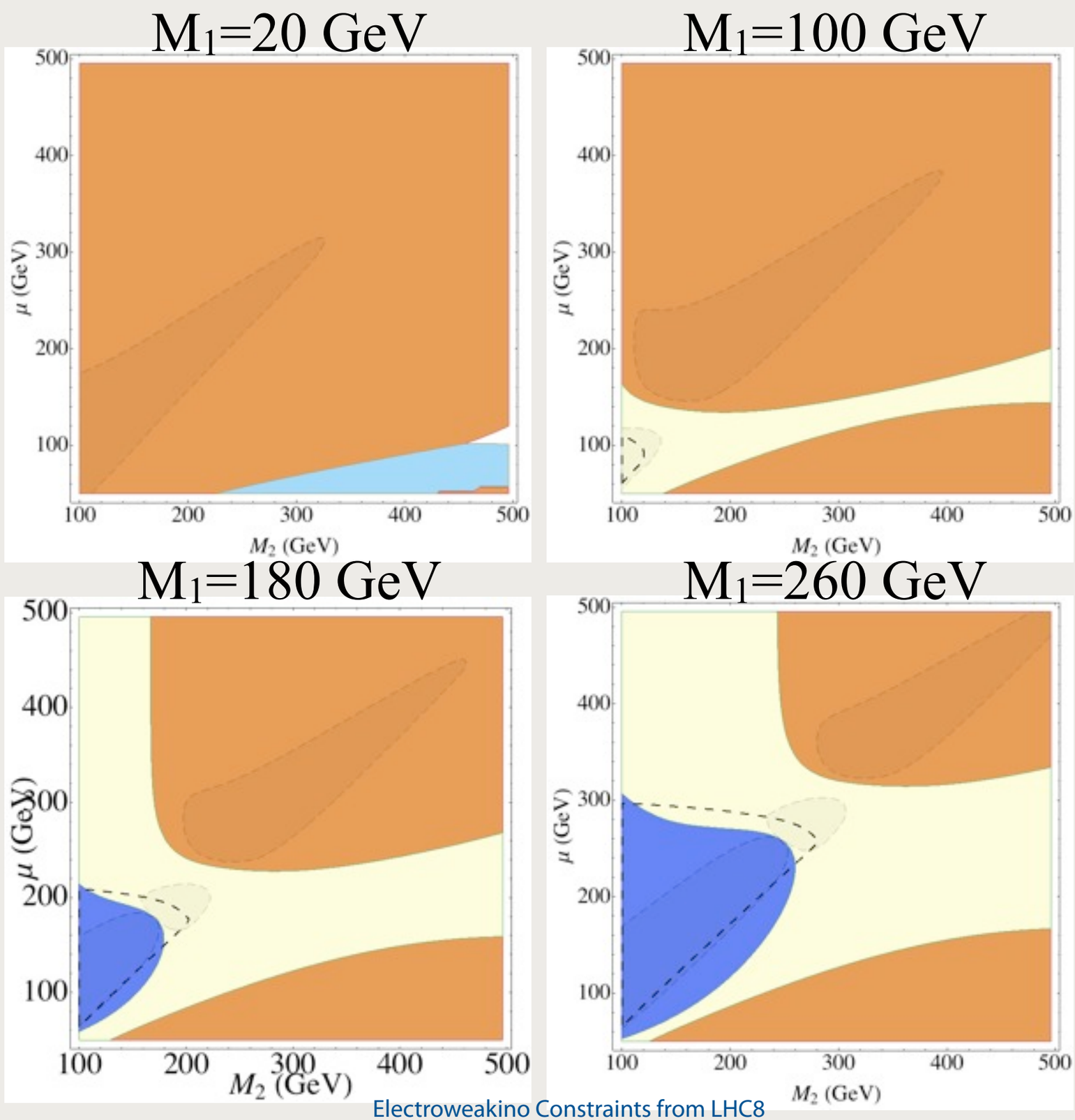
Primary Decay Modes - $\chi_1^{\pm}$



$BR(X_1^{\pm} \to X_1^0 W^{\pm})$		
<50%	>50%	>75%

$M_{X_1^{\pm}} - M_{X_1^0} < M_{W^{\pm}}$

Primary Decay Modes - $\chi_2^{\pm}$



$BR(X_2^{\pm} \to X_1^{\pm} Z)$		
<50%	>50%	>75%
$BR(X_2^{\pm} \to X_3^0 W^{\mp})$		
<50%	>50%	>75%
$BR(X_2^{\pm} \to X_2^0 W^{\mp})$		
<50%	>50%	>75%
$BR(X_2^{\pm} \to X_1^0 W^{\mp})$		
<50%	>50%	>75%

$M_{X_2^{\pm}} - M_{X_2^0} < M_{W^{\pm}}$

Experimental Searches

- ATLAS
  - Dilepton + 0 Jets (ATLAS-CONF-2013-049)
  - Same Sign Dilepton (ATLAS-CONF-2013-007)
  - Di-Tau (ATLAS-CONF-2013-028)
  - Trilepton (ATLAS-CONF-2013-035)
    - + Trilepton (arXiv:1402.7029)
  - Four or More Leptons (ATLAS-CONF-2013-036)
  - Dilepton Razor (ATLAS-CONF-2013-089)
  - Jets + MET (ATLAS-CONF-2013-047)
  - Monojet (ATLAS-CONF-2013-068)

Experimental Searches

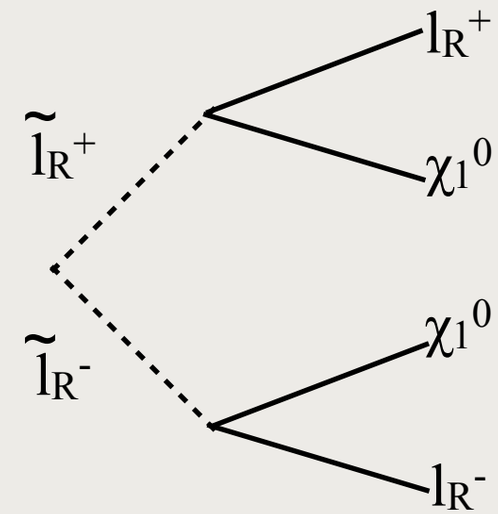
- CMS
  - Trilepton Regions 1-4 (CMS-PAS-SUS-13-006)
  - Quad Lepton (CMS-PAS-SUS-13-006)
  - Same-Sign Lepton (CMS-PAS-SUS-13-006)
  - Dilepton + Jets (CMS-PAS-SUS-13-006)
  - Lepton + H->bb (CMS-PAS-SUS-13-017)
  - Monojet (CMS-PAS-EXO-12-048)

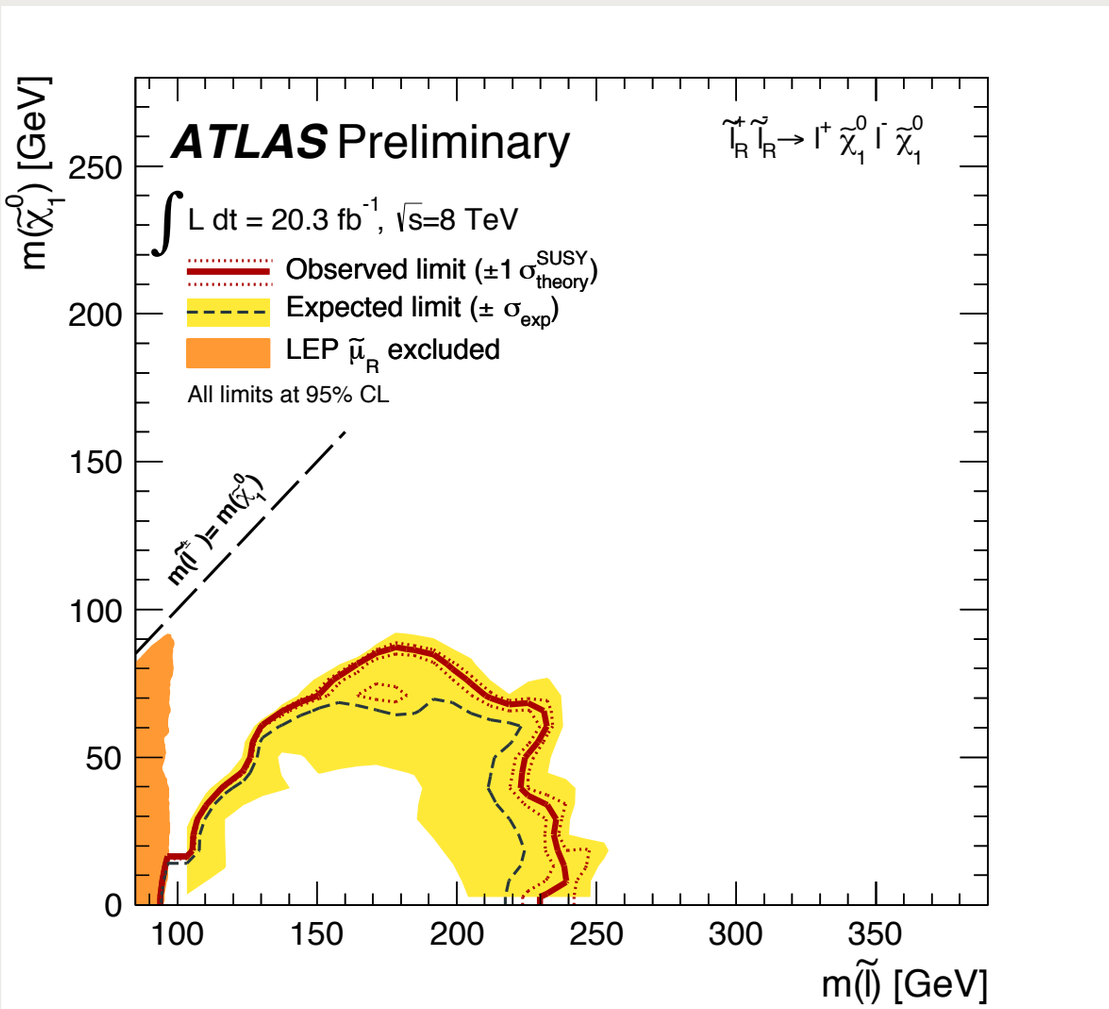
Mechanics

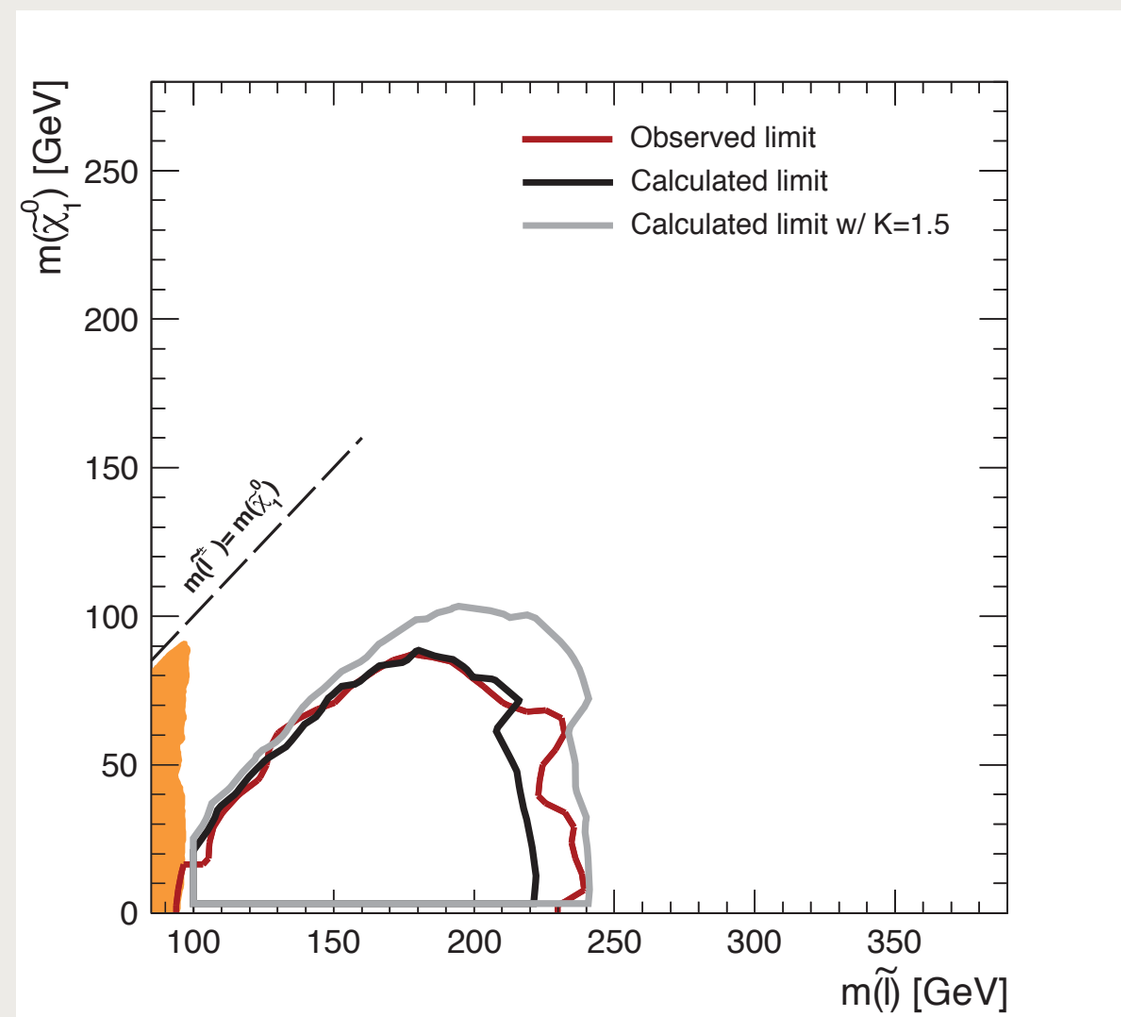
- MadGraph 5 (cross sections compared to Prospino)
  - Electroweakino Pair Production (21: $\chi_i^0\chi_j^0$, $\chi_i^0\chi_j^\pm$, $\chi_i^\pm\chi_j^\pm$)
  - Hard scattering + {0,1} Jet
- Pythia 6.4
  - Decay hard element, fully inclusive signals
  - MLM Matching {0,1} Jet <-> Radiated Jets
- Delphes 3
  - Trigger, Identification, Jet Reconstruction @ working point
- Seer (My own code)
  - Cuts and Signal Regions
  - Extra MET smearing (pileup)
- 95% C.L. using CLs
- Spectrum Generators:
  - SUSYHit
  - SoftSUSY

Vetting Seer

- Dilepton: ATLAS CONF 2013 049

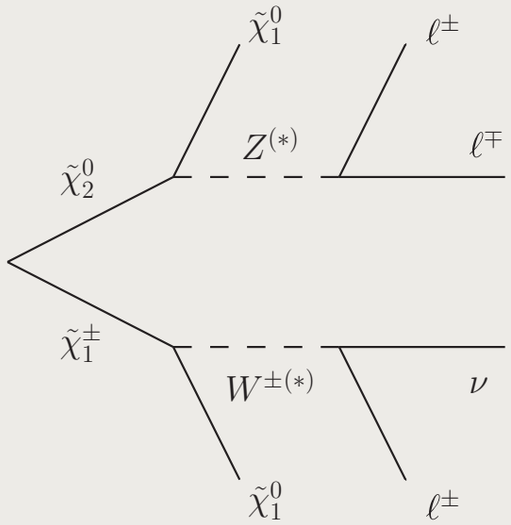


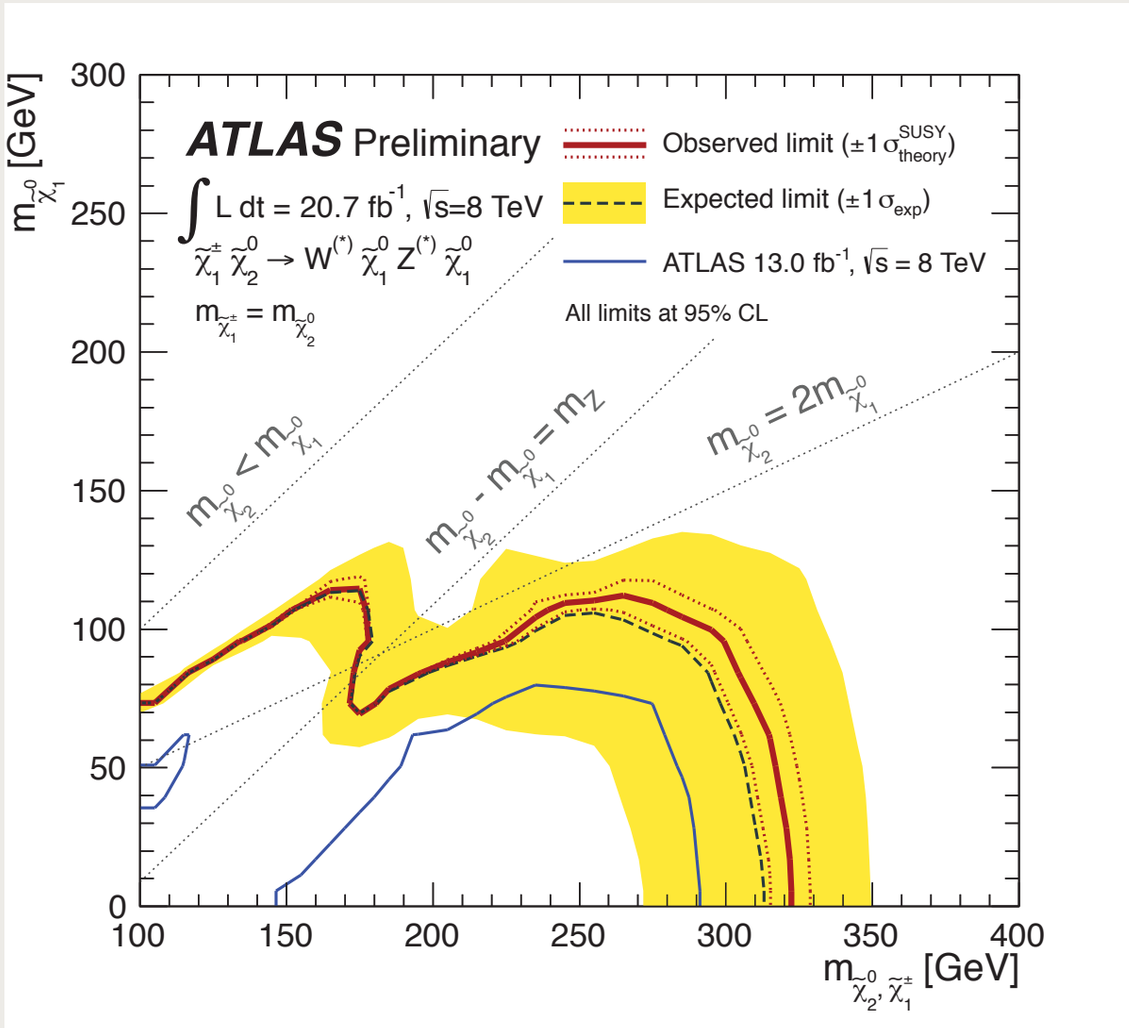


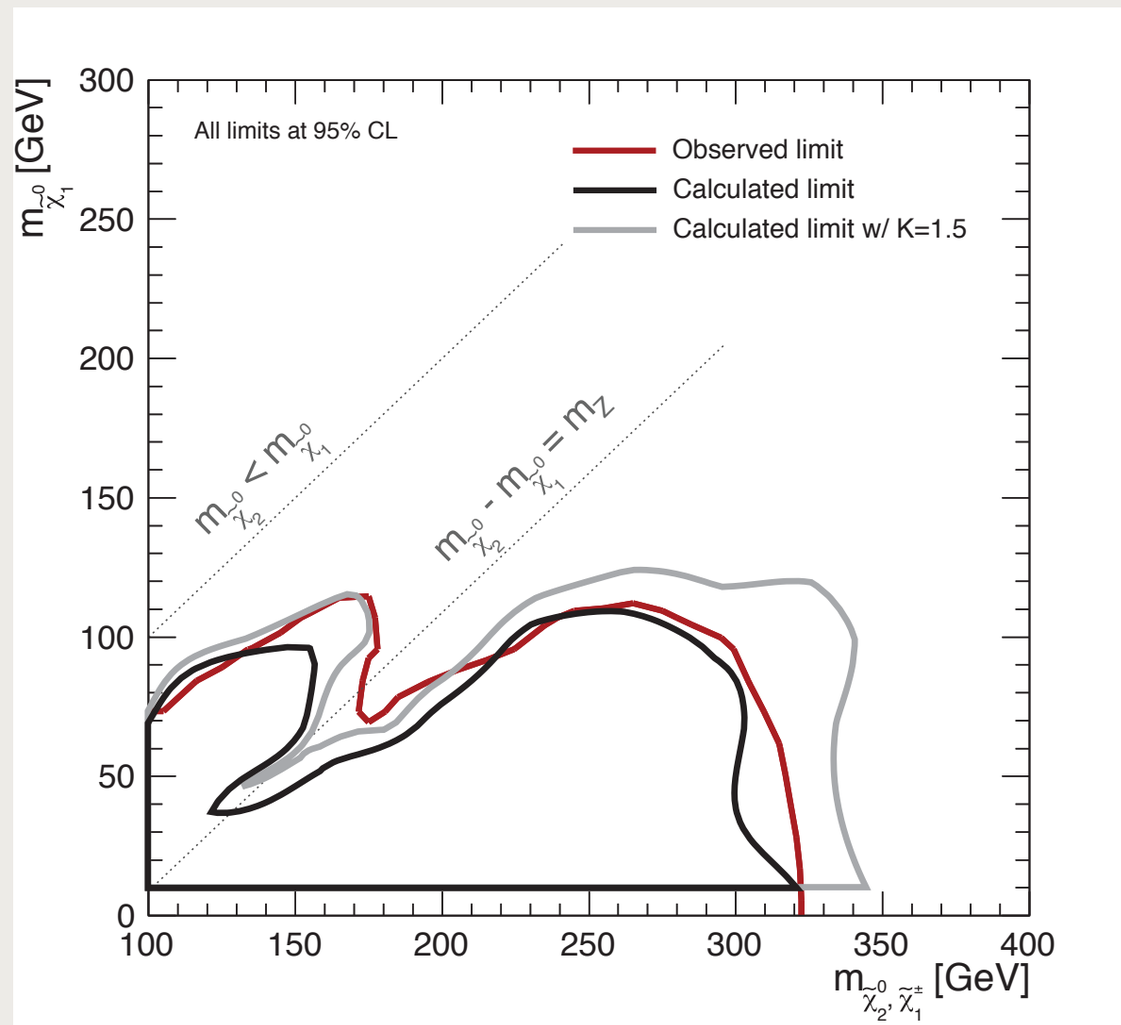


Vetting Seer

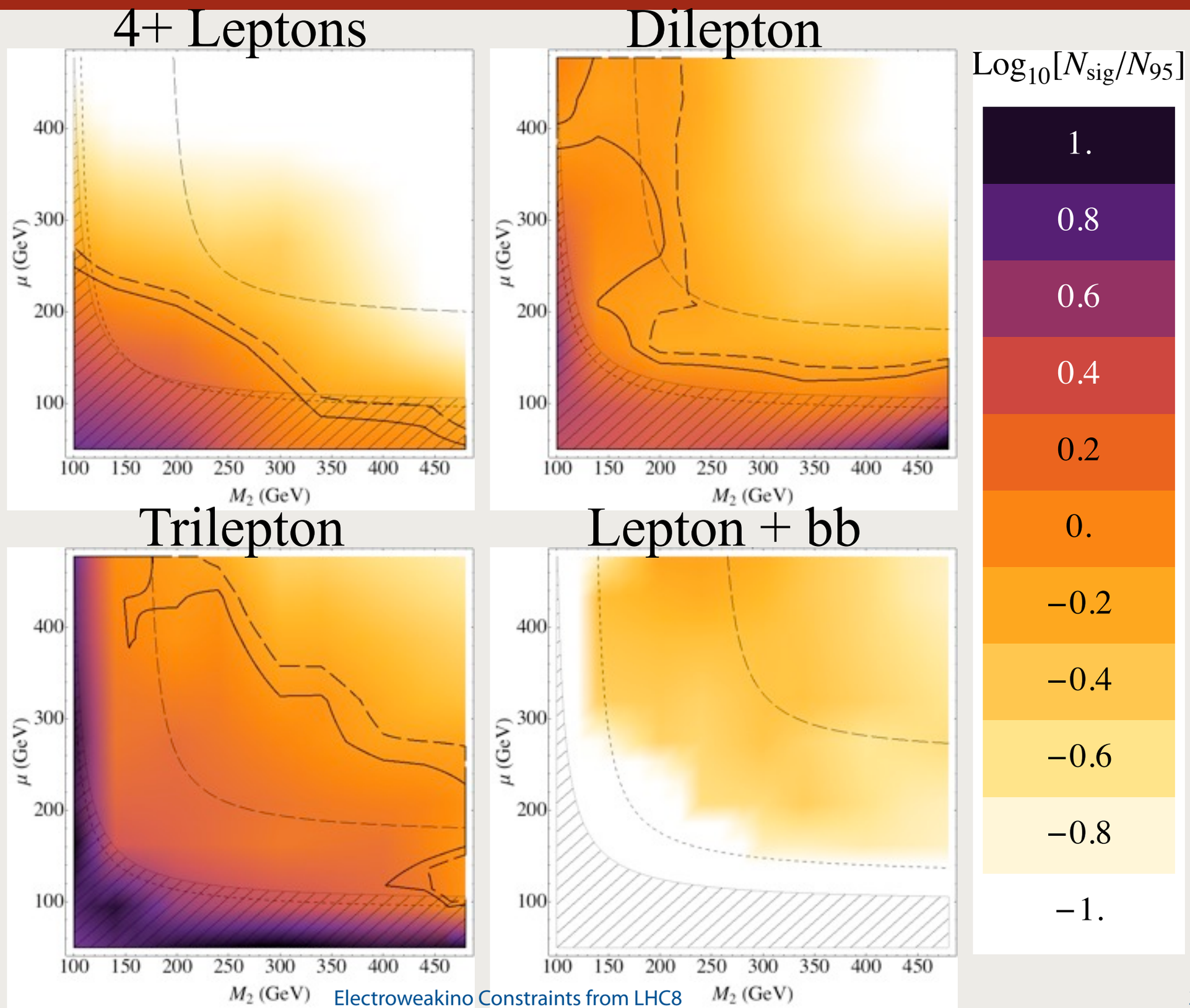
- Trilepton: ATLAS CONF 2013 035







M_1=20 GeV



M_{X2}-M_{X1}<2$M_{Z/W/H}$

M_{X2}-M_{X1}<$M_{Z/W/H}$

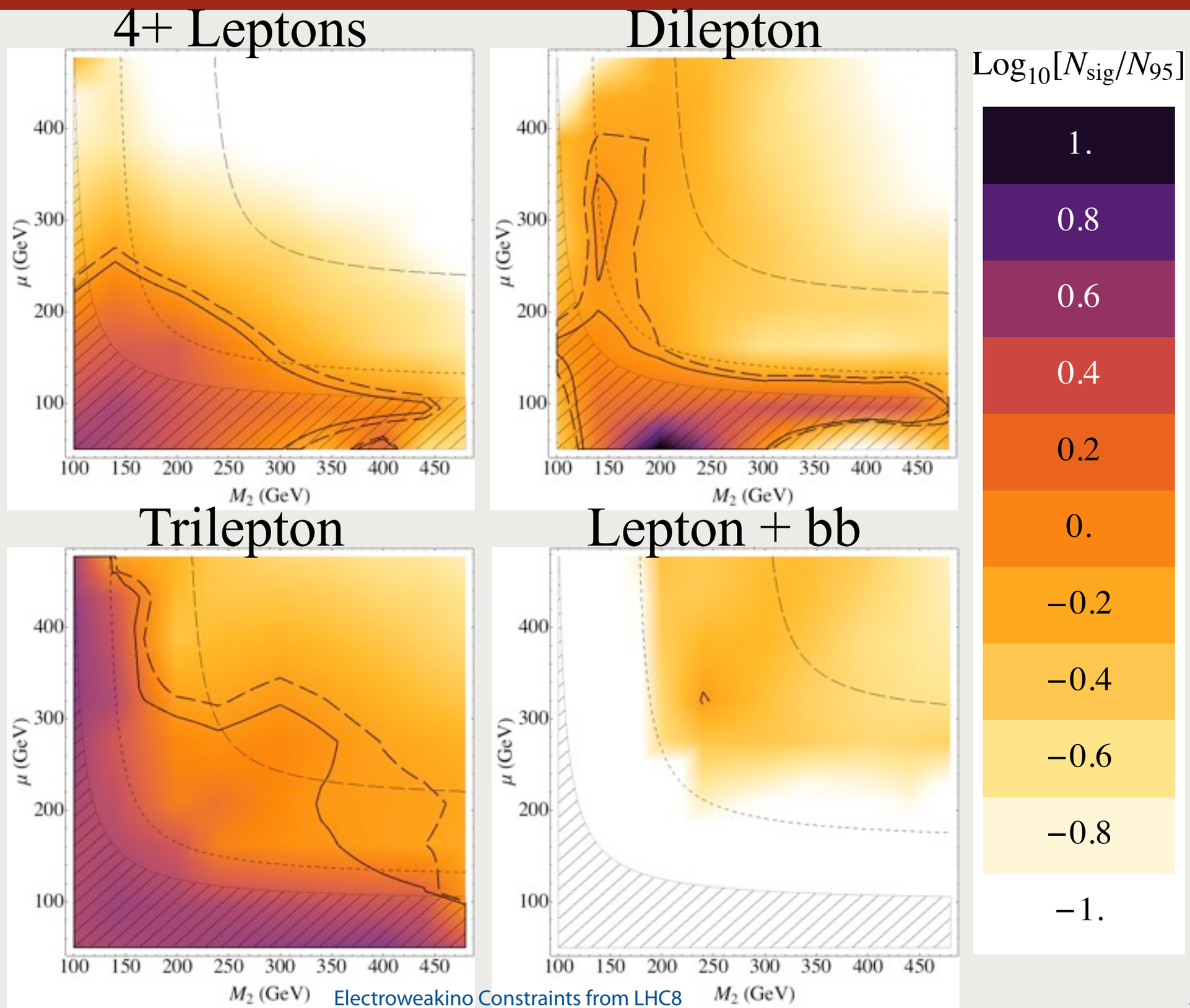
M_{X2}-M_{X1}<15 GeV

LEP Bound

95% C.L. exclusion

95% C.L. exclusion w/ K=1.2

M_1=60 GeV


4+ Leptons
Dilepton
Trilepton
Lepton + bb
μ (GeV)
M_2 (GeV)
100 150 200 250 300 350 400 450
100 200 300 400
$\mathrm{Log}_{10}[N_{\mathrm{sig}}/N_{95}]$
1.
0.8
0.6
0.4
0.2
0.
−0.2
−0.4
−0.6
−0.8
−1.
M_{X2}-M_{X1}<2$M_{Z/W/H}$
M_{X2}-M_{X1}<$M_{Z/W/H}$
M_{X2}-M_{X1}<15 GeV
LEP Bound
95% C.L. exclusion
95% C.L. exclusion w/ K=1.2

M_1=100 GeV

M_{X2}-M_{X1}<2$M_{Z/W/H}$

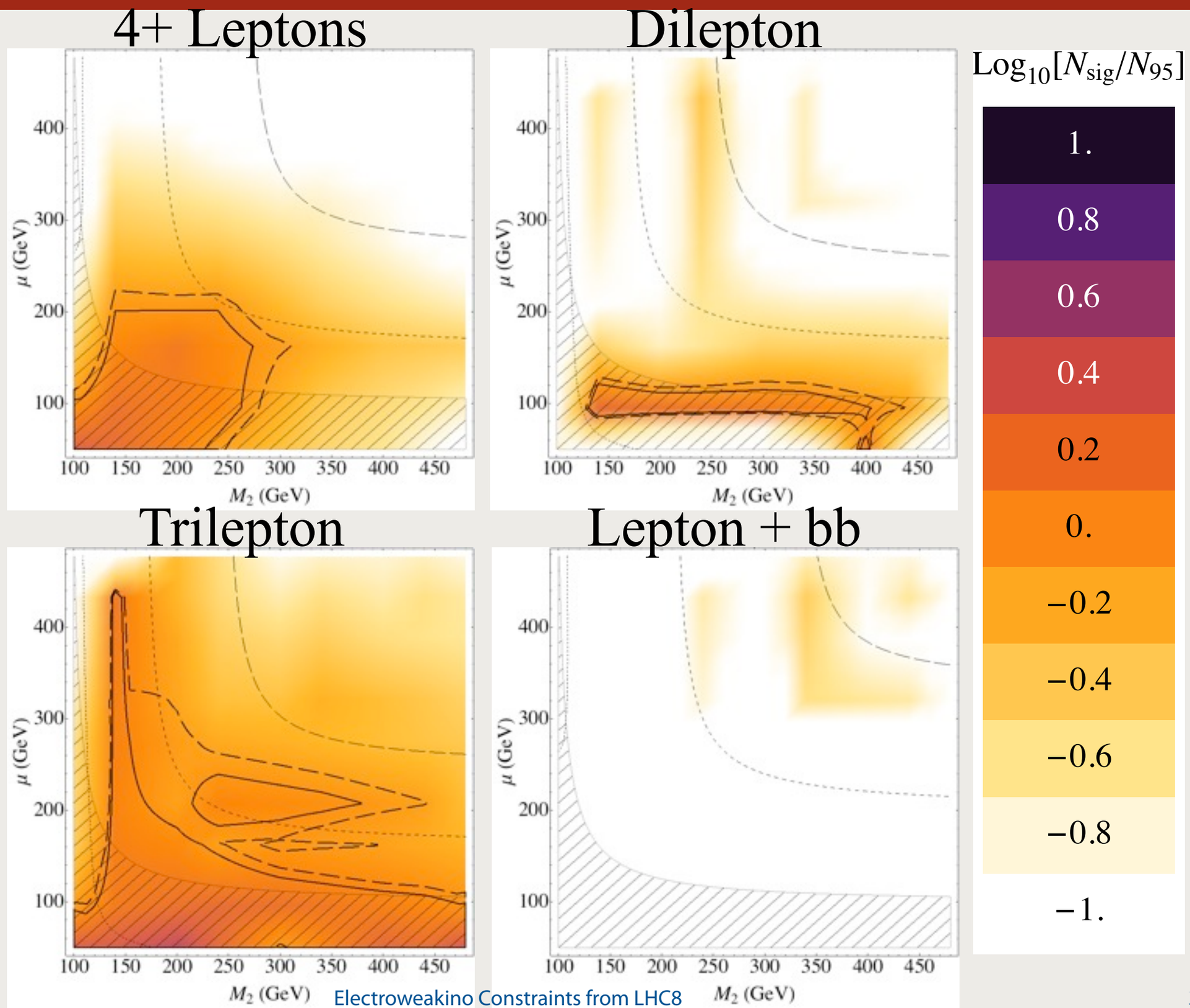
M_{X2}-M_{X1}<$M_{Z/W/H}$

M_{X2}-M_{X1}<15 GeV

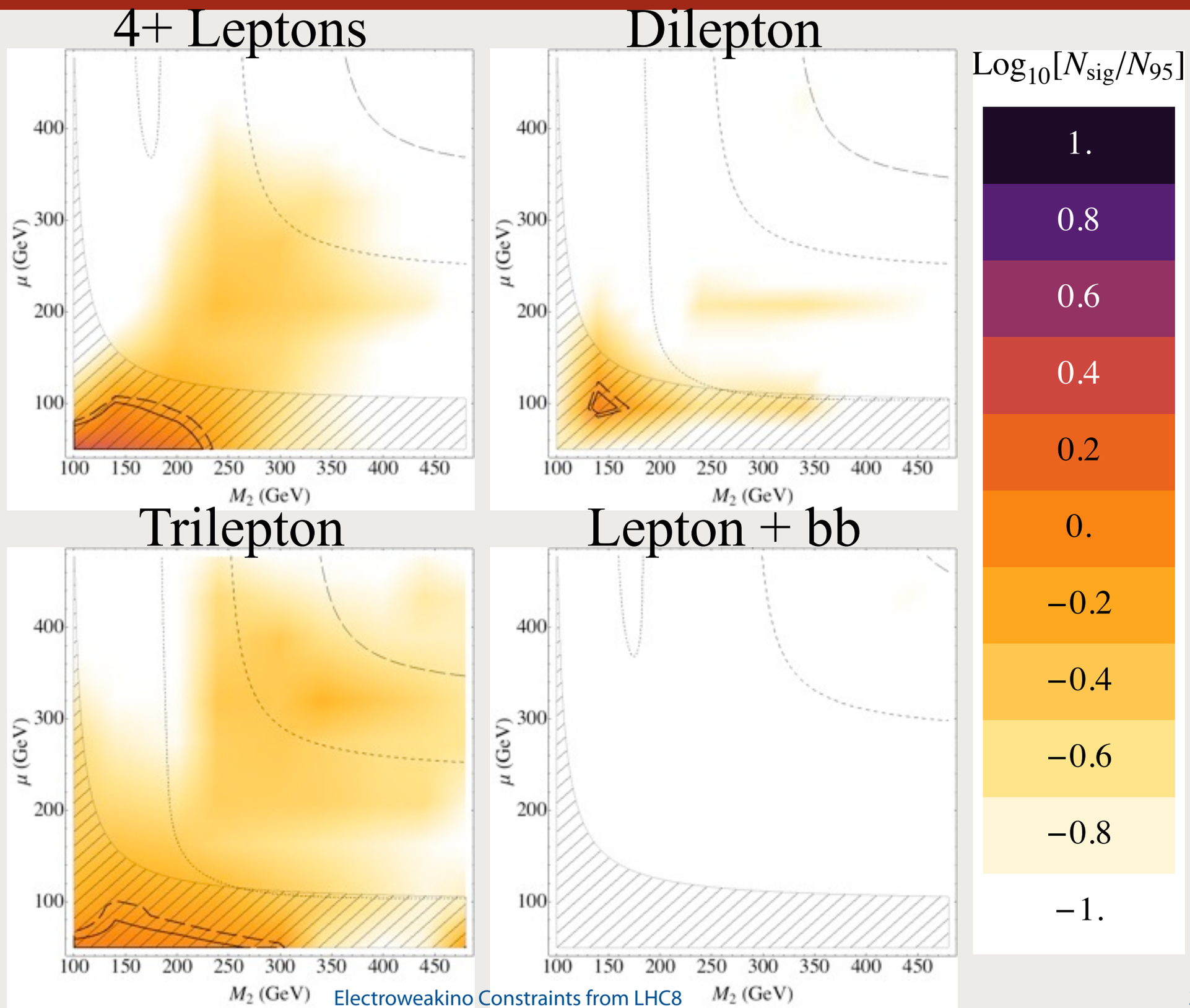
LEP Bound

95% C.L. exclusion

95% C.L. exclusion w/ K=1.2



M_1=180 GeV



M_{X2}-M_{X1}<2$M_{Z/W/H}$

M_{X2}-M_{X1}<$M_{Z/W/H}$

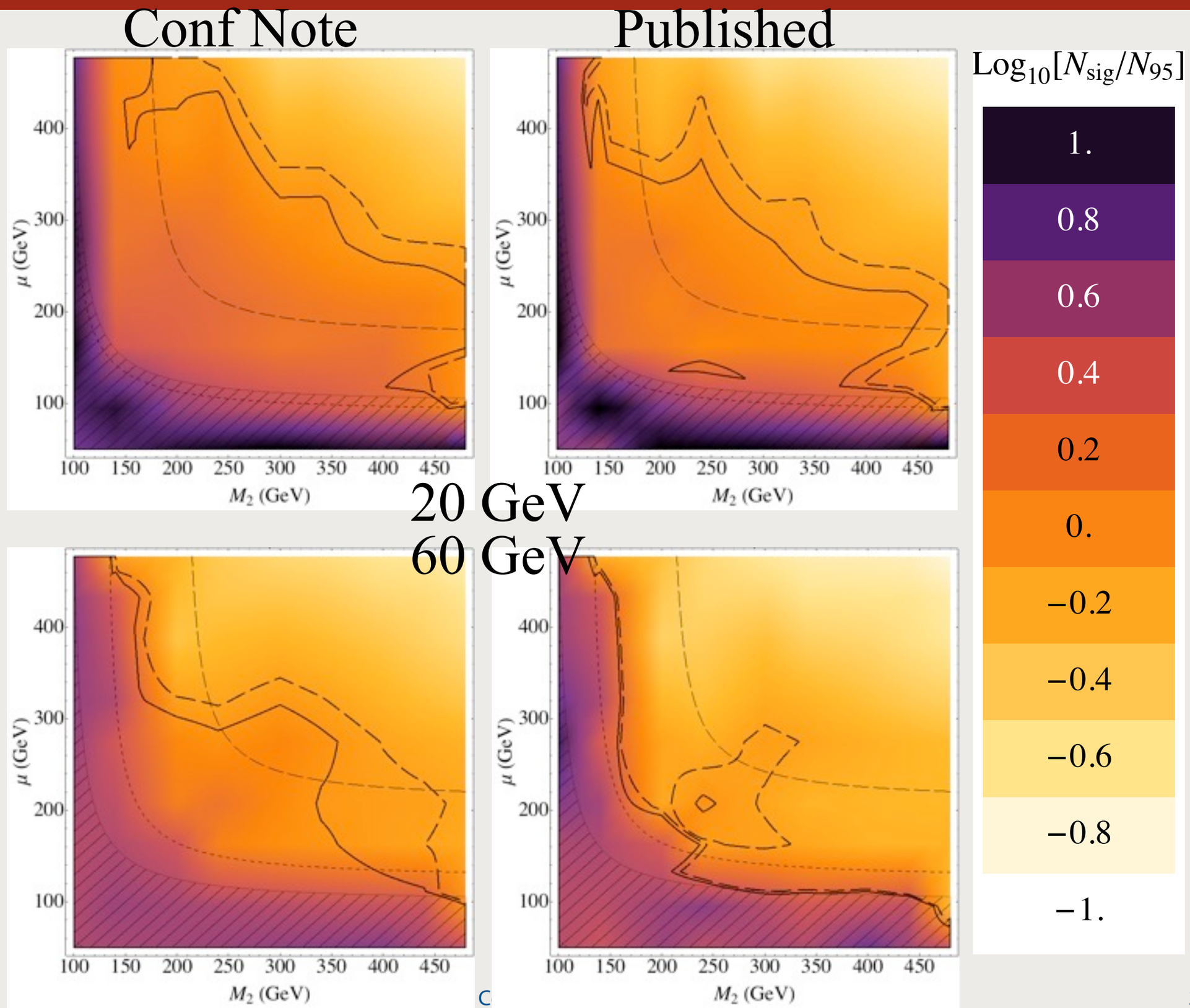
M_{X2}-M_{X1}<15 GeV

LEP Bound

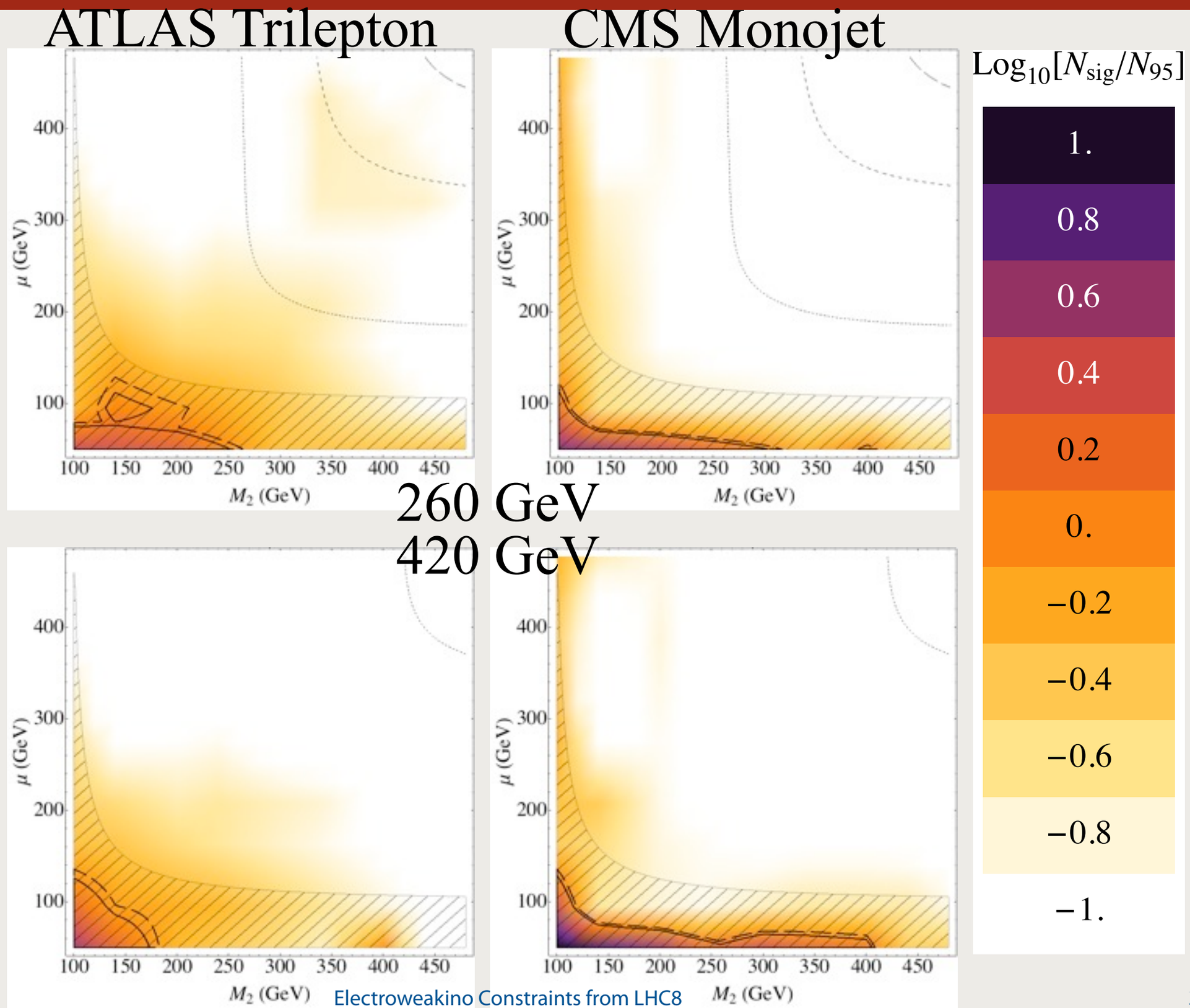
95% C.L. exclusion

95% C.L. exclusion w/ K=1.2

3Lep Conf Note vs Published



Large M_1



M_{X2}-M_{X1}<2$M_{Z/W/H}$

M_{X2}-M_{X1}<$M_{Z/W/H}$

M_{X2}-M_{X1}<15 GeV

LEP Bound

95% C.L. exclusion

95% C.L. exclusion w/ K=1.2

Trilepton

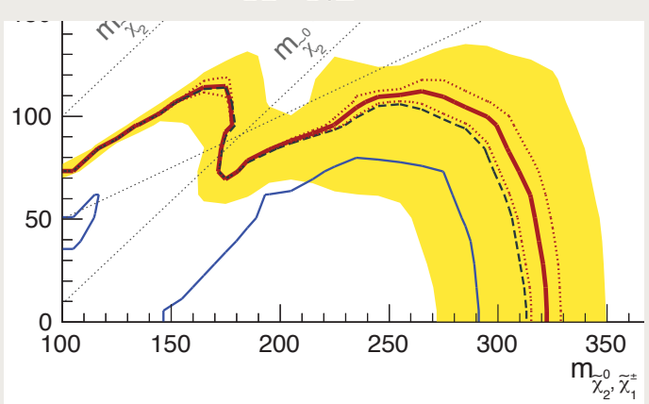
M_{X1}-M_{N1}<2M_W

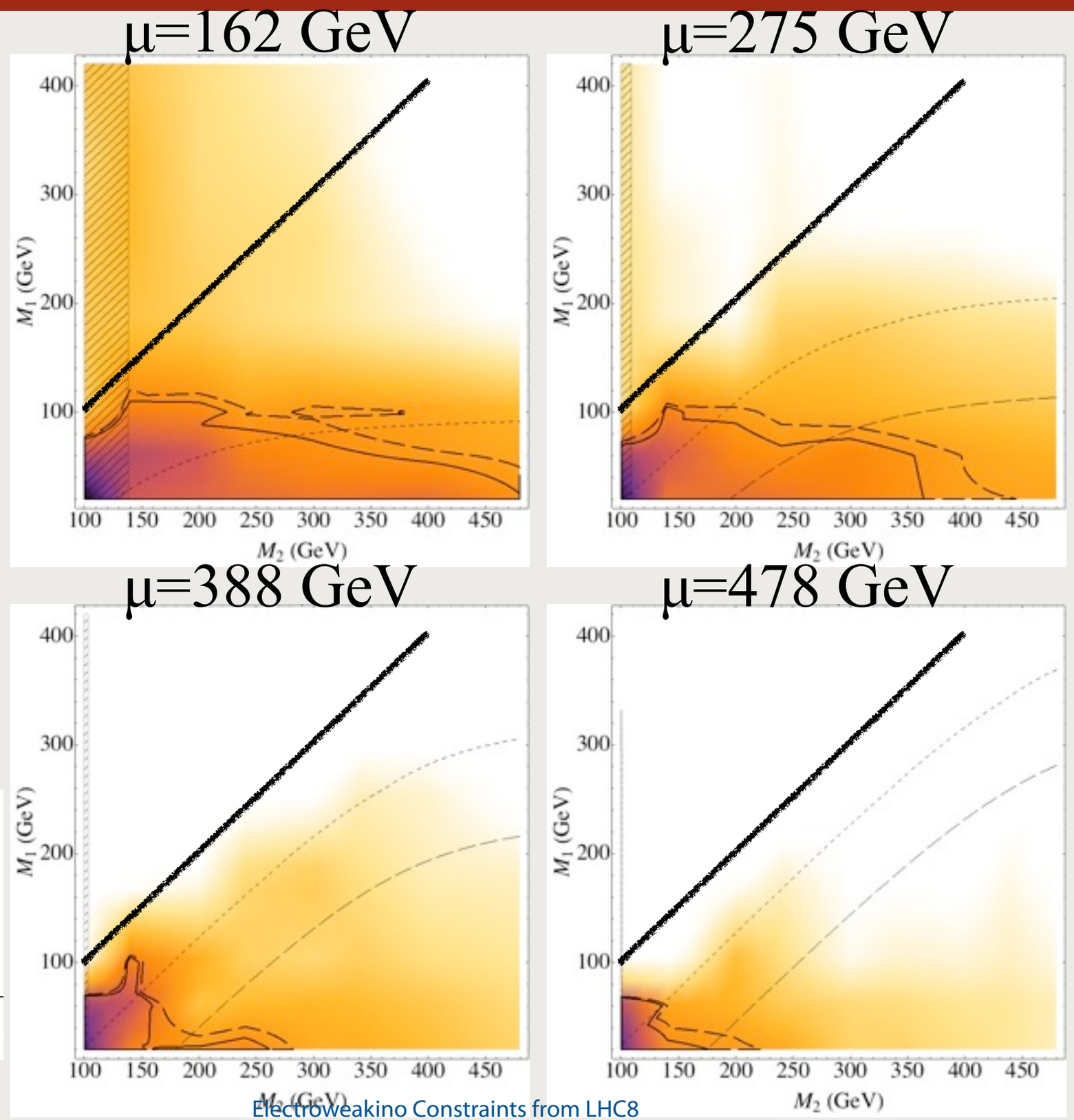
M_{X1}-M_{N1}<M_W

LEP Bound

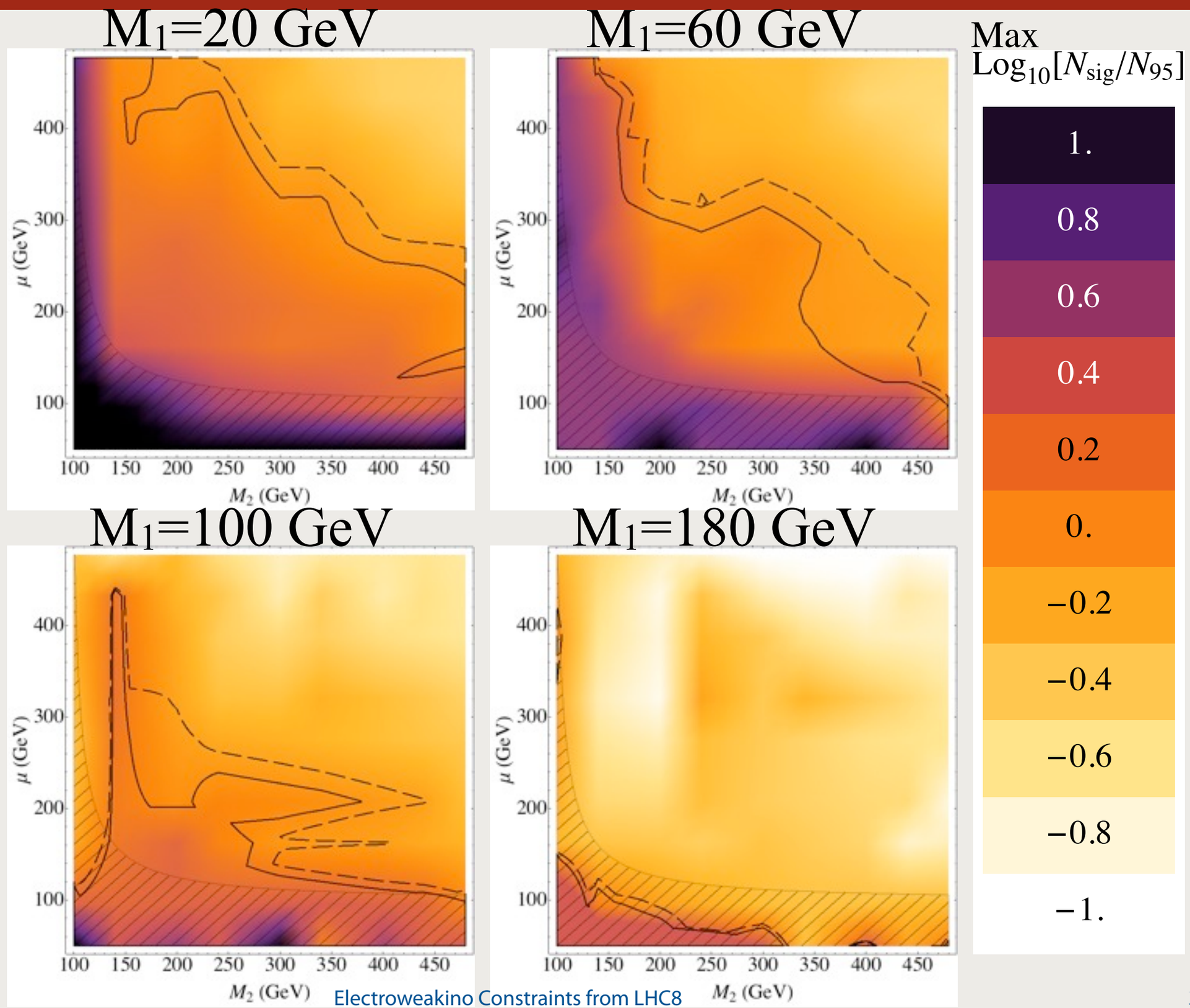
95% C.L. exclusion

95% C.L. exclusion w/ K=1.2





Combined



LEP Bound

95% C.L. exclusion

95% C.L. exclusion w/ K=1.2

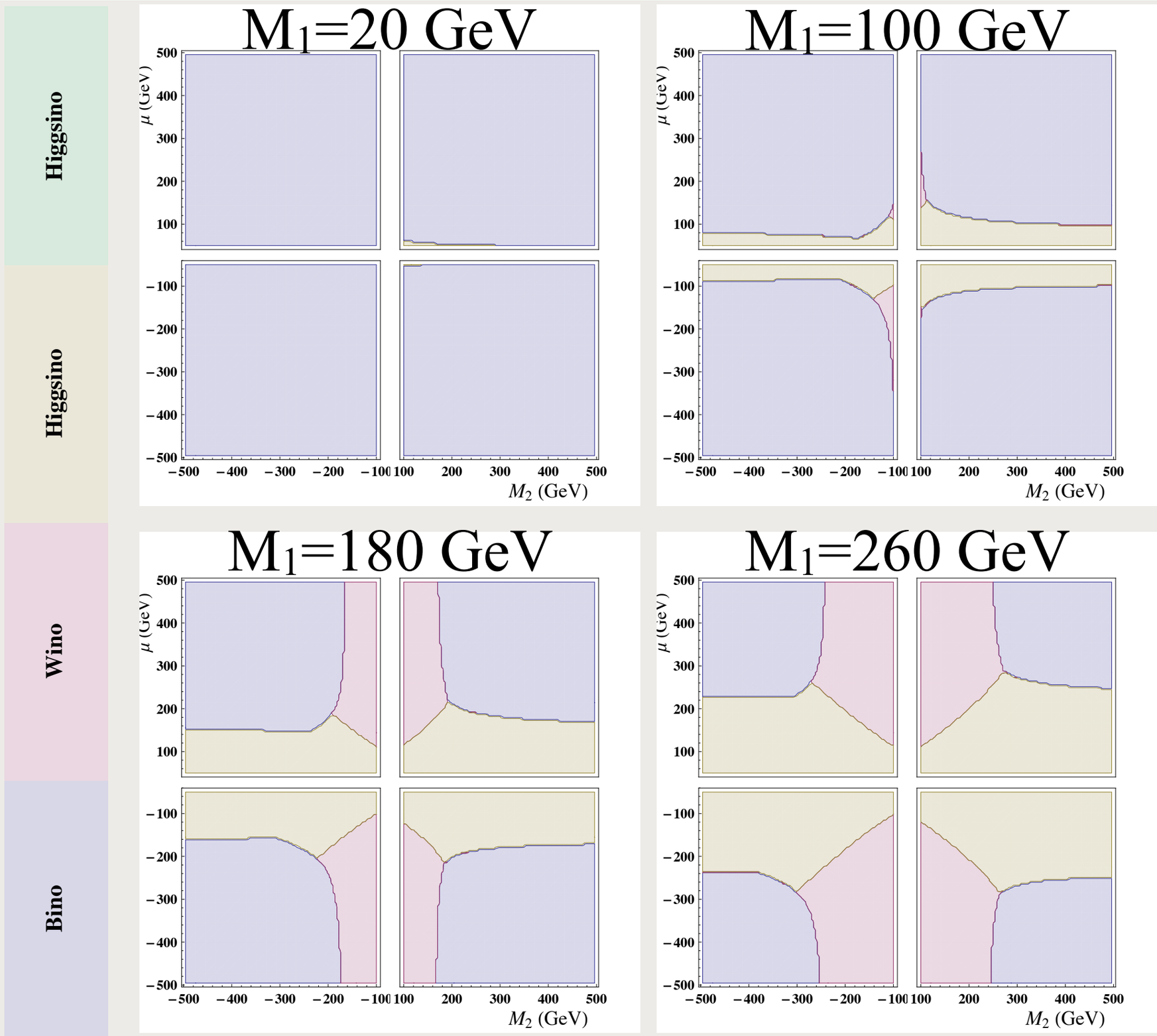
Summary

- Inclusive production important as χ_3^0, $\chi_2^\pm$ can be comparable
- Conservative limits placed on general electroweakino spectra
- Limits nearly non-existent for large M_1>150 GeV
- Compressed spectra searches important for regions where $M_2 << \mu, M_1$ || $\mu << M_2, M_1$, but large M_1 not unreachable.

End of talk

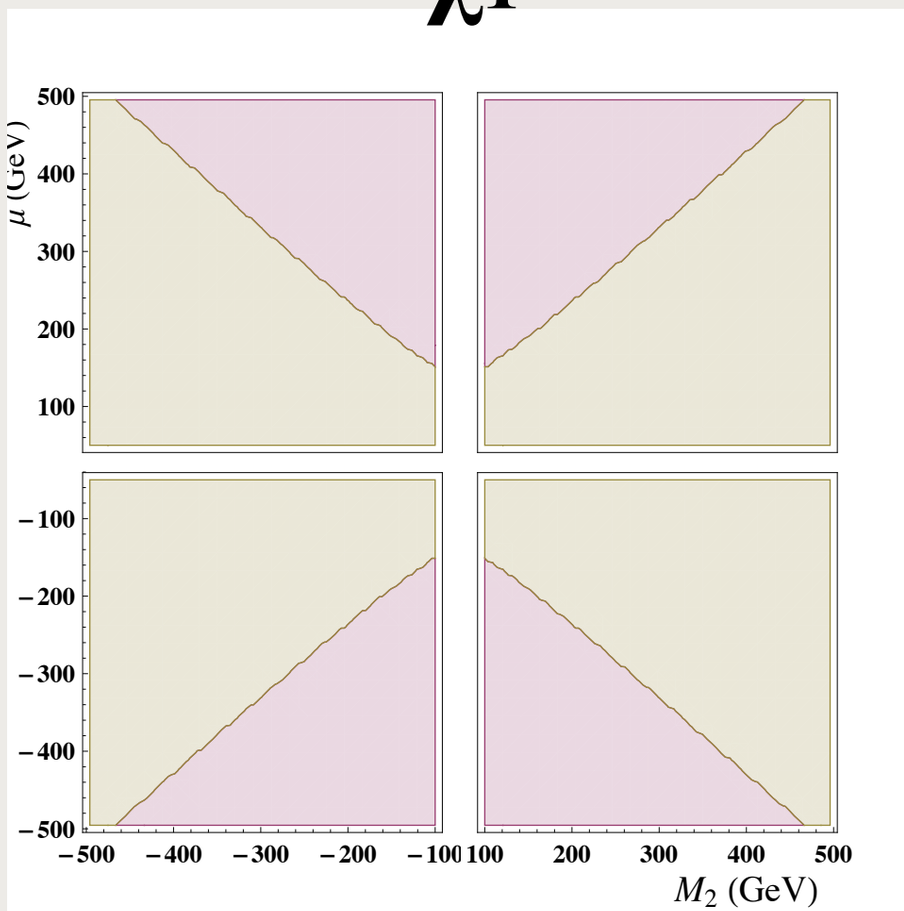
- Thank you! Questions?

Composition - χ_1^0

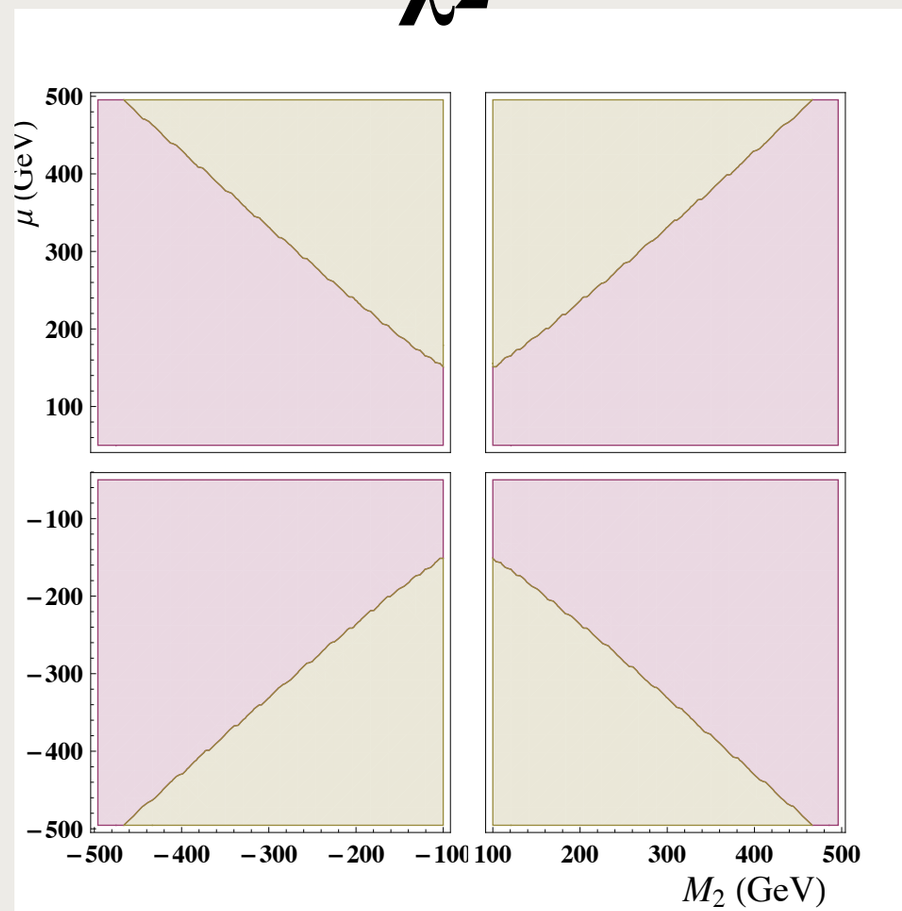


Composition - $\chi_1^\pm$, $\chi_2^\pm$

$\chi_1^\pm$

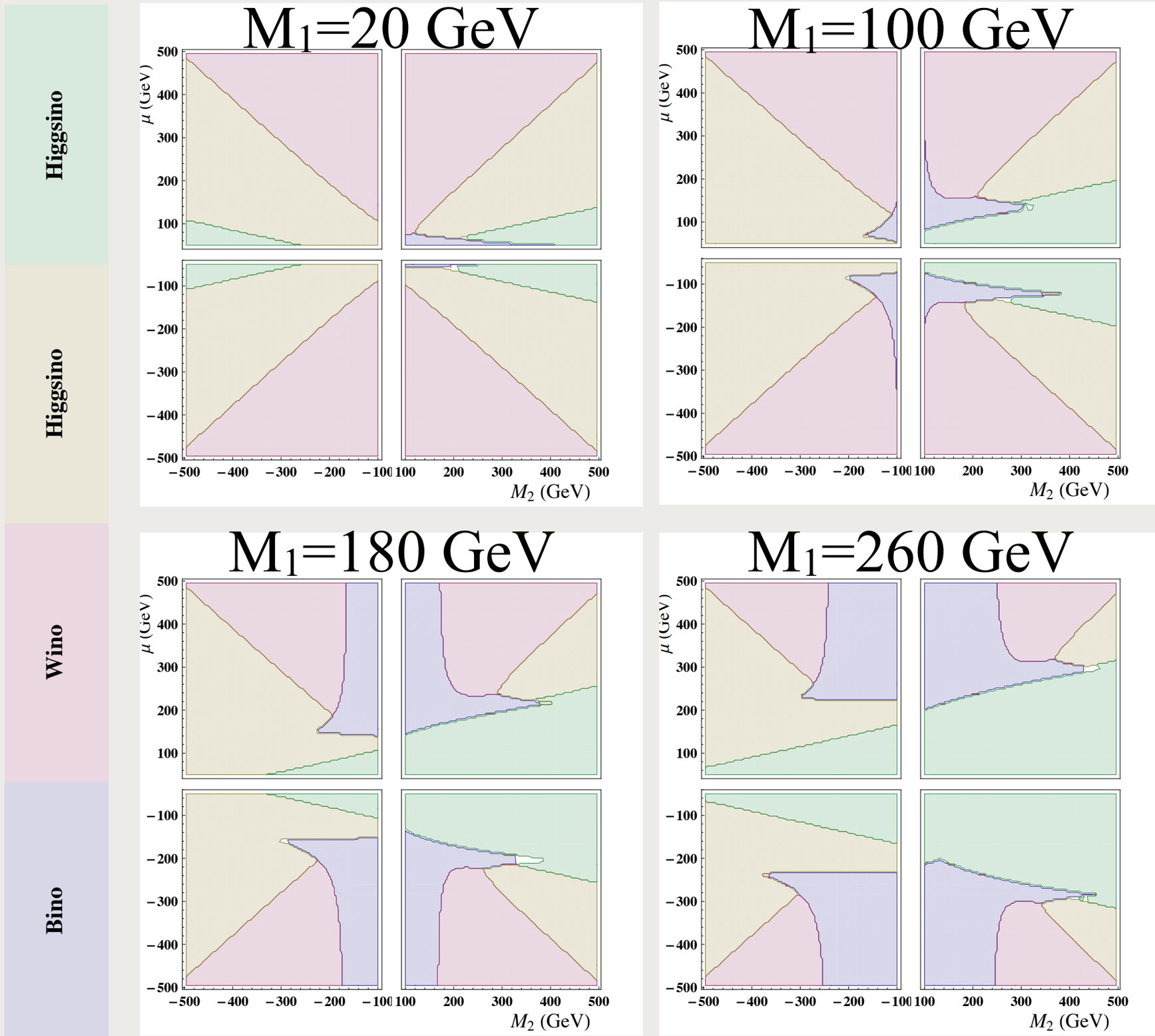


$\chi_2^\pm$

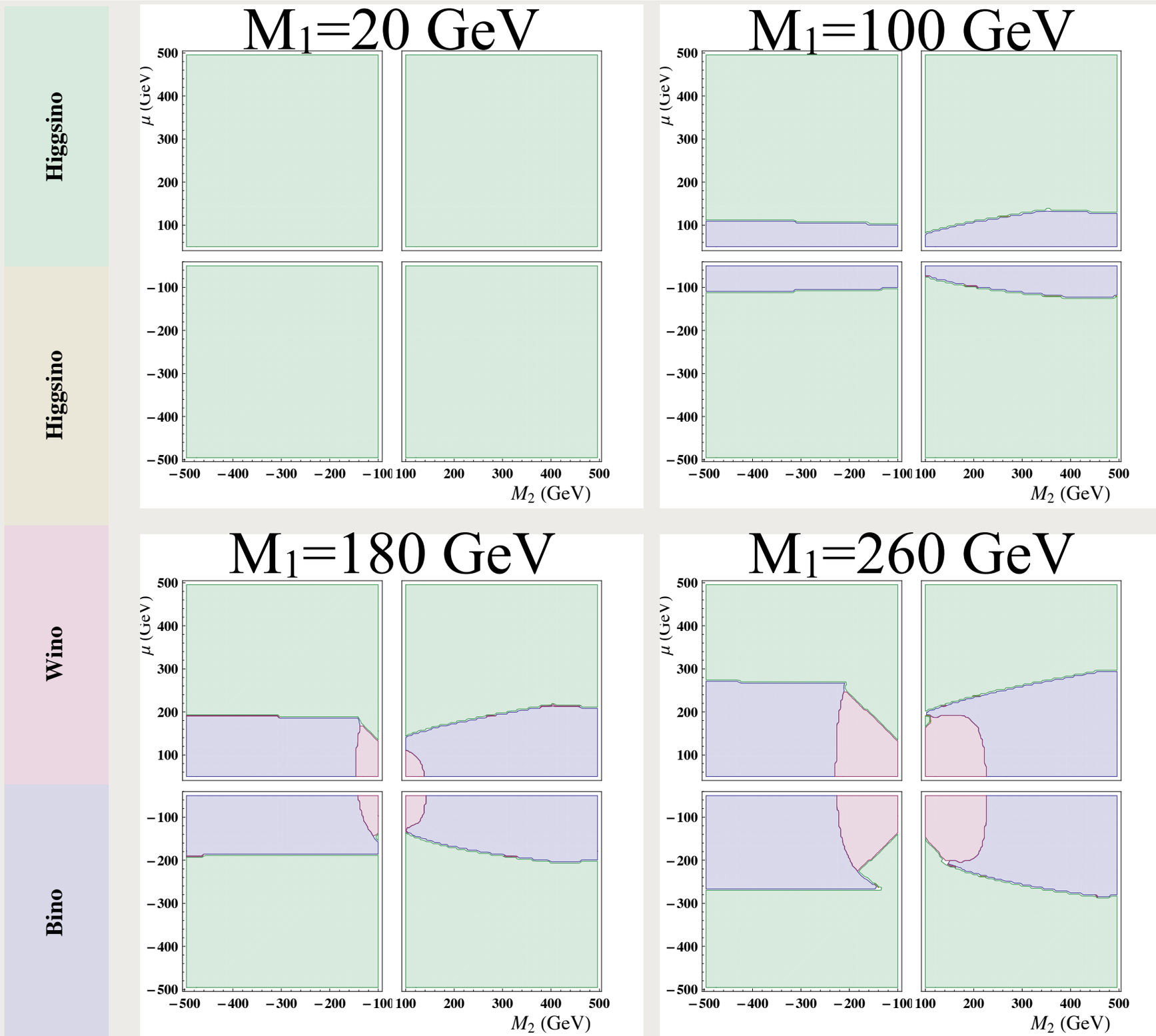


Wino **Higgsino**

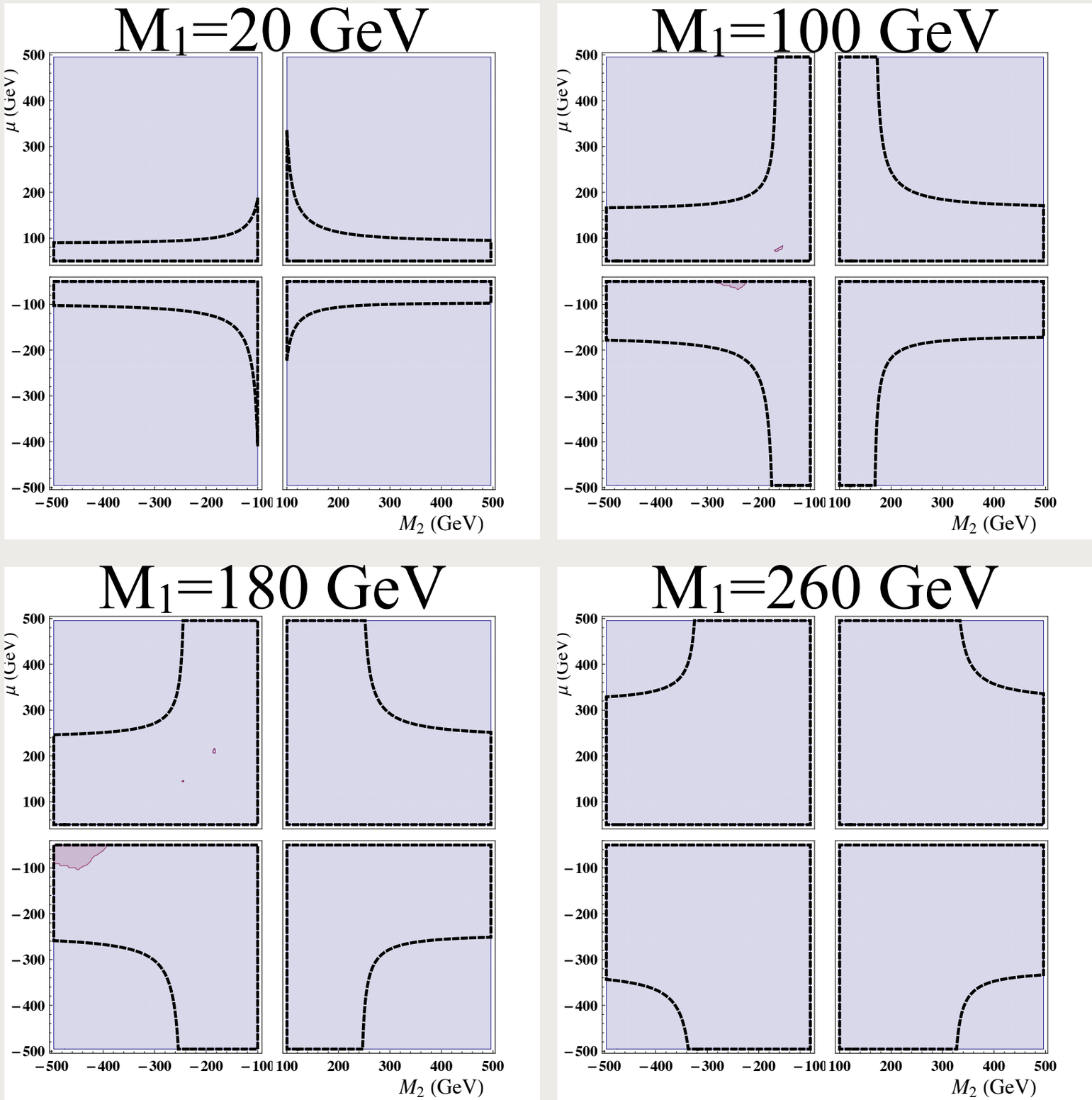
Composition - χ_2^0



Composition - χ_3^0



Primary Decay Modes - $\chi_1^{\pm}$

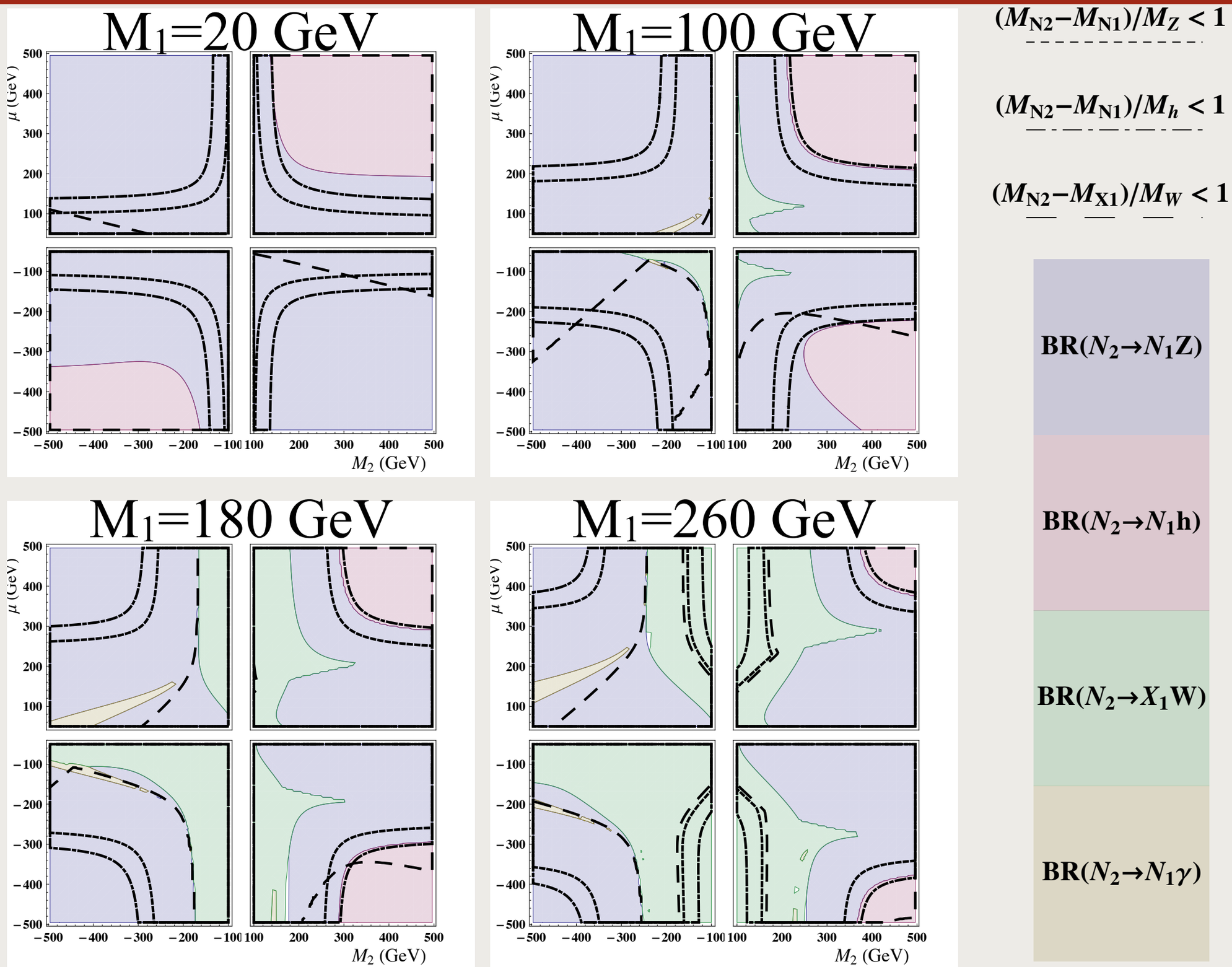


$(M_{X1}-M_{N1})/M_W < 1$

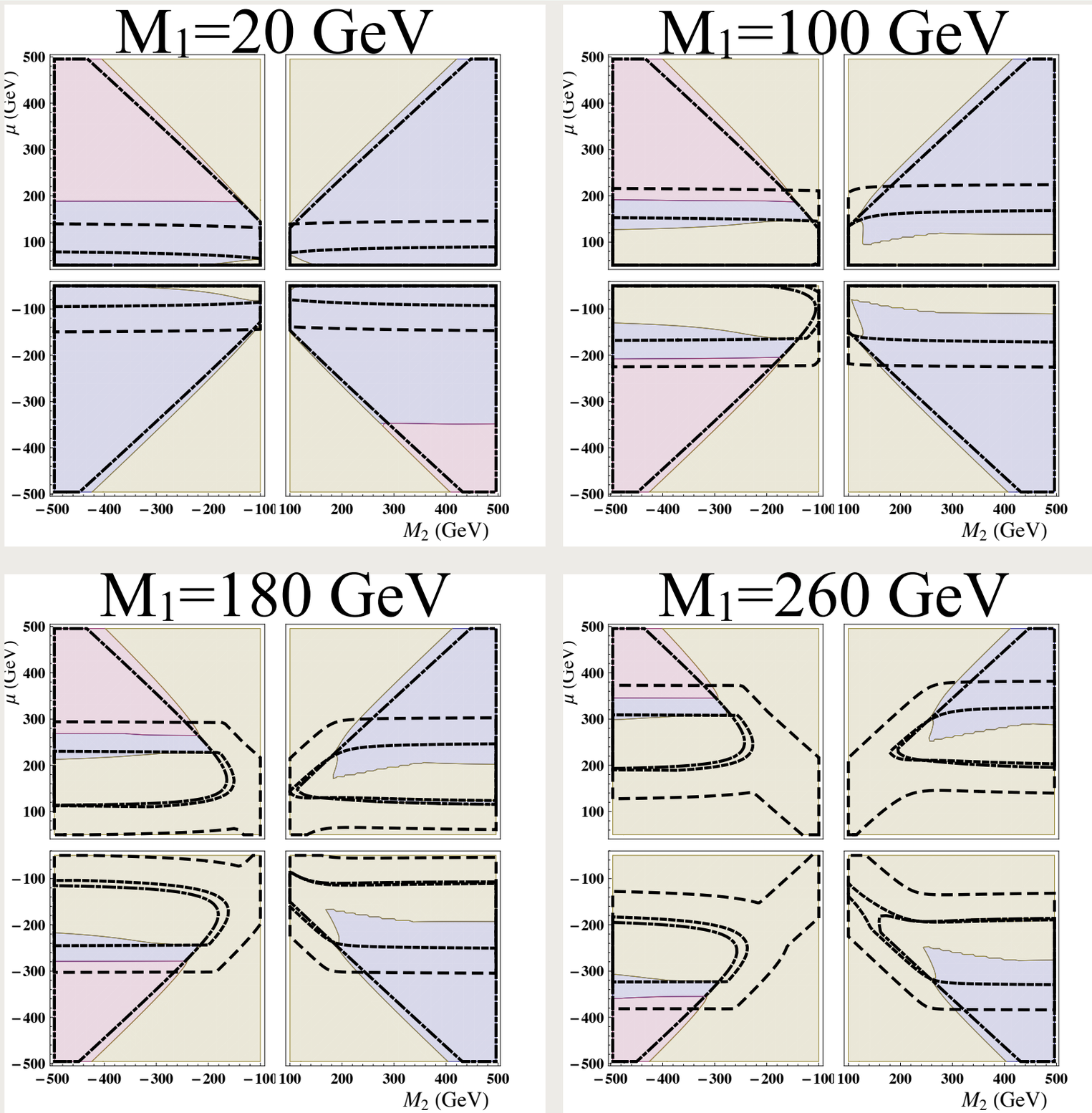
$BR(X_1 \to N_1 W)$

$BR(X_1 \to N_2 W)$

Primary Decay Modes - χ_2^0



Primary Decay Modes - χ_3^0



$(M_{N3}-M_{N1})/M_Z < 1$

$(M_{N3}-M_{N1})/M_h < 1$

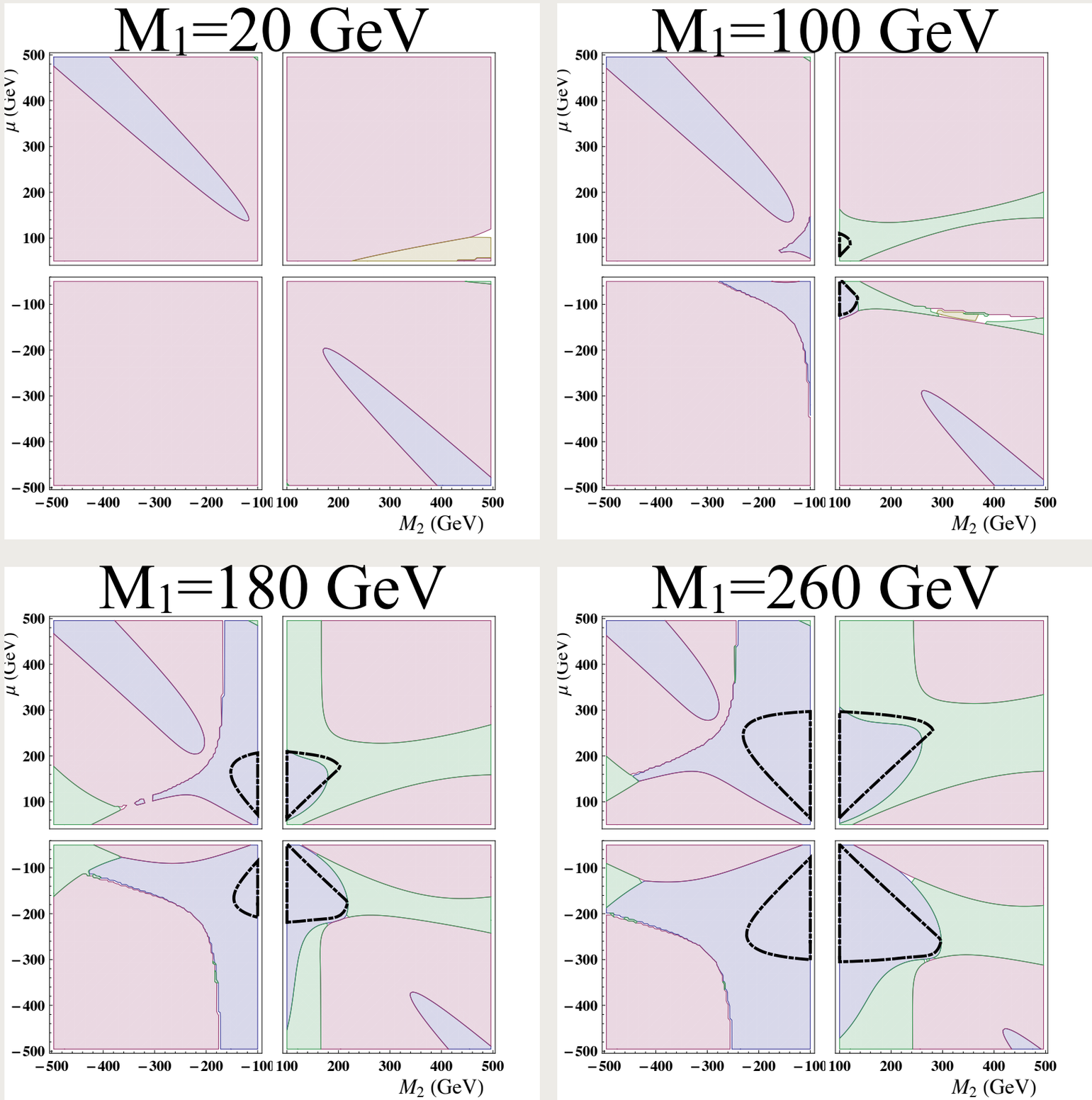
$(M_{N3}-M_{X1})/M_W < 1$

$BR(N_3 \to N_1 Z)$

$BR(N_3 \to N_1 h)$

$BR(N_3 \to X_1 W)$

Primary Decay Modes - $\chi_2^{\pm}$



$(M_{X2}-M_{N1})/M_W < 1$

$(M_{X2}-M_{N2})/M_W < 1$

$(M_{X2}-M_{X1})/M_Z < 1$

$BR(X_2 \to N_1 W)$

$BR(X_2 \to N_2 W)$

$BR(X_2 \to X_1 Z)$

$BR(X_2 \to N_3 W)$