Supersymmetric multiple Higgs doublet models: MSSM with nonlinearly realized electroweak symmetry

S.T. LOVE

DPF 2011
Providence, RI
August 8-12, 2011

OUTLINE

- Introduction to model
- Vacuum stability constraints on parameter space
- Mass spectra
- Composition of light scalars and inos in terms of MSSM and constrained fields
- Modifications to Higgs scalar production and decay

Collaborators: T.E. Clark
T. ter Veldhuis

arXiv:hep-ph/1107.3116

Introduction

- Assume electroweak symmetry breaking arises from novel, unknown strongly interacting supersymmetric dynamics
- Model independent means of parametrizing its effects is through a SUSY nonlinear sigma model where the $SU(2)_L \times U(1)$ electroweak symmetry nonlinearly realized through an additional pair of constrained Higgs doublet superfields
- Quarks, leptons and their SUSY partners acquire mass only from MSSM Higgs doublet pairs whose VEVs are catalyzed by their superpotential coupling to the constrained doublets
- W and Z boson masses arise from VEVs of both the MSSM and constrained doublets

MSSM plus EW breaking sector

$$W_{\text{Mix}} = \mu_{12} H_u \epsilon H_d' + \mu_{21} H_u' \epsilon H_d \qquad H_d' \epsilon H_u' = v_u' v_d'/2$$

- MSSM sector includes pair of Higgs doublets and μ_{11} parameter term

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

- SUSY nonlinear sigma model includes second pair of constrained Higgs doublets with vacuum values

$$H_u' = \begin{pmatrix} H_u^{+\prime} \\ H_u^{0\prime} \end{pmatrix} = \begin{pmatrix} i\Pi^+ \\ \Sigma - i\Pi^0 \end{pmatrix} \quad , \quad H_d' = \begin{pmatrix} H_d^{0\prime} \\ H_d^{-\prime} \end{pmatrix} = \begin{pmatrix} \Sigma + i\Pi^0 \\ i\Pi^- \end{pmatrix}$$

$$< 0|H_u'|0 >= \begin{pmatrix} 0 \\ v_u'/\sqrt{2} \end{pmatrix} \qquad < 0|H_d'|0 >= \begin{pmatrix} v_d'/\sqrt{2} \\ 0 \end{pmatrix}$$

- Imposition of constraint $\Sigma = \sqrt{\frac{v_u' v_d'}{2} - \vec{\Pi} \cdot \vec{\Pi}}$ breaks electroweak symmetry
- Electroweak breaking not tied to SUSY breaking as in MSSM
- After including W_{Mix}, the MSSM Higgs doublet pairs acquire VEVs
- Total VEV is $v = \sqrt{v_u^2 + v_d^2 + 2v'^{\,2}} \simeq 246 \ \text{GeV}$

$$< 0|H_u|0 >= \begin{pmatrix} 0 \\ v_u/\sqrt{2} \end{pmatrix} \qquad < 0|H_d|0 >= \begin{pmatrix} v_d/\sqrt{2} \\ 0 \end{pmatrix}$$

- Soft SUSY breaking limited to MSSM sector

$$\begin{aligned} \mathcal{L}_{\not{S}} = {} & \frac{1}{2} M_1 \left(\lambda\lambda + \bar{\lambda}\bar{\lambda} \right) + \frac{1}{2} M_2 \left(\lambda^i \lambda^i + \bar{\lambda}^i \bar{\lambda}^i \right) \\ & - m_u^2 H_u^\dagger H_u - m_d^2 H_d^\dagger H_d - \mu_{11} B H_u \epsilon H_d - \mu_{11} B H_u^\dagger \epsilon H_d^\dagger . \end{aligned}$$

Parameter Space

- Scalar potential secured from model action which includes $SU(2)_L \times U(1)$ SUSY Yang-Mills action, SUSY nonlinear sigma model constructed in terms of gauged Kahler metric, the superpotential and SUSY breaking terms
- For simplicity, the electroweak symmetry breaking sector is assumed to respect custodial $SU(2)_V$ global symmetry so that $v'_u = v'_d \equiv v'$
- Hence there are 3 electroweak minimum breaking conditions which we use to fix the parameters m_u^2, m_d^2, μ_{21}
- Consequently, the mass spectrum depends on the 7 remaining parameters

$\tan\beta = v_u/v_d$

μ_{11}

M_1, M_2

$b = -\mu_{11} B$

← Usual MSSM parameters

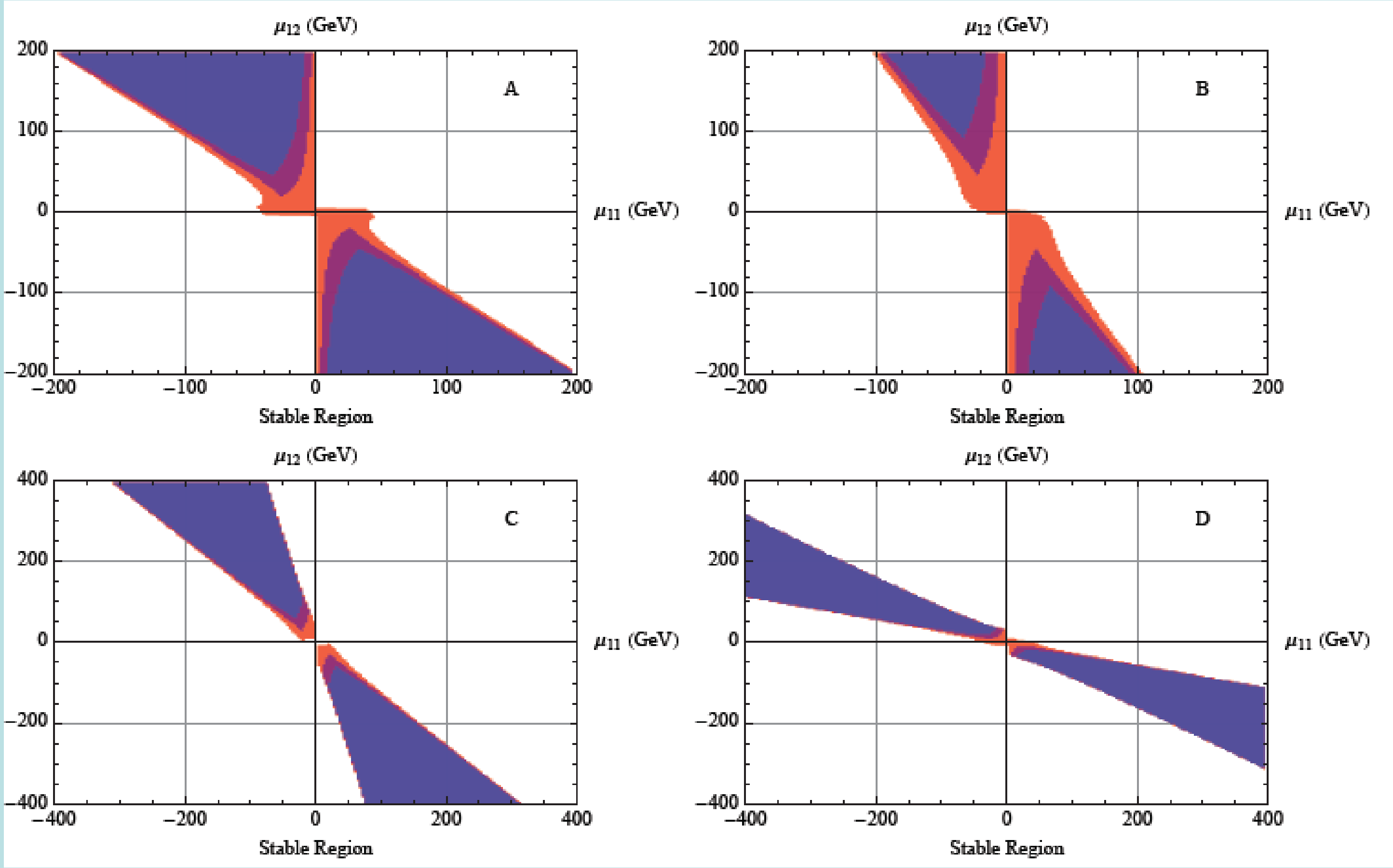
μ_{12}

$\tan\theta = \sqrt{(v_u^2 + v_d^2)/2v'^2}$

← Additional parameters

Stability of scalar potential

Stability region of parameter space determined by requiring all scalar squared masses to be positive



$A : \tan\beta = 1\ ;\quad \tan\theta = 1$

$B : \tan\beta = 1\ ;\quad \tan\theta = 2$

$C : \tan\beta = 2\ ;\quad \tan\theta = 2$

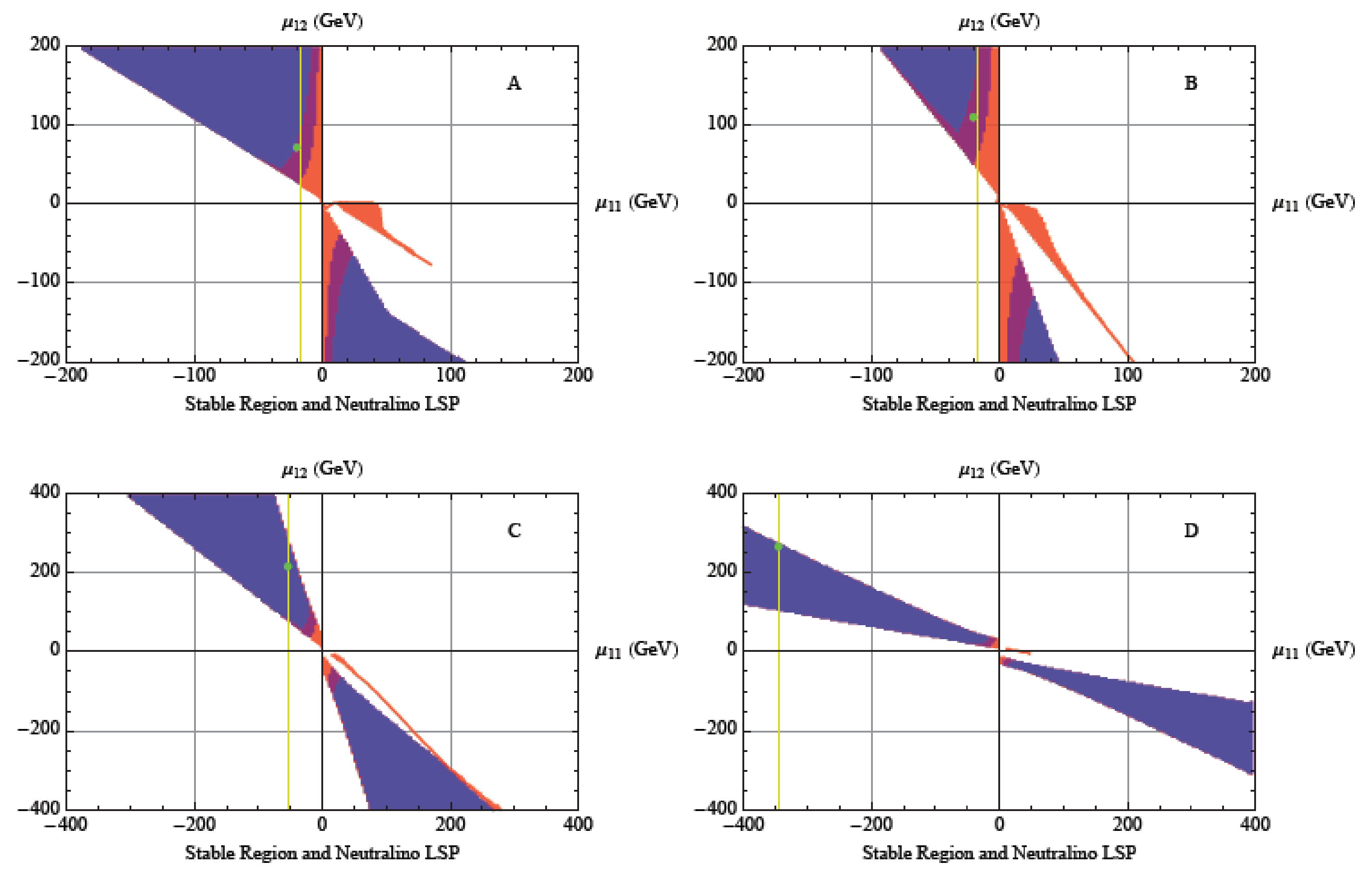
$D : \tan\beta = 10\ ;\quad \tan\theta = 2$

$b = -4000\ GeV^2$: orange + violet + blue

$b = 4000\ GeV^2$: violet + blue

$b = 12000\ GeV^2$: blue

The model exhibits an unbroken R-parity which insures the stability the lightest SUSY partner. Demanding it to be a neutralino further restricts the parameter space.



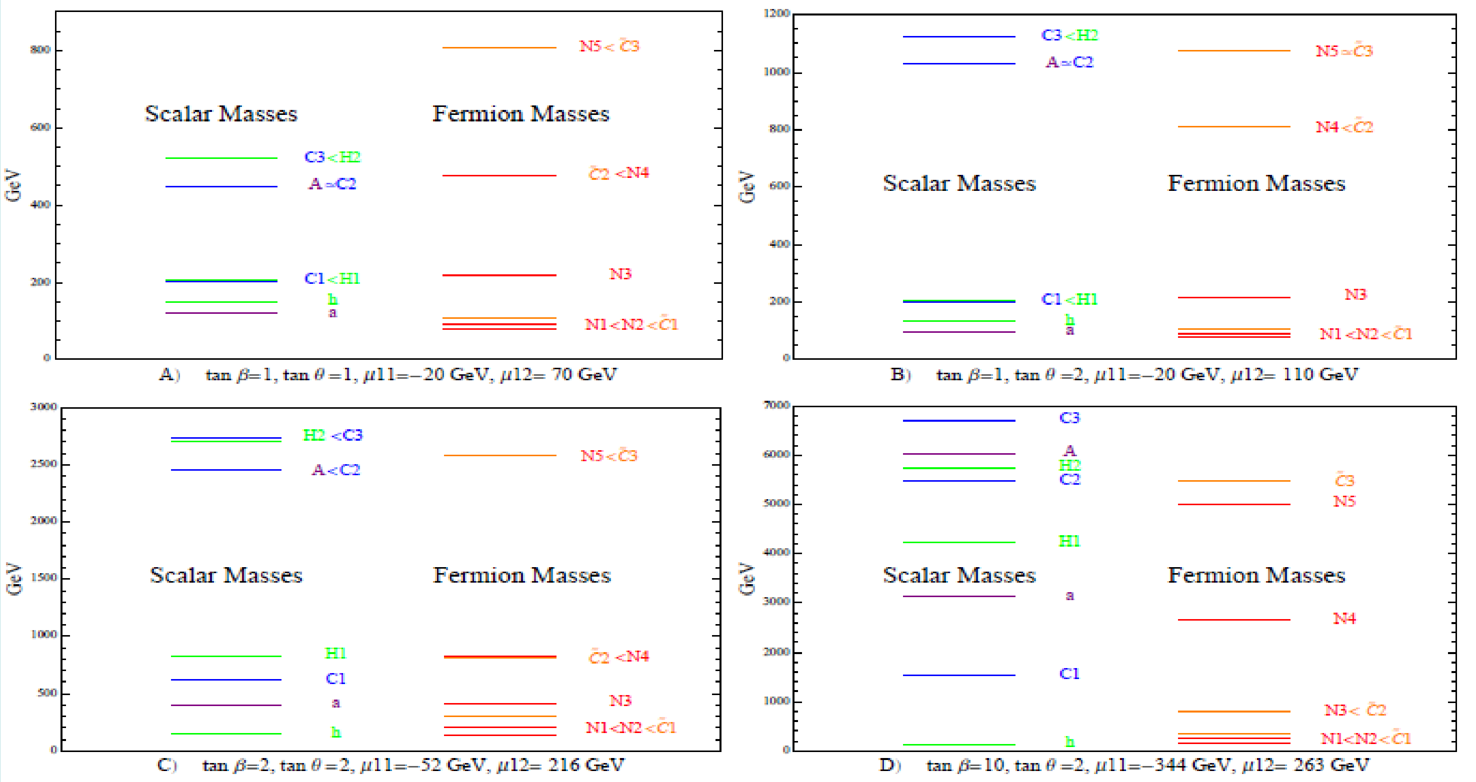
The green dots indicate the points in parameter space to be used in the mass spectrum plots to follow. Yellow lies indicate the value of μ_{11} along which the parameter μ_{12} is scanned. For each plot, the gaugino SUSY breaking masses are $M_1 = 200\ \text{GeV}\ ,\ M_2 = 800\ GeV$

Mass Spectrum

MSSM plus components of one neutral and two charged chiral superfields

Neutral scalars: h, H1, H2 ; Neutral pseudo scalars: a, A

Charged scalars: C1, C2, C3; Neutralinos: N1,… N5; Charginos: $\tilde{C}1$, $\tilde{C}2$, $\tilde{C}3$



A) $\tan\beta$=1, $\tan\theta$=1, μ11=−20 GeV, μ12= 70 GeV

B) $\tan\beta$=1, $\tan\theta$=2, μ11=−20 GeV, μ12= 110 GeV

C) $\tan\beta$=2, $\tan\theta$=2, μ11=−52 GeV, μ12= 216 GeV

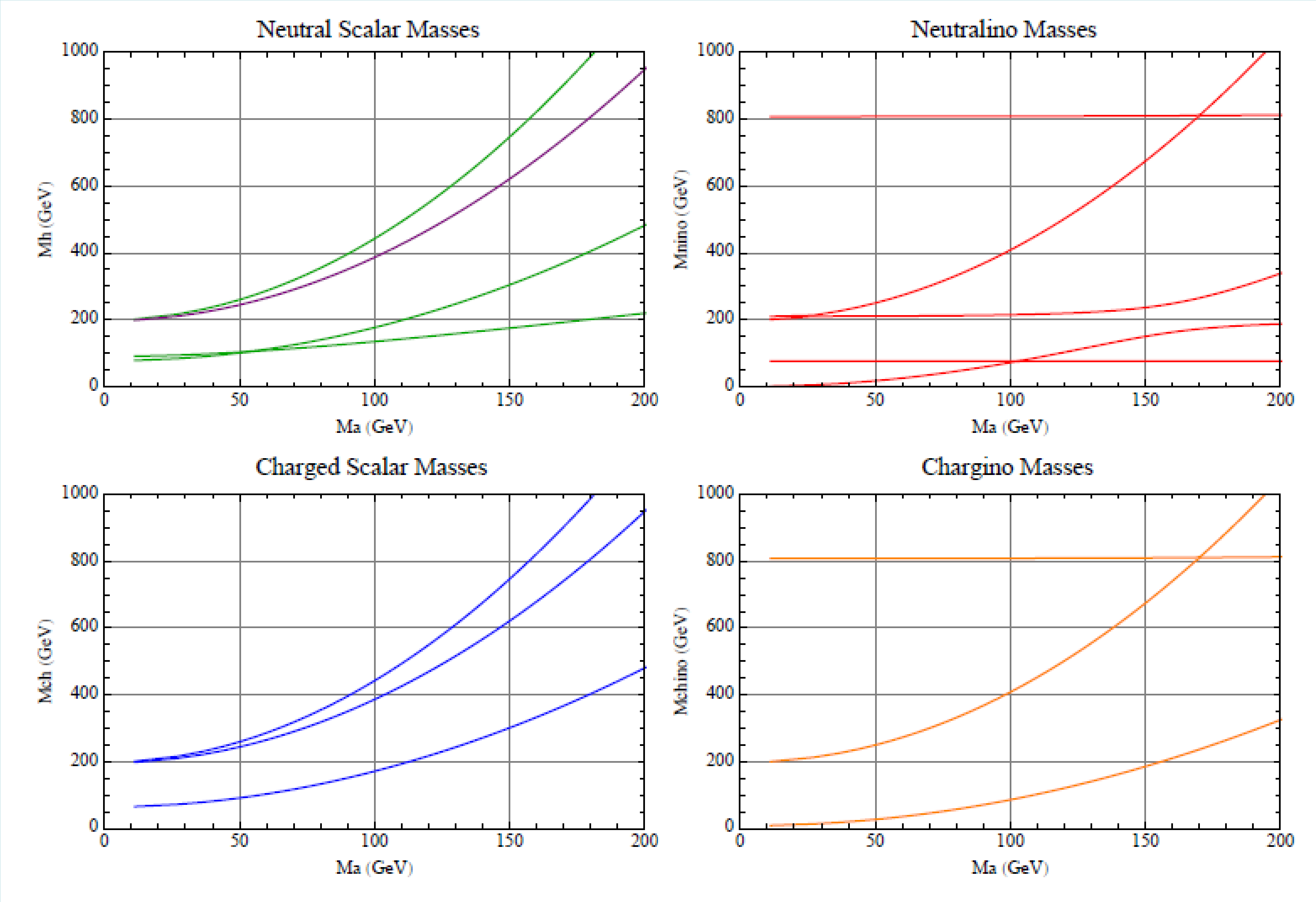
D) $\tan\beta$=10, $\tan\theta$=2, μ11=−344 GeV, μ12= 263 GeV

$$\begin{aligned} M_1 &= 200\ \text{GeV} \\ M_2 &= 800\ \text{GeV} \\ b &= 4000\ \text{GeV} \end{aligned}$$

Spectrum for point in stability region given by green dot

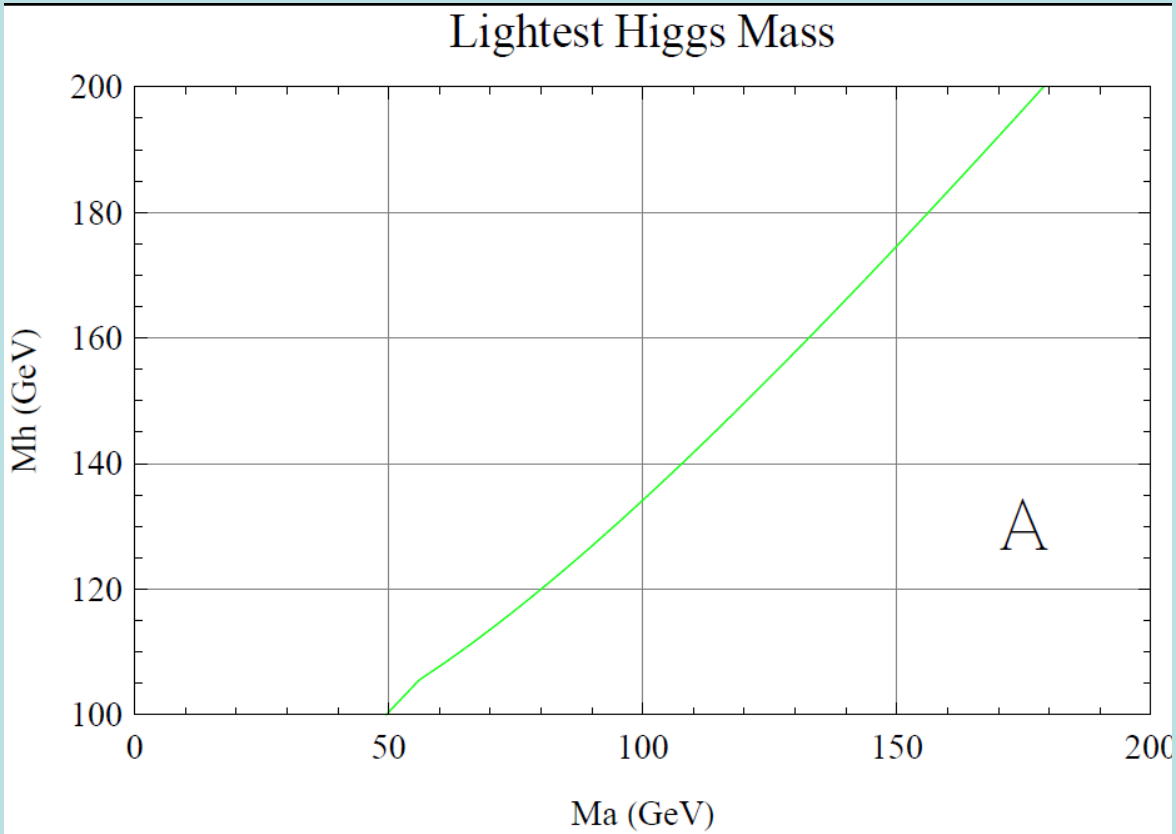
Lightest spin zero particle could be scalar or pseudoscalar

Region $A : \tan\beta = 1 \ ; \ \ \tan\theta = 1$ with $\mu_{11} = -12 \ GeV^2$



$A : \tan\beta = 1 \; ; \;\; \tan\theta = 1$

$\mu_{11} = -12\ GeV^2$



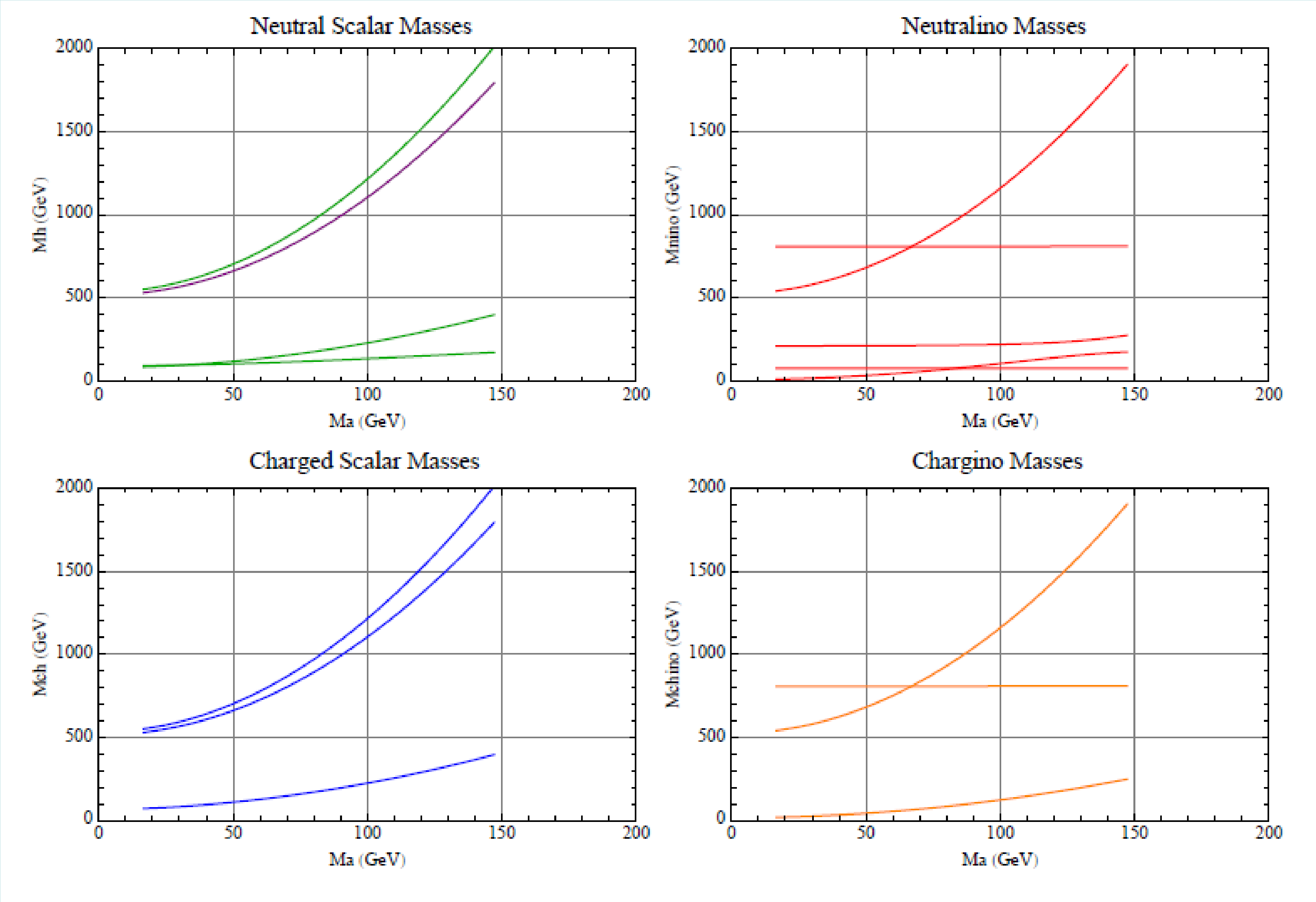
Experimental bound: $m_a > 93.4\ GeV$

Lightest neutral scalar $130\ GeV < m_h < 200\ GeV$ for $93.4\ GeV < m_a < 178\ GeV$

MSSM mass bound obviated

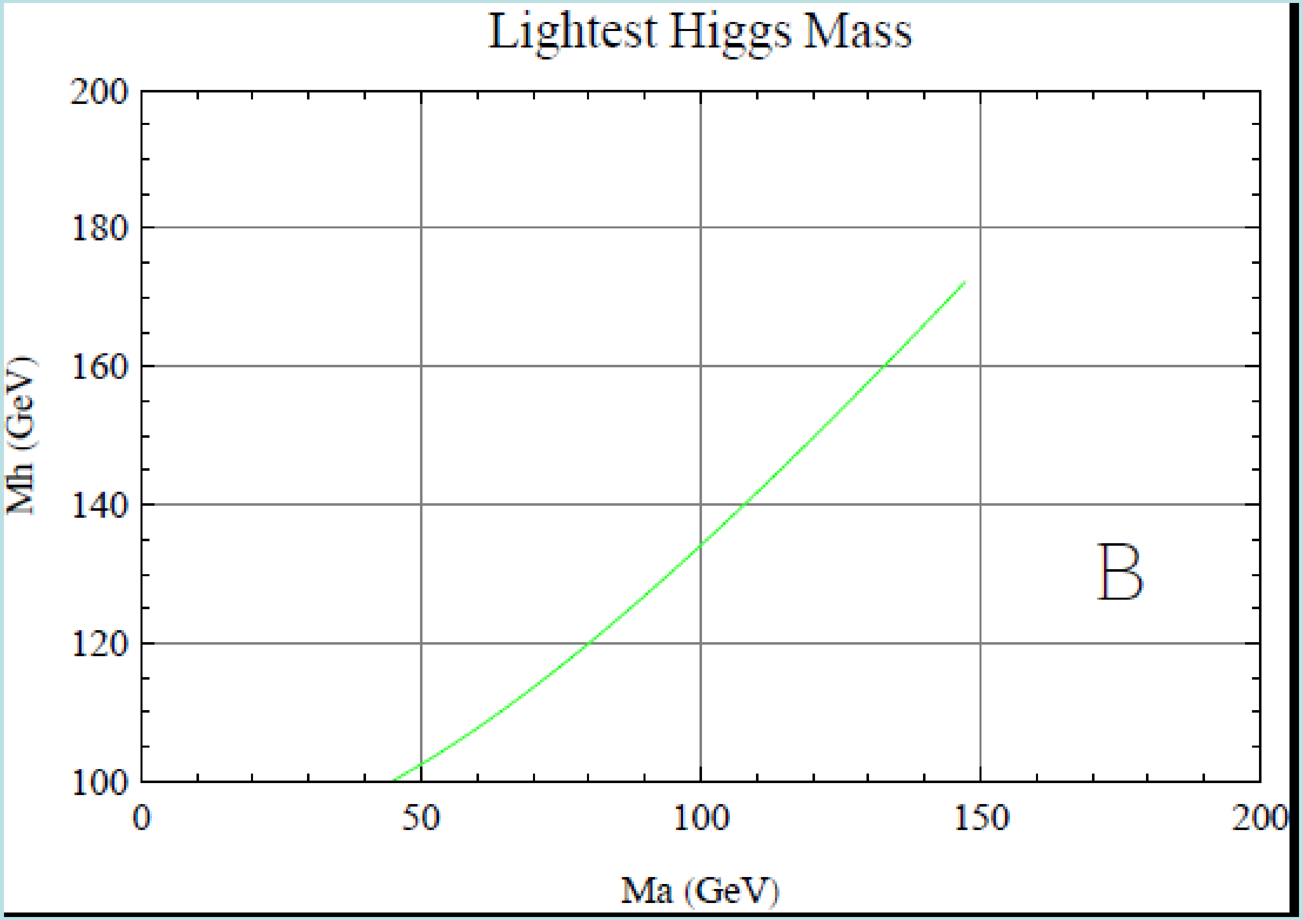
Lighter m_h values possible with different parameters

Region $B : \tan\beta = 1\ ;\ \ \tan\theta = 2$ with $\mu_{11} = -16\ GeV^2$



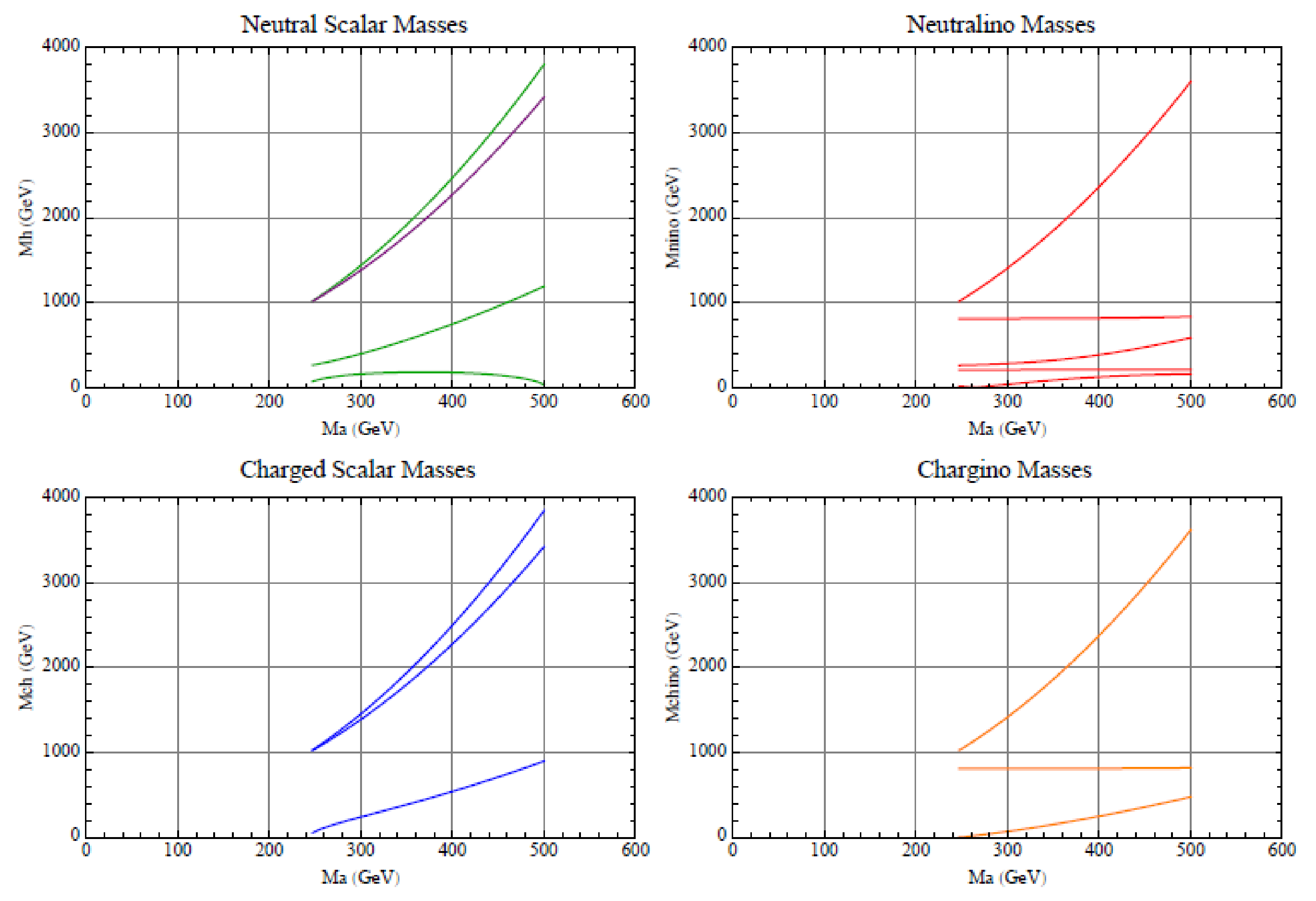
$B : \tan\beta = 1\ ;\ \ \tan\theta = 2$

$\mu_{11} = -16\ GeV^2$



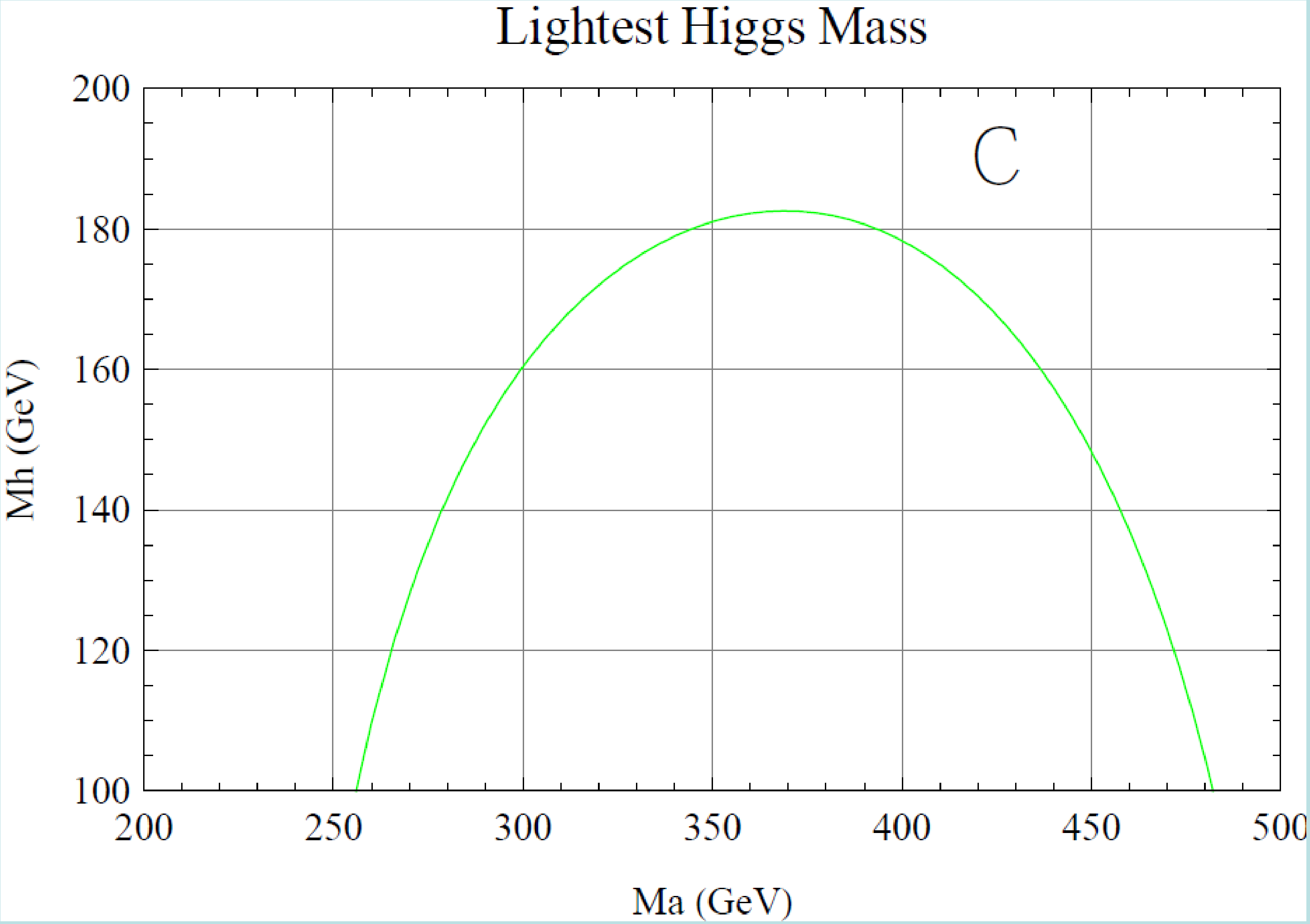
Lightest neutral scalar $130\ GeV < m_h < 172\ GeV$ for $93.4\ GeV < m_a < 148\ GeV$

Region $C : \tan\beta = 2 \ ; \ \ \tan\theta = 2$ with $\mu_{11} = -52\ GeV^2$



$C : \tan\beta = 2\ ;\ \ \tan\theta = 2$

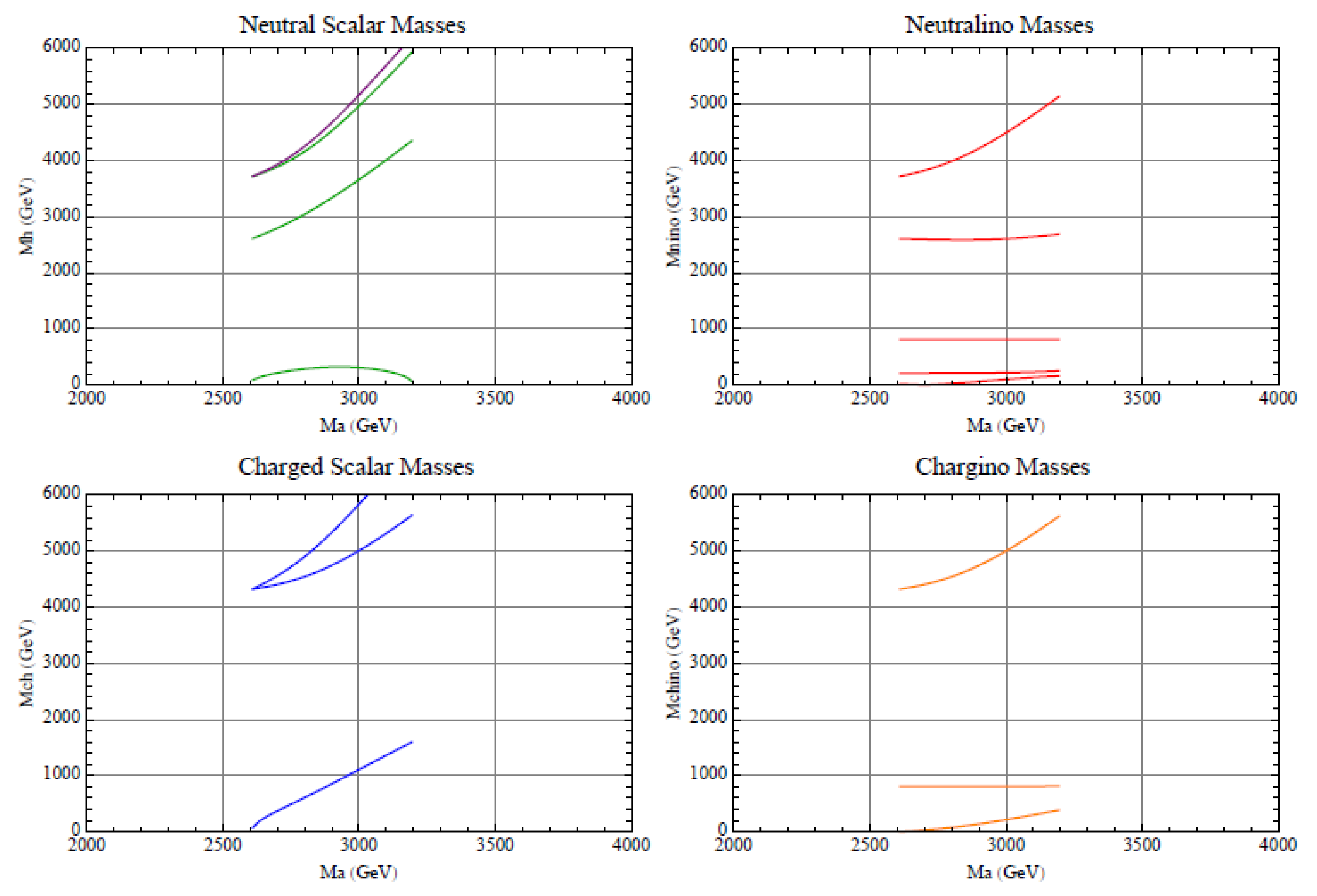
$\mu_{11} = -52\ GeV^2$



Lightest neutral scalar $182\ GeV > m_h > 115\ GeV$ for $370\ GeV < m_a < 475\ GeV$

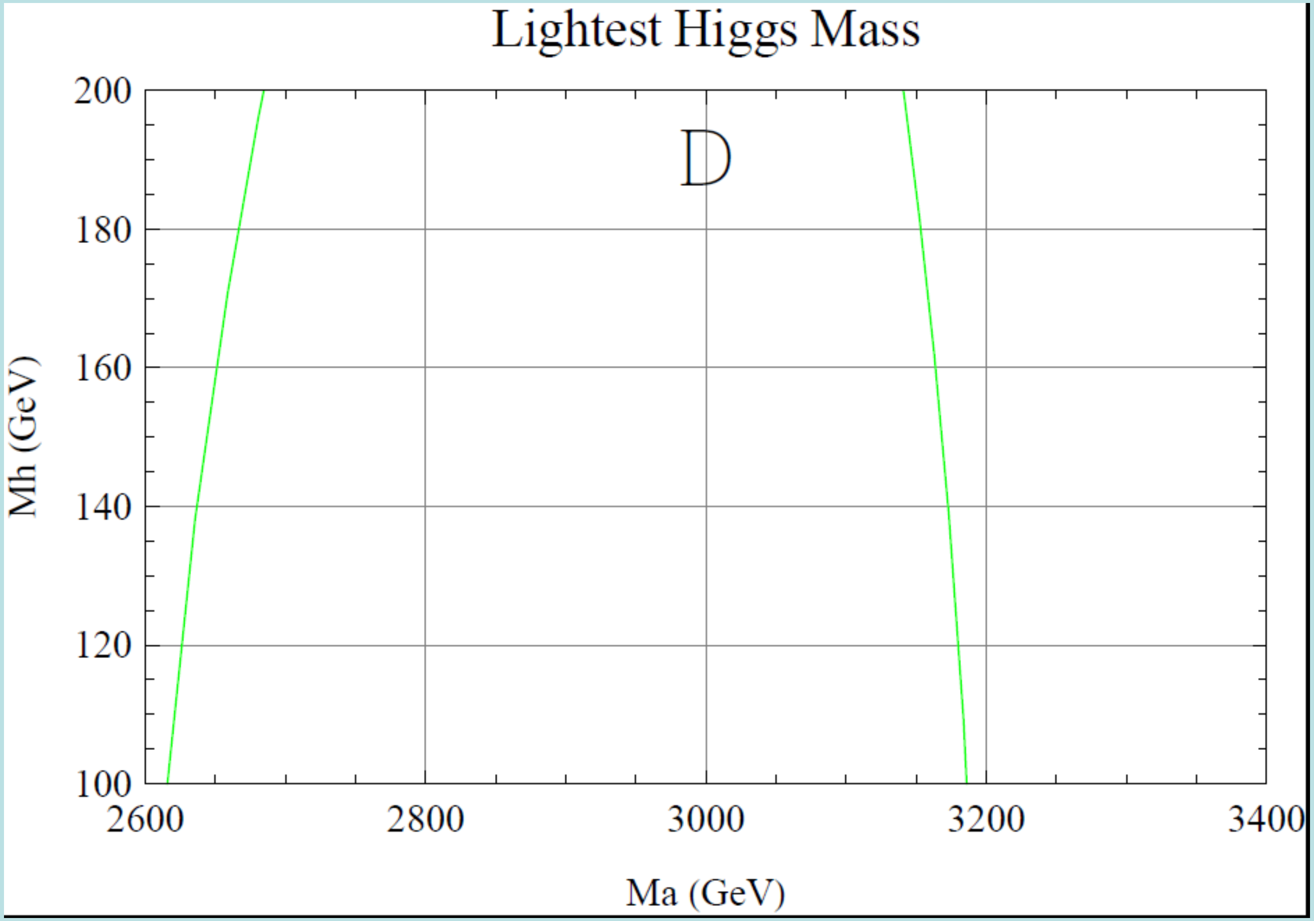
For $m_a <\sim 350\ GeV$, conflict with expt limits on chargino mass

Region $D : \tan\beta = 10\ ;\ \ \tan\theta = 2$ with $\mu_{11} = -344\ GeV^2$



$D : \tan\beta = 10 \; ; \;\; \tan\theta = 2$

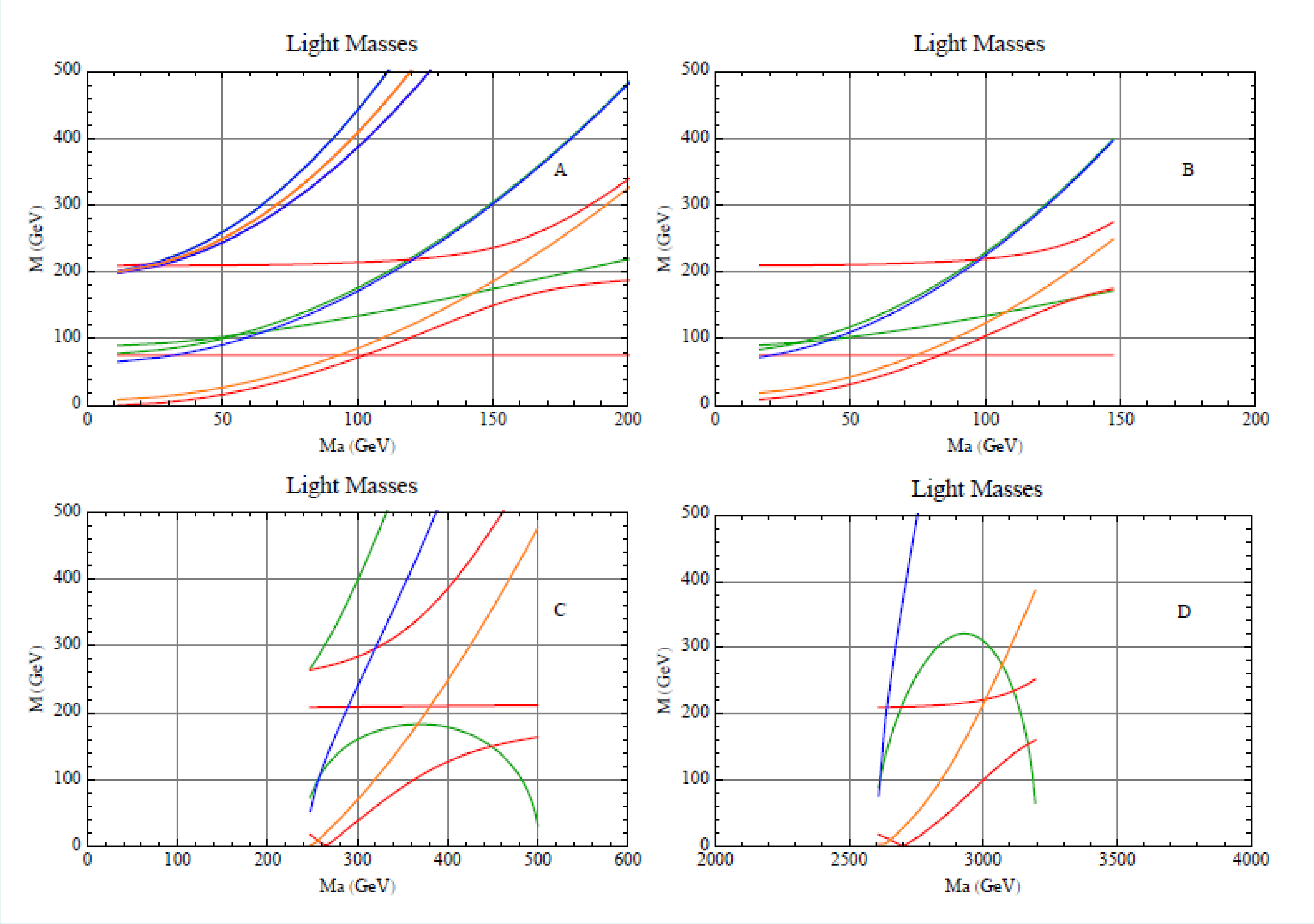
$\mu_{11} = -344 \; GeV^2$



Lightest neutral scalar $200 \; GeV > m_h > 115 \; GeV$ for $3140 \; GeV < m_a < 3180 \; GeV$

For $m_a <\sim 3000 \; GeV$, tension with current expt limit of lightest chargino/neutralino masses

Detailed spectra



green: neutral scalars ; blue: charged scalars; red: neutralinos ; orange: charginos

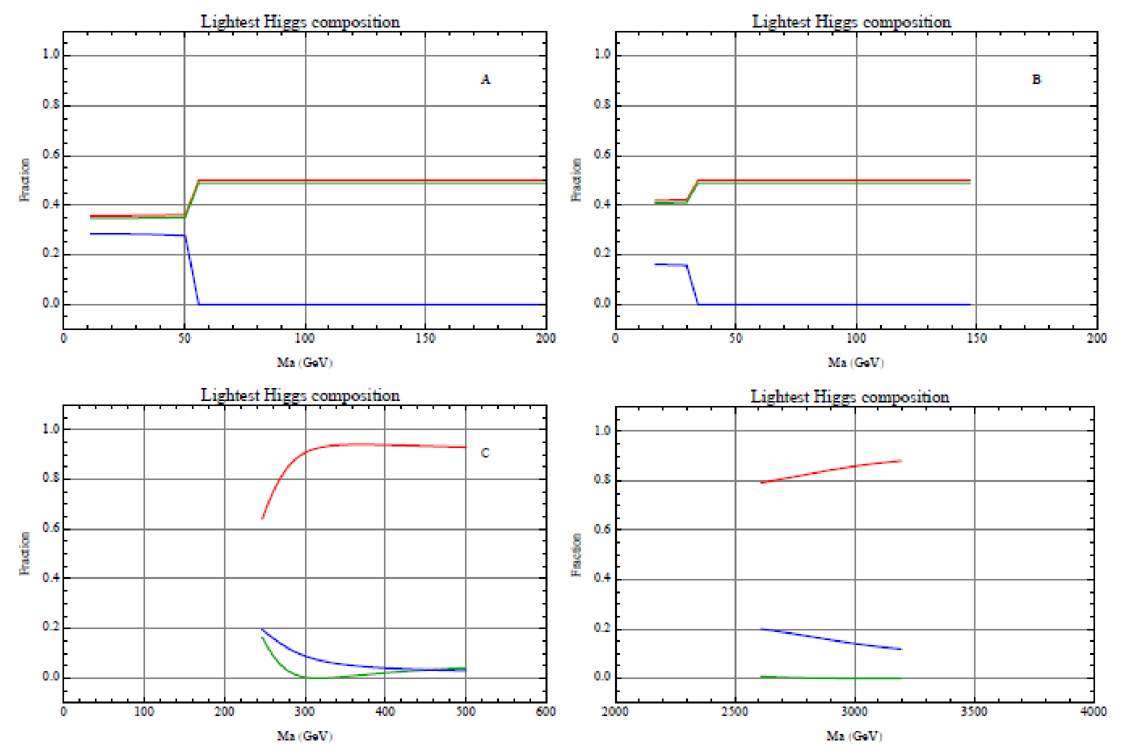
Near degeneracies in regions A, B consequence of $\tan\beta = 1$

Lightest neutral Higgs boson composition

Linear combination of the MSSM neutral Higgs scalars

$S_u = \frac{1}{\sqrt{2}}(H_u^{0\dagger} + H_u^0)$ $S_d = \frac{1}{\sqrt{2}}(H_d^{0\dagger} + H_d^0)$ and the constrained neutral scalar S_π :

$$h = a_u S_u + a_d S_d + a_\pi S_\pi$$



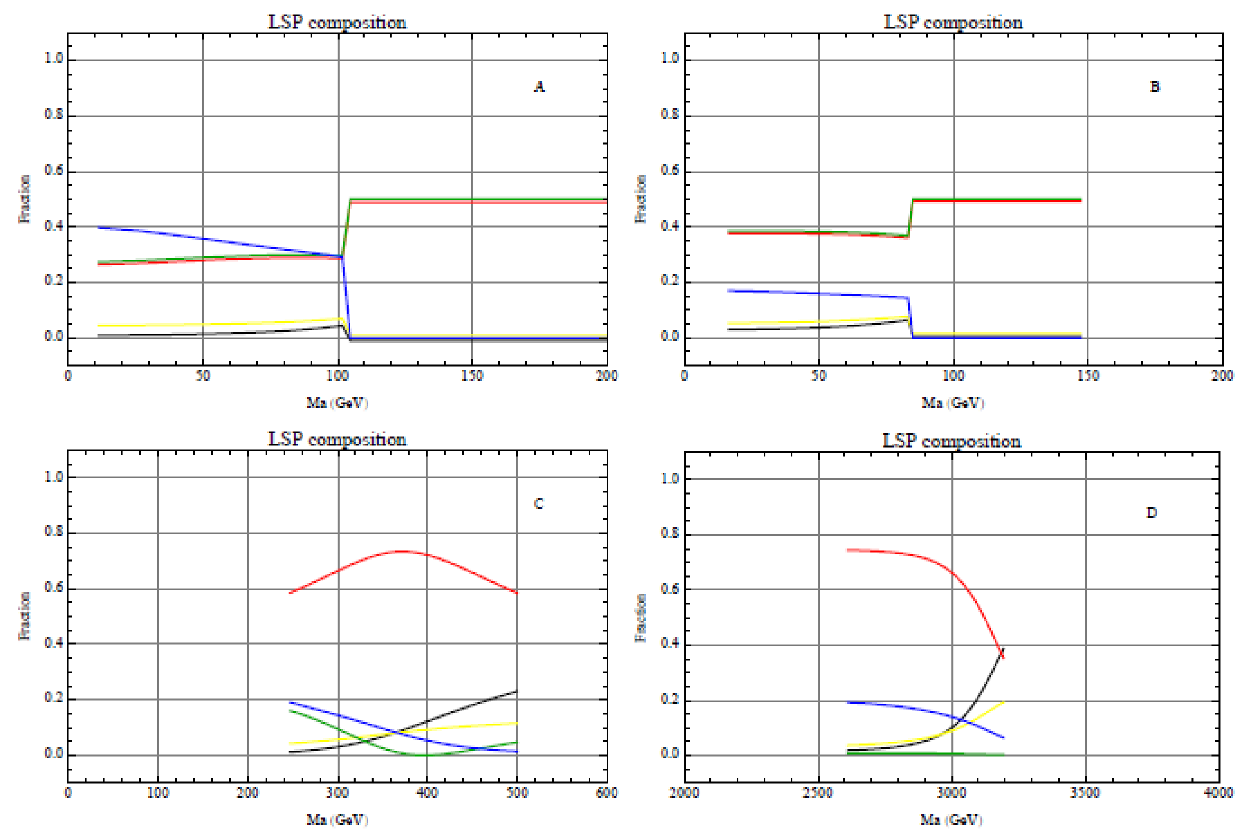
Red: $|a_u|^2$; Green: $|a_d|^2$; Blue: $|a_\pi|^2$

For m_h values discussed previously;

Regions A, B: h is essentially all MSSM

Region C: S_π content $\sim 6 - 4\%$; Region D: S_π content $\sim 13 - 12\%$

Lightest Neutralino: N1, Composition



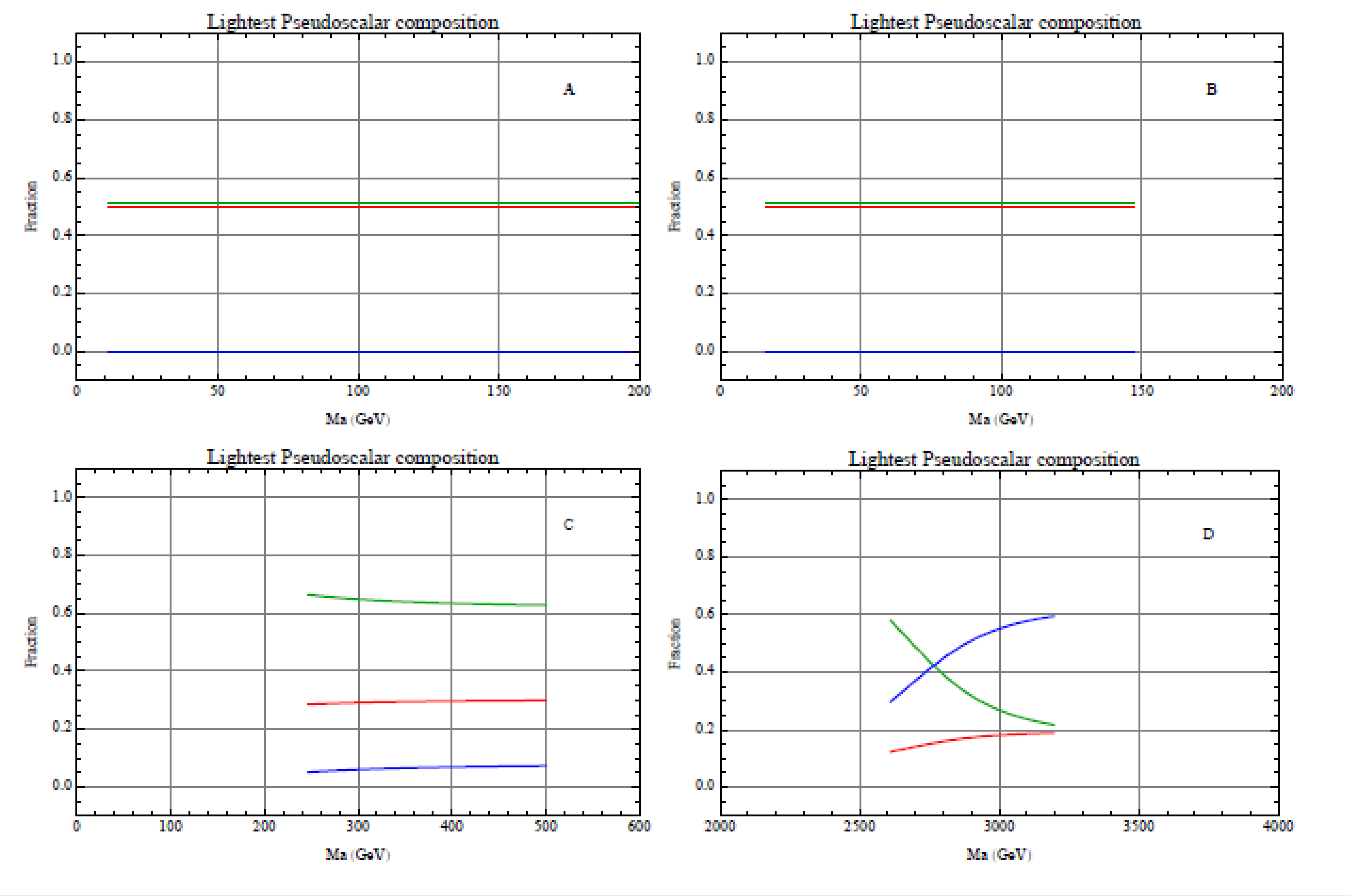
Black: λ_γ ; Yellow: λ_Z; Red: $\tilde{H}_u^0$; Green: $\tilde{H}_d^0$; Blue: $\tilde{\pi}^0$ fractions

$\tilde{\pi}^0$ composition for regions A,B,C for region of m_h under consideration quite small;

Identification of LSP with dark matter same as MSSM

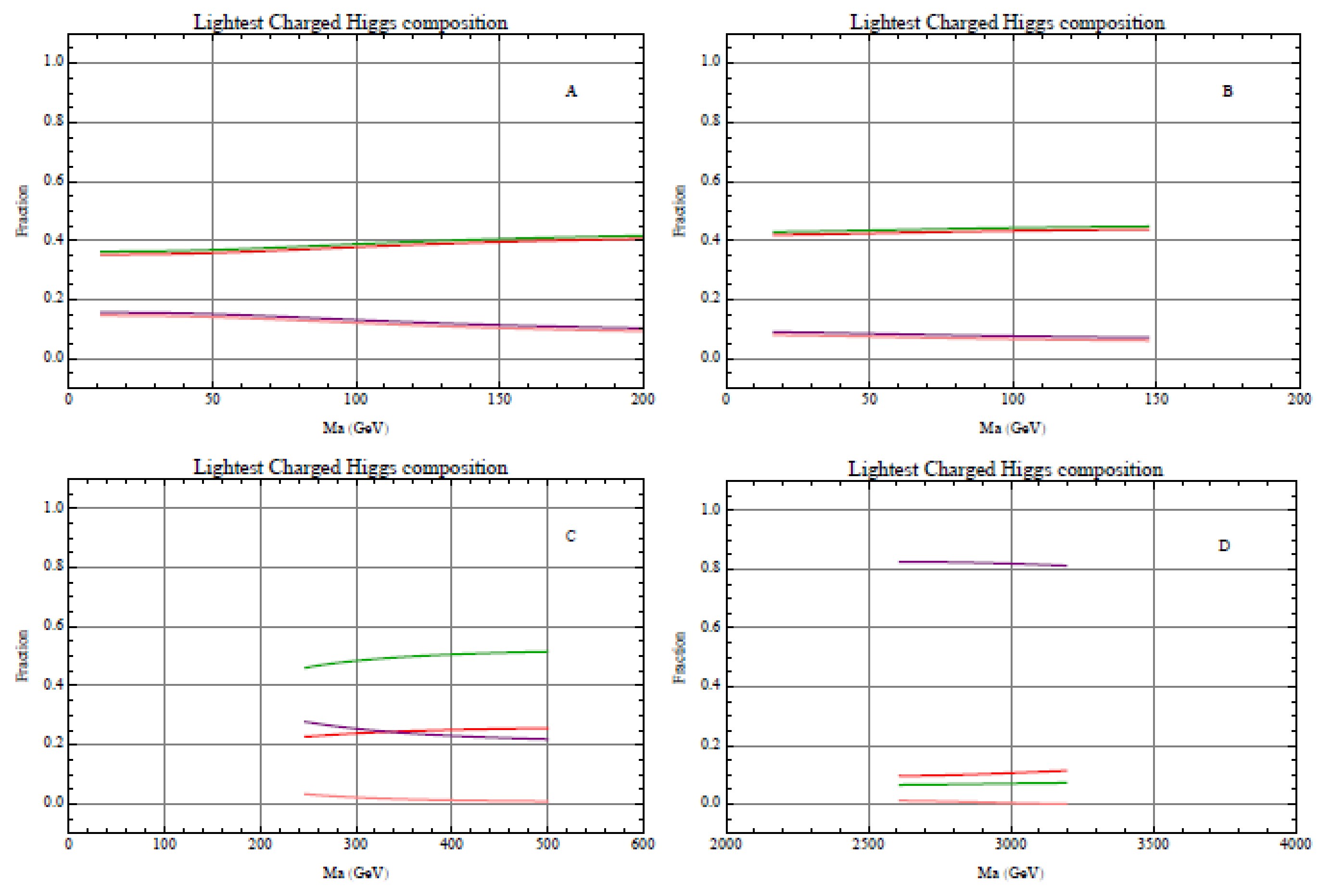
$\tilde{\pi}^0$ composition for region D somewhat larger $\sim 10 - 5\%$

Lightest Pseudoscalar Composition



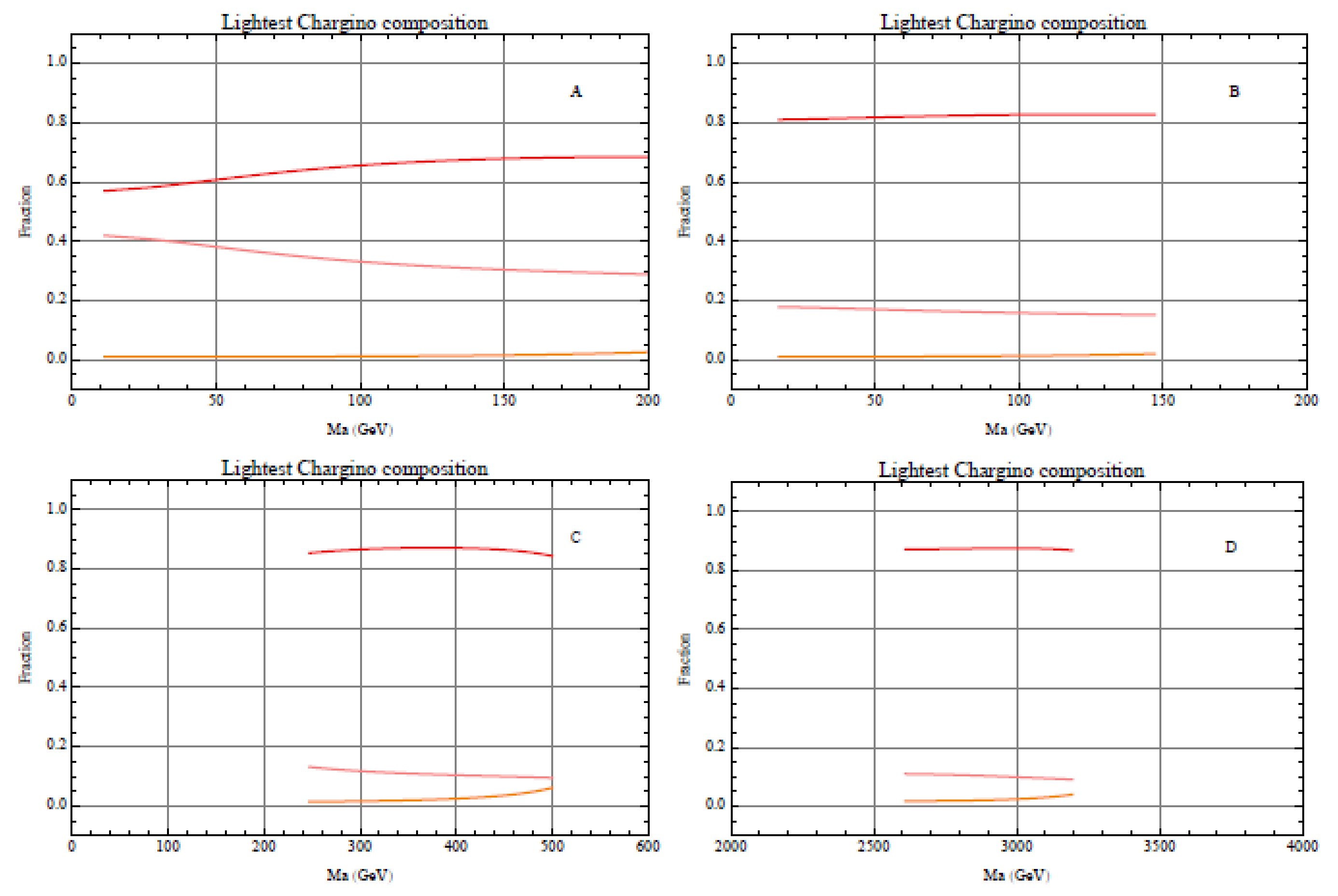
Red: $P_u = \frac{i}{\sqrt{2}}(H_u^{0\dagger} - H_u^0)$; Green: $P_d = \frac{i}{\sqrt{2}}(H_d^{0\dagger} - H_d^0)$; Blue: $P_{\bar{\pi}}$ fractions

Lightest Charged Higgs Composition



Red: H_u^+ ; Green: $H_d^{-\dagger}$; Pink: π^+ ; Purple: $\pi^{-\dagger}$

Lightest Chargino Decomposition



Orange: $\tilde{W}^+$; red: $\tilde{H}_u^+$; pink: $\tilde{\pi}^+$

Perturbative Yukawa Couplings

- Only MSSM Higgs fields couple directly to standard model fields
- MSSM Higgs field VEVs only contribute a portion of v=246 GeV
- Matter field Yukawa couplings must be proportionately larger to compensate for smaller v_u, v_d values.

Placing a perturbative bound on size of Yukawa couplings: $y < 4\pi$, results in bounds on $\tan\beta$ and $\tan\theta$:

$$\begin{aligned}
\left(1+\frac{1}{\tan^2\theta}\right)\left(1+\frac{1}{\tan^2\beta}\right) &= \frac{y_t^2 v^2}{2m_t^2} \leq \frac{8\pi^2 v^2}{m_t^2} \sim 160 \\
\left(1+\frac{1}{\tan^2\theta}\right)\left(1+\tan^2\beta\right) &= \frac{y_b^2 v^2}{2m_b^2} \leq \frac{8\pi^2 v^2}{m_b^2} \sim 2\times 10^5 \\
\left(1+\frac{1}{\tan^2\theta}\right)\left(1+\tan^2\beta\right) &= \frac{y_\tau^2 v^2}{2m_\tau^2} \leq \frac{8\pi^2 v^2}{m_b^2} \sim 1.5\times 10^6
\end{aligned}$$

In addition to very small $\tan\theta$ values, also excluded are regions with fractionally small values of $\tan\theta$ and $\tan\beta$ (e.g. $\tan\theta = 0.1$ and $\tan\beta = 1$) as well as excessively large values of $\tan\beta$

Higgs Production

For moderate $\tan\beta$, top quark loop gives dominant contribution to gluon fusion Higgs production at the LHC. Lightest neutral Higgs scalar can be written as a linear combination of the MSSM Higgs fields and the constrained Higgs fields as

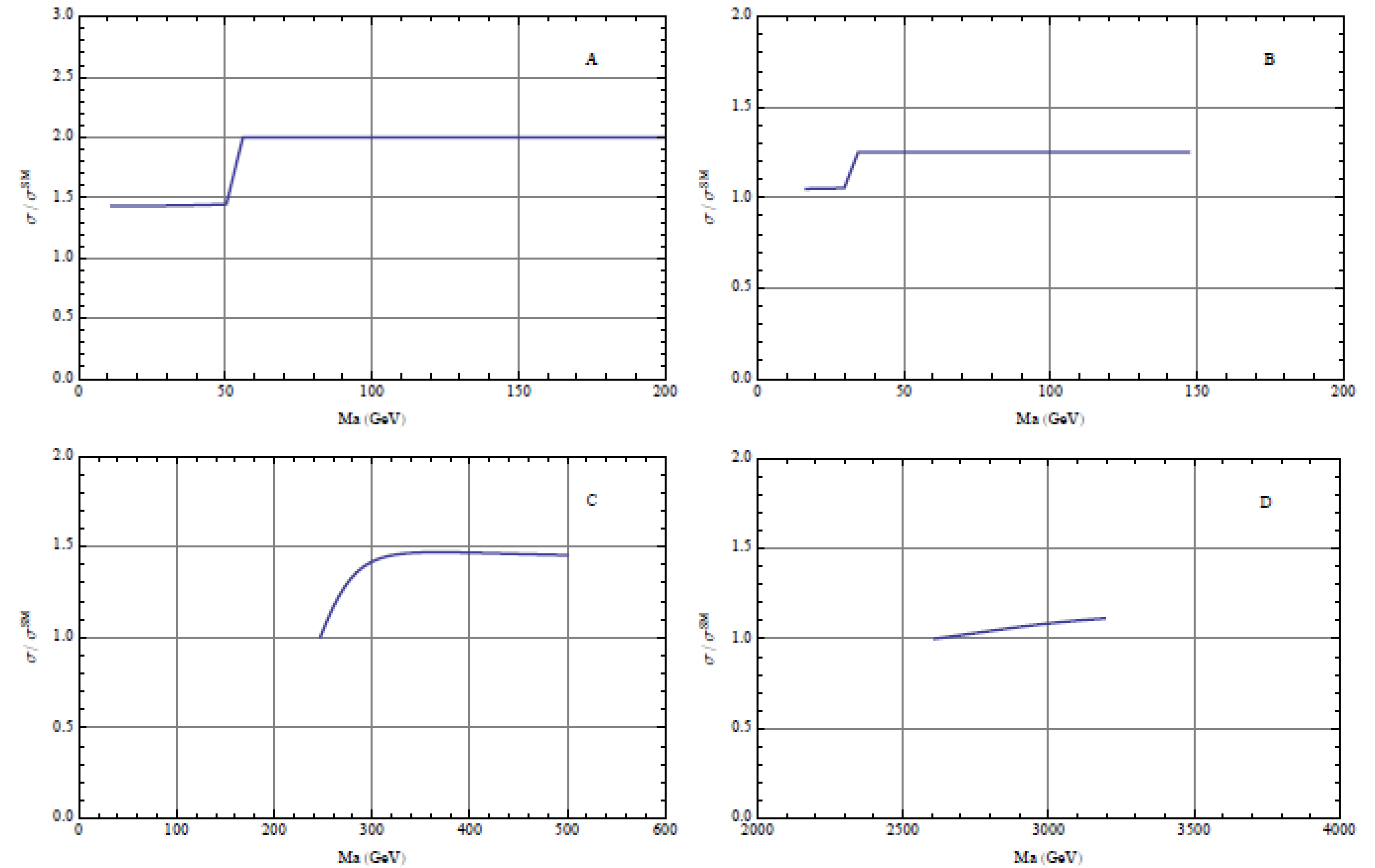
$$h = a_u S_u + a_d S_d + a_\pi S_\pi$$

Top quark only interacts with S_u component with enhanced Yukawa coupling $m_t/(v \sin\theta \sin\beta)$. Higgs production cross section is that of standard model modified by an overall factor so that

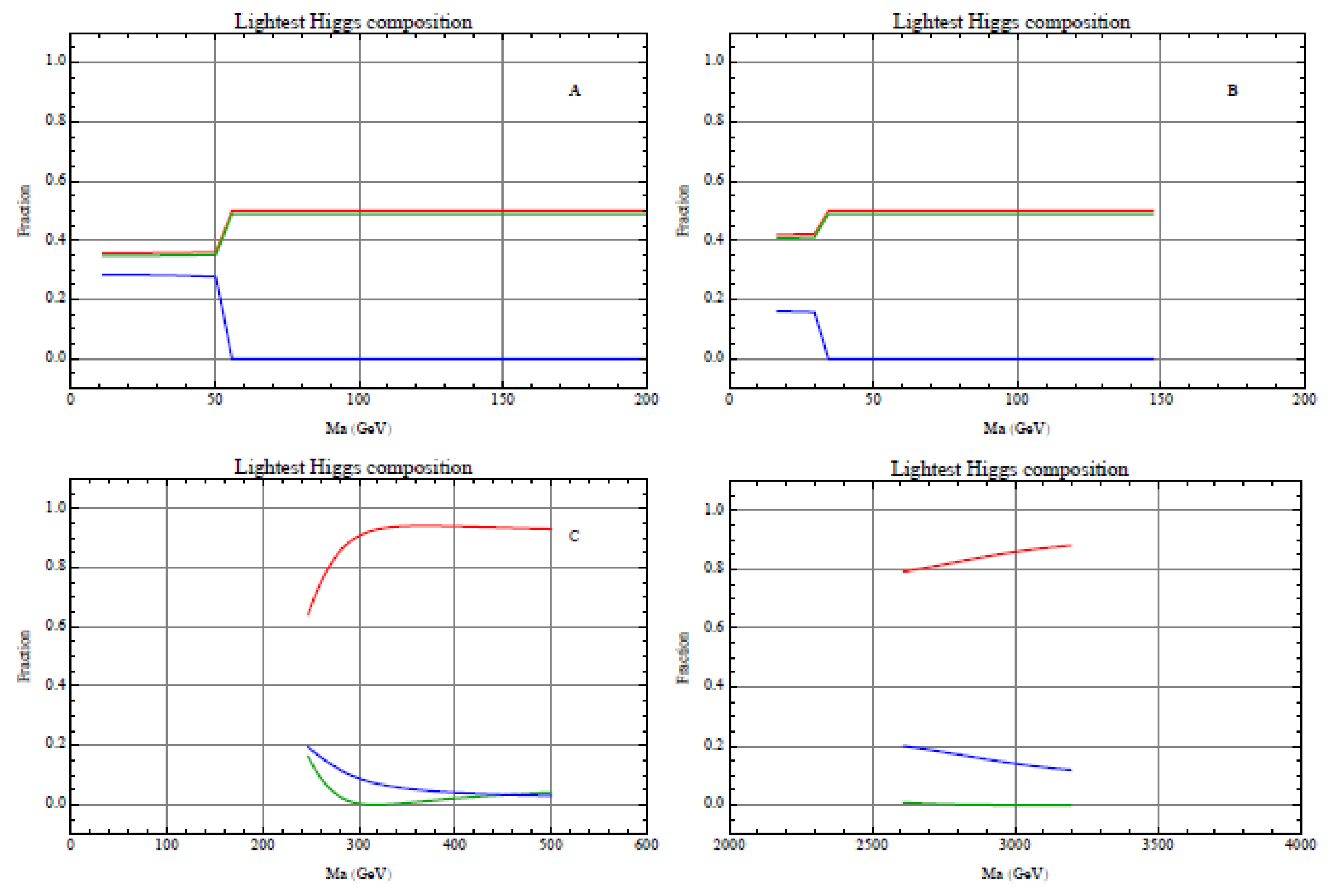
$$\sigma = |a_u|^2 \left(1 + \frac{1}{\tan^2\theta}\right) \left(1 + \frac{1}{\tan^2\beta}\right) \sigma^{\mathrm{SM}}$$

which depends on detail of S_u content.

Ratio of gluon fusion Higgs scalar production to the standard model result



Cross section enhancement follows since S_u comprises at least ½ the Higgs scalar.



Red: S_u ; Green: S_d ; Blue: S_π

Higgs Decay

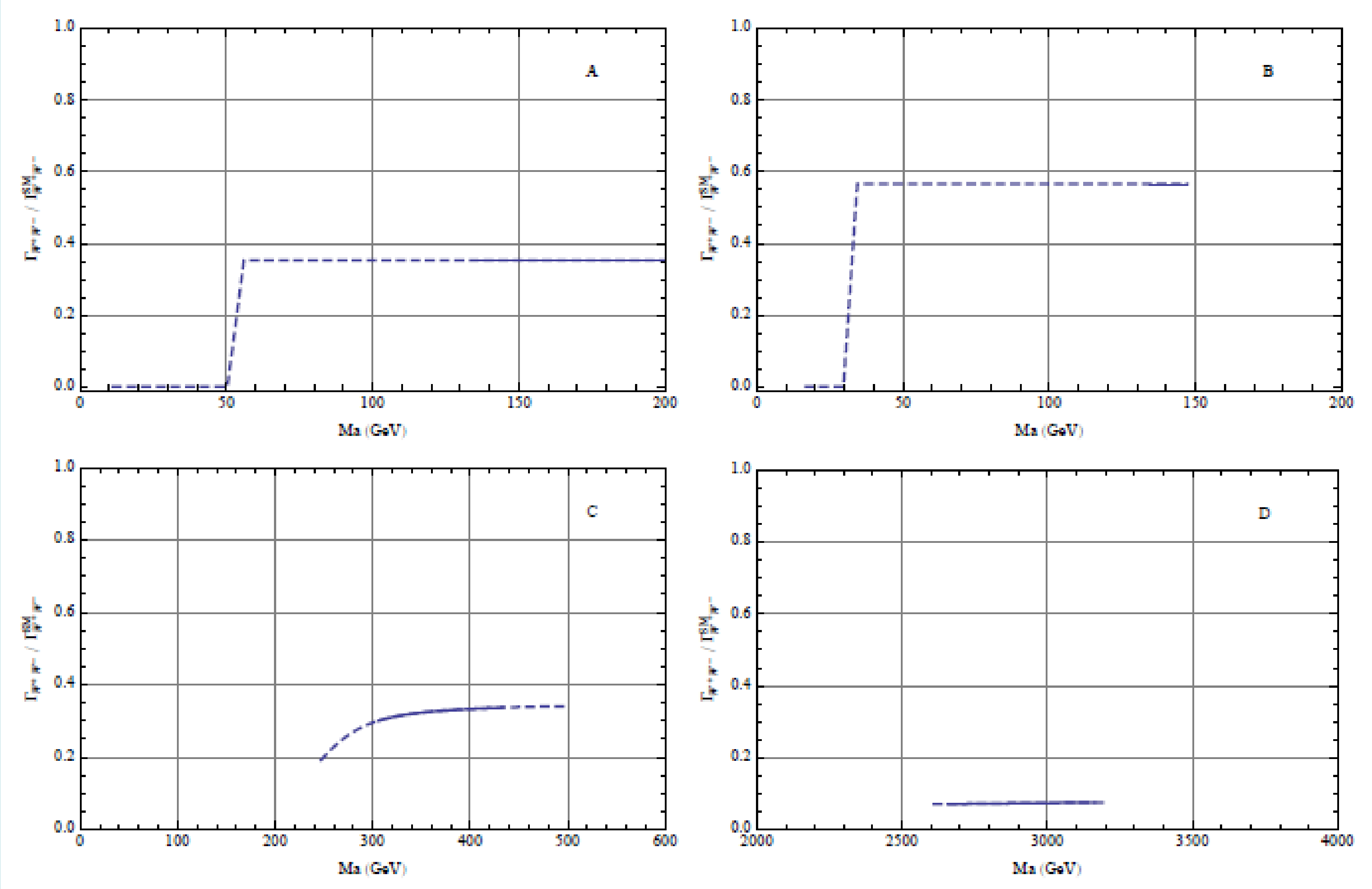
Differences from the standard model arise from presence of multiple mixing angles β , θ in the vacuum expectation values and the various particle content in h

$$h = a_u S_u + a_d S_d + a_\pi S_\pi$$

$h \to W^+W^-$

Since $v'_u = v'_d$, the coupling of S_π to the W^+W^- pair cancels. Consequently, the process proceeds only through S_u and S_d yielding a tree level rate

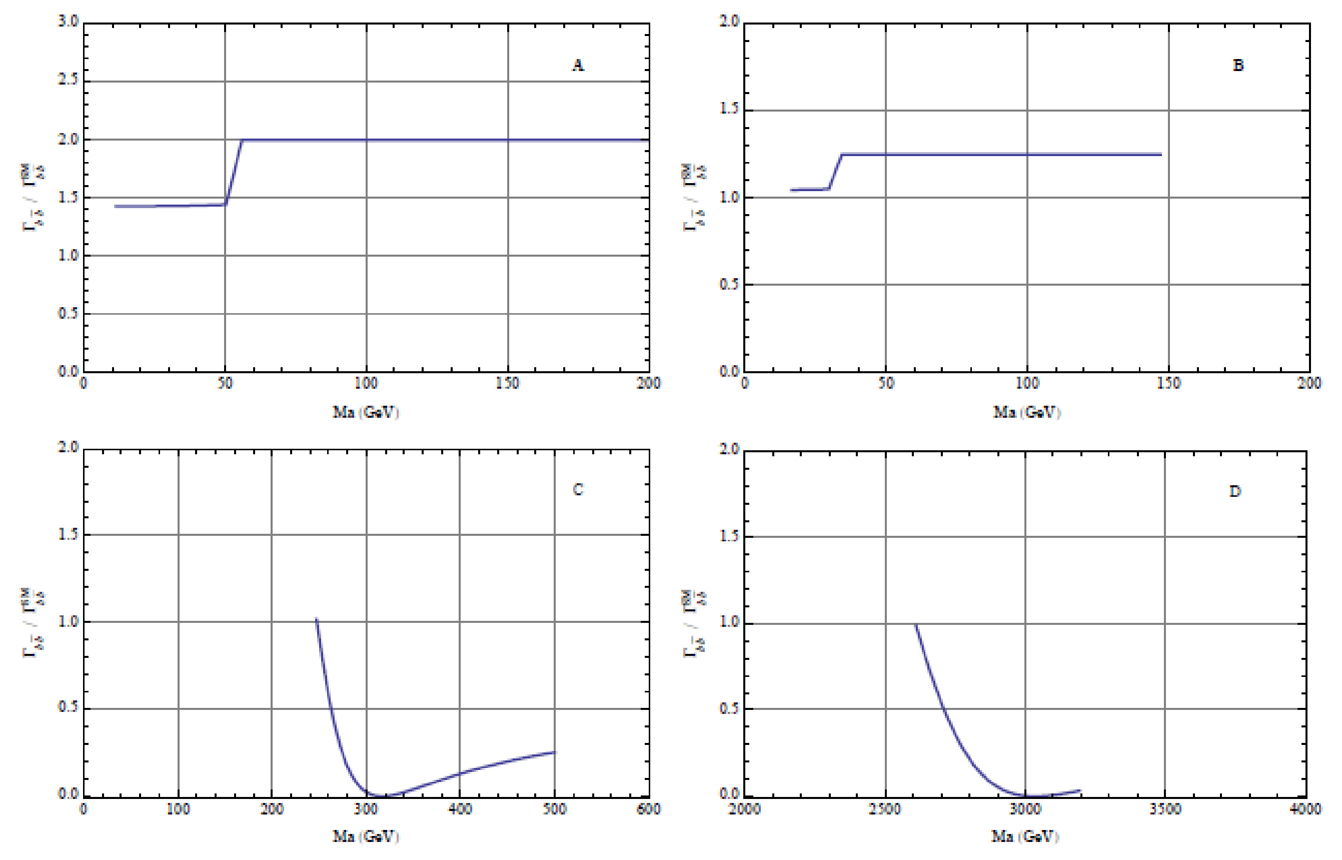
$$\Gamma_{W+W^-} = \left(\frac{\tan^2\theta}{1+\tan^2\theta}\right)\left(\frac{1}{1+\tan^2\beta}\right)|a_u \tan\beta + a_d\ |^2\,\Gamma^{\mathrm{SM}}_{W+W^-}$$



$h \longrightarrow \bar{b}b$

Depends on b-Yukawa enhancement and S_d constituent fraction of h.

Leads to modified tree level rate $\Gamma_{b\bar{b}} = |a_d|^2 \left(1 + \frac{1}{\tan^2\theta}\right)(1+\tan^2\beta)\,\Gamma^{\rm SM}_{b\bar{b}}$



Enhancement in regions A, B resulting from mixing angle factors.

Suppression regions C, D consequence of very small admixture of S_d in h.

Summary

- Introduced model with the MSSM coupled to a gauged SUSY nonlinear sigma model constructed using two constrained Higgs doublet fields which characterize effects strongly interacting electroweak symmetry breaking sector in model independent fashion.
- Coupling of constrained Higgs doublets to MSSM Higgs doublets catalyze the later VEVs which in turn give masses to quarks, leptons and their SUSY partners.
- Vacuum stability bounds on model parameters were delineated including those arising from having the lightest SUSY partner be a neutralino
- Various regions of parameter space were explored.
- Model has viable mass spectrum. The lightest Higgs scalar mass is not bounded from above by M_Z at tree level as in the MSSM
- Throughout most of parameter space explored, lightest Higgs scalar was composed mainly of MSSM fields with some admixtude of nonlinearly transforming Higgs fields. Similarly lightest neutralino was predominantly MSSM fields and could be identified as dark matter candidate
- Modifications to the lightest Higgs scalar production and decay due to the presence additional vacuum expectation values and Higgs field mixing were considered