ILC Physics in Florence

Neutralino Dark Matter and τ polarization: a way to distinguish SUSY-GUT from CMSSM

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Firenze, 12/09/2007

First part:
SUSY-GUTs, SUSY see-saw and Neutralino DM

based on L.C., Y. Mambrini, S. Vempati, arXiv:0704.3518 [hep-ph]

Neutralino Dark Matter

MSSM neutralinos: $\left(\tilde{B}, \tilde{W}_3, \tilde{H}_d^0, \tilde{H}_u^0\right)$

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

Lightest eigenvalue: $\tilde{\chi}_1^0 = Z_{11}\tilde{B} + Z_{12}\tilde{W}_3 + Z_{13}\tilde{H}_d^0 + Z_{14}\tilde{H}_u^0$

R-parity makes the LSP stable → candidate for CDM

Relic density (WMAP): $0.087 \lesssim \Omega_{DM} h^2 \lesssim 0.138$

CMSSM and three WMAP “corridors”

CMSSM: $m_0,\ M_{1/2},\ A_0,\ \tan\beta$ $\longrightarrow$ $M_{\rm GUT} \simeq 2\times 10^{16}\,{\rm GeV}$

Mostly “Bino”: $\tilde{\chi}^0_1 = Z_{11}\tilde{B} + Z_{12}\tilde{W}_3 + Z_{13}\tilde{H}^0_d + Z_{14}\tilde{H}^0_u$

Small annihilation cross-section → too large relic density

$$0.087 \lesssim \Omega_{DM} h^2 \lesssim 0.138$$

Peculiar conditions to enhance cross-section are needed!

CMSSM and three WMAP "corridors"

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Mostly "Bino": $\tilde\chi_1^0 = Z_{11}\tilde B + Z_{12}\tilde W_3 + Z_{13}\tilde H_d^0 + Z_{14}\tilde H_u^0$

- *Stau coannihilation:* $\tilde\chi_1^0 + \tilde\tau_1 \longrightarrow \tau + Z_0(\gamma)$

  $m_{\tilde\chi_1^0} \simeq m_{\tilde\tau_1}$ → close to the "stau LSP" region

- *A-pole funnel:* $\tilde\chi_1^0 + \tilde\chi_1^0 \longrightarrow f + \bar f$ $\quad 2\,m_{\tilde\chi_1^0} \simeq m_{A^0}$

- *Focus point:* for small μ → close to the "no EWSB" region ($\mu^2 < 0$)
  enhancement of the higgsino components

CMSSM and three WMAP "corridors"

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  enhancement of the higgsino components

$$W_{\rm MSSM} = Y^u\ Q\ u^c\ h_u + Y^d\ Q\ d^c\ h_d + Y^e\ L\ e^c\ h_d + \mu\ h_u\ h_d$$

$$10 = \begin{pmatrix} 0 & u^c & -u^c & -u & -d \\ -u^c & 0 & u^c & -u & -d \\ u & -u^c & 0 & -u & -d \\ u & u & u & 0 & e^c \\ d & d & d & -e^c & 0 \end{pmatrix}_L \qquad \bar{5} = \begin{pmatrix} d^c \\ d^c \\ d^c \\ e \\ \nu \end{pmatrix}_L$$

$$W_{SU(5)_{RN}} = Y^u\ 10\ 10\ 5_u + Y^d\ 10\ \bar{5}\ \bar{5}_d + Y^\nu\ \bar{5}\ 1\ 5_u + M_R\ 1\ 1 + \mu\ 5_u\ \bar{5}_d$$

CMSSM vs. $SU(5)_{RN}$

$$W_{\rm MSSM} = Y^u\ Q\ u^c\ h_u + Y^d\ Q\ d^c\ h_d + Y^e\ L\ e^c\ h_d + \mu\ h_u\ h_d$$

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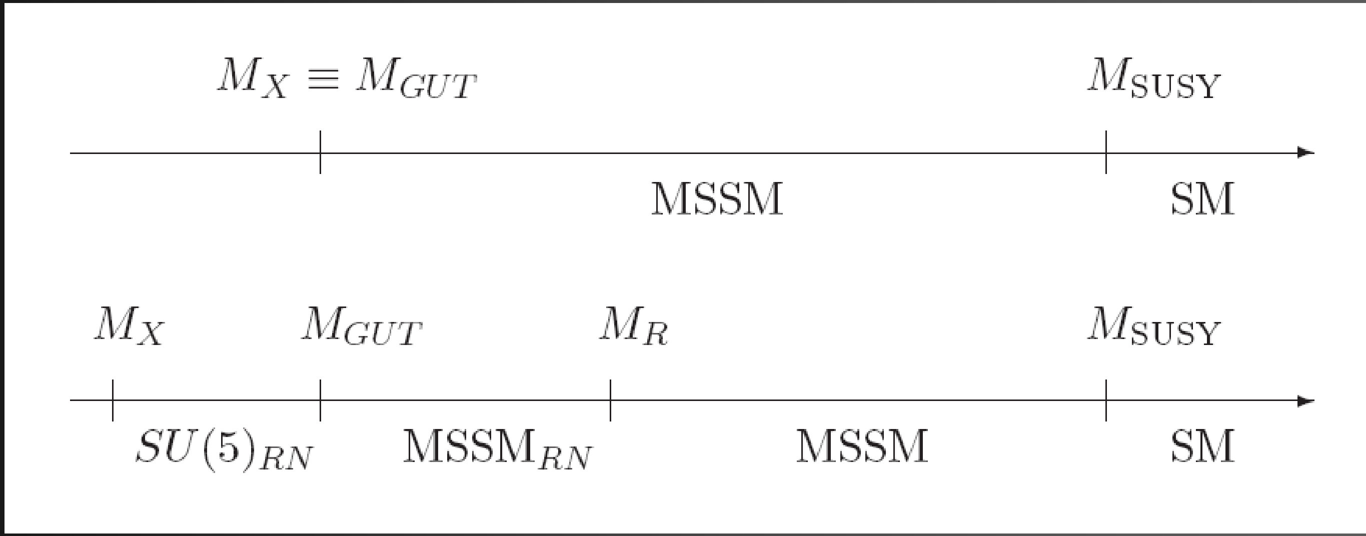
CMSSM vs. $SU(5)_{RN}$



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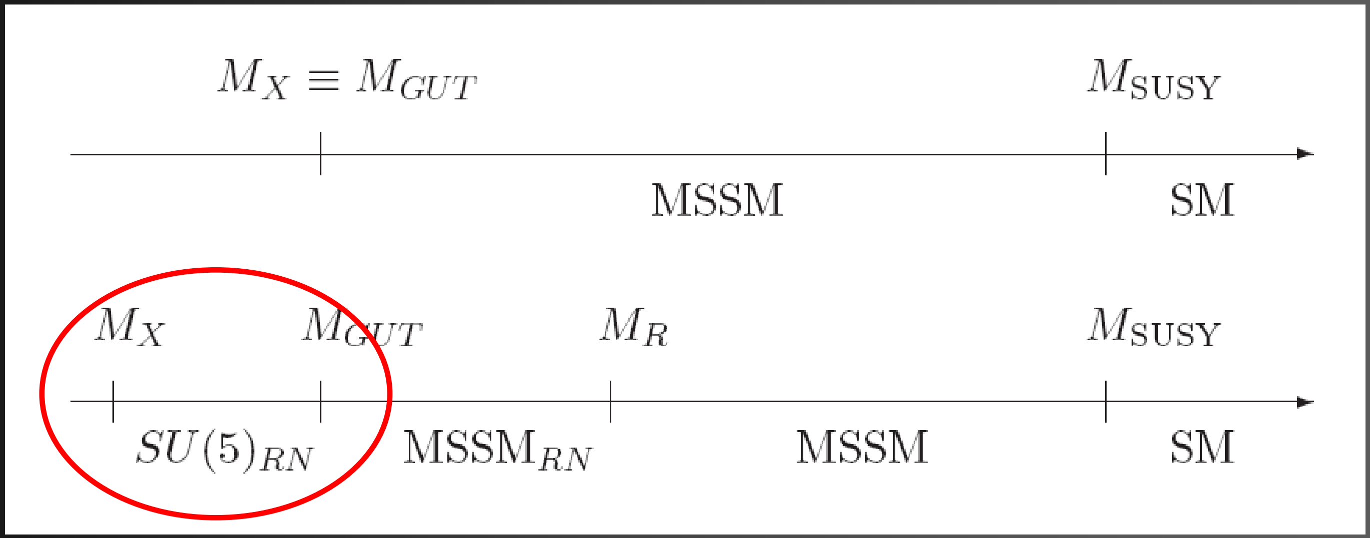
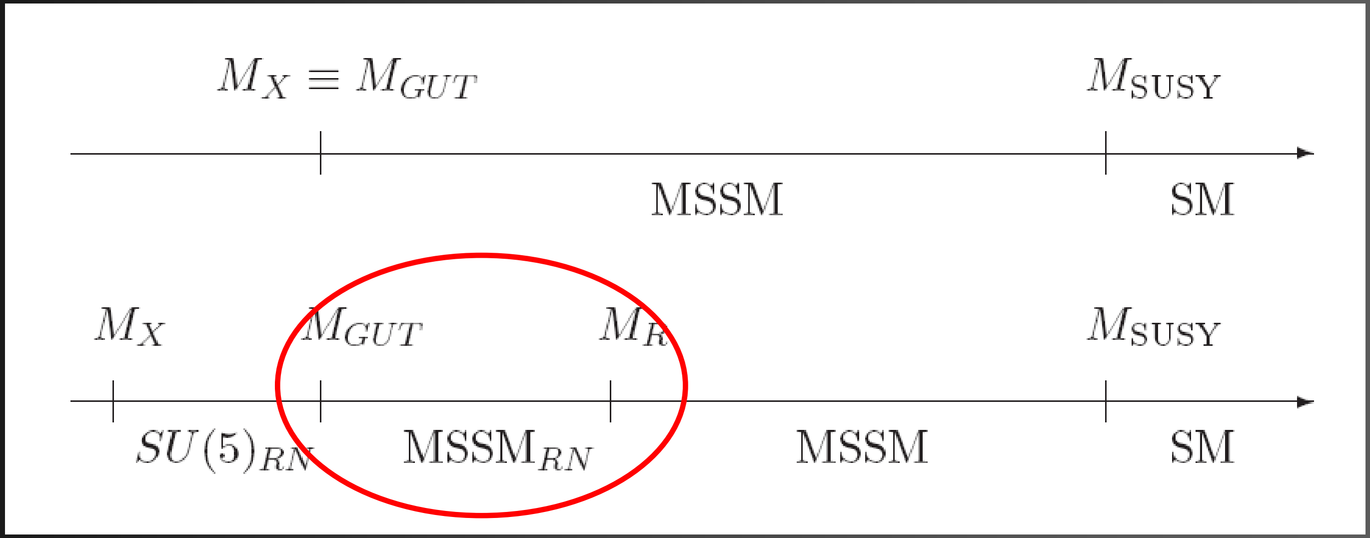
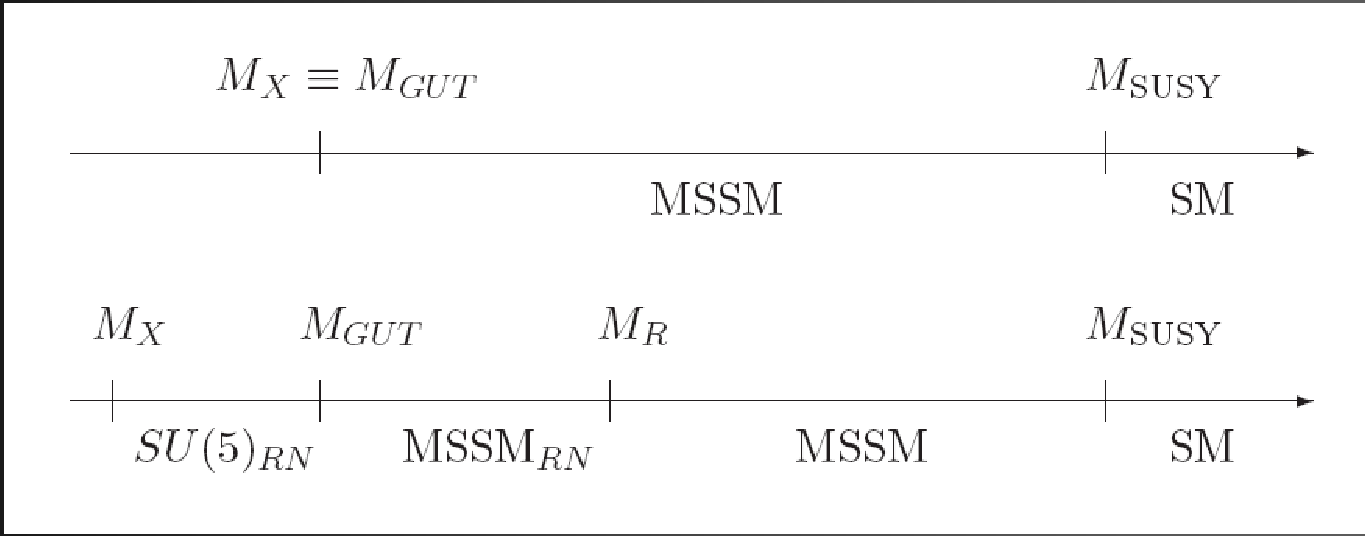
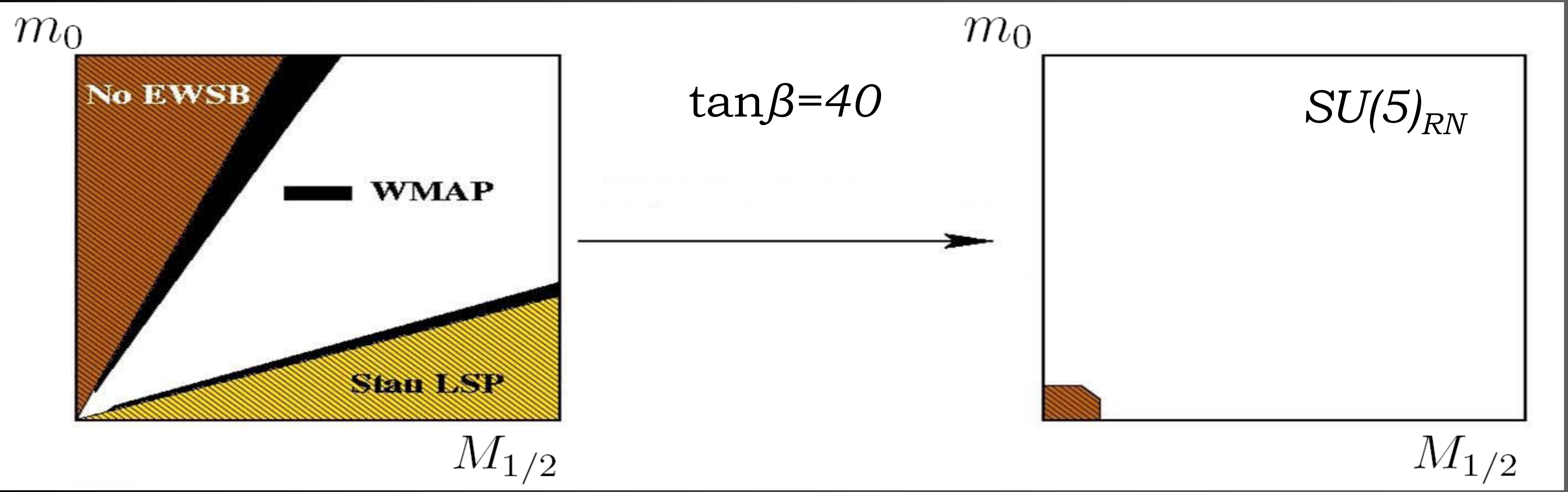


CMSSM vs. $SU(5)_{RN}$



$SU(5)_{RN}$ parameter space

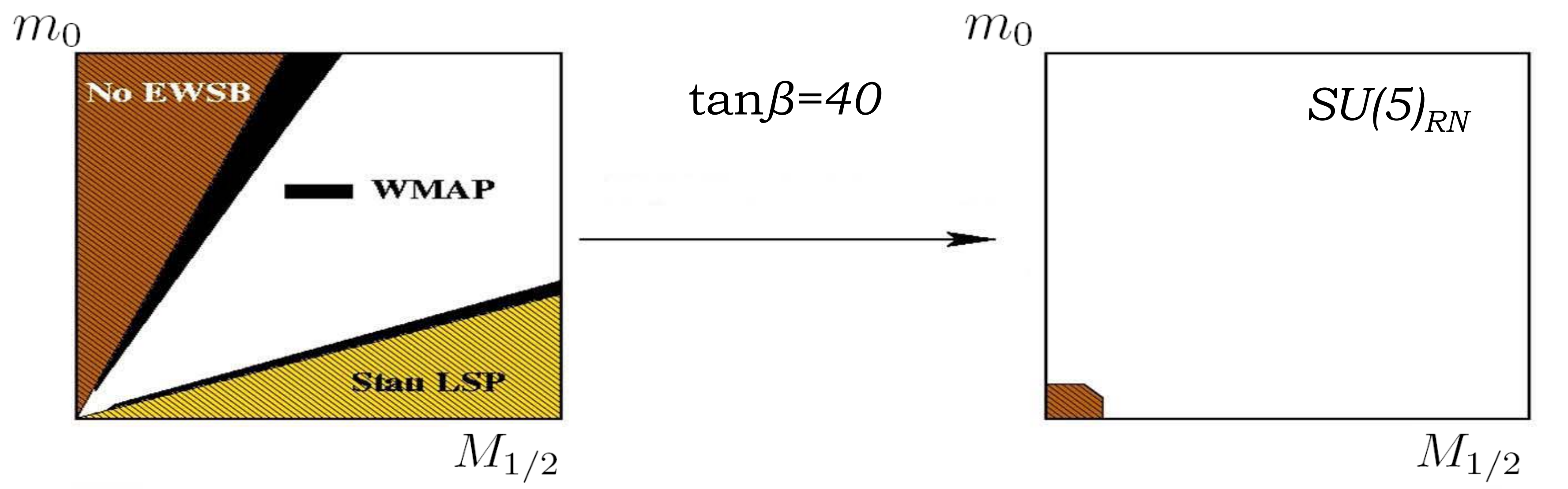




$SU(5)_{RN}$ parameter space

I)

II)

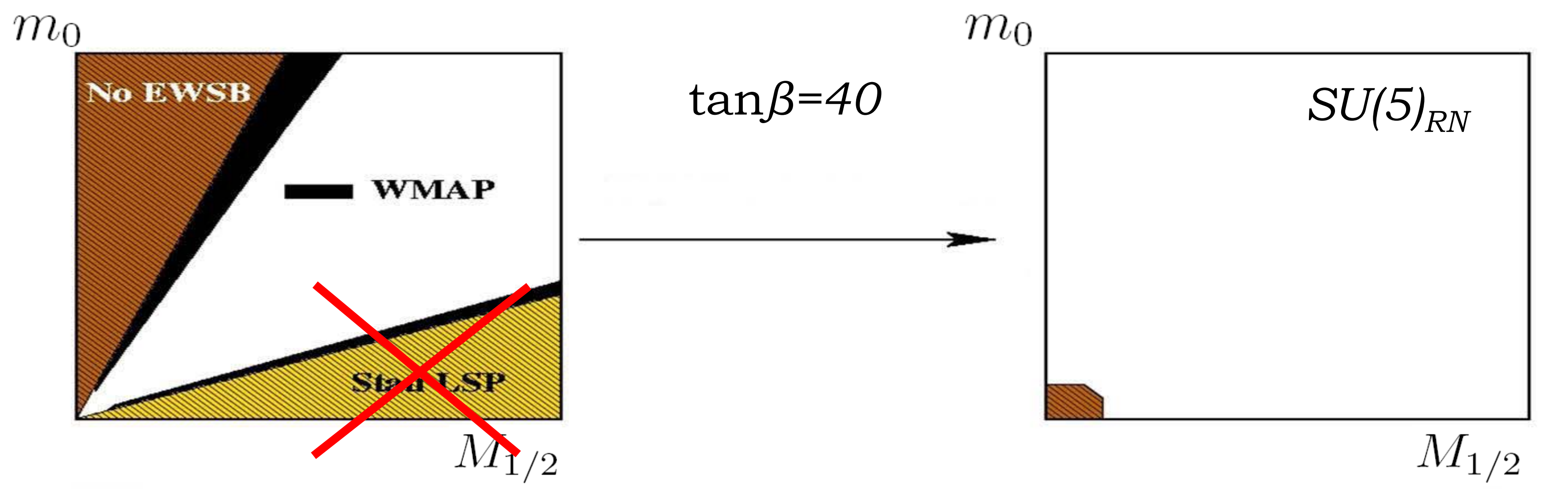


$SU(5)_{RN}$ parameter space

I) $$M_X \longrightarrow M_{\rm GUT} \Rightarrow m^2_{\tilde{\tau}_R}(M_{\rm GUT}) \simeq \frac{144}{20\pi}\alpha_5 M^2_{1/2} \ln(\frac{M_X}{M_{\rm GUT}}) \simeq 0.25\ M^2_{1/2}$$

(right stau mass for $m_0 = 0$)

II)



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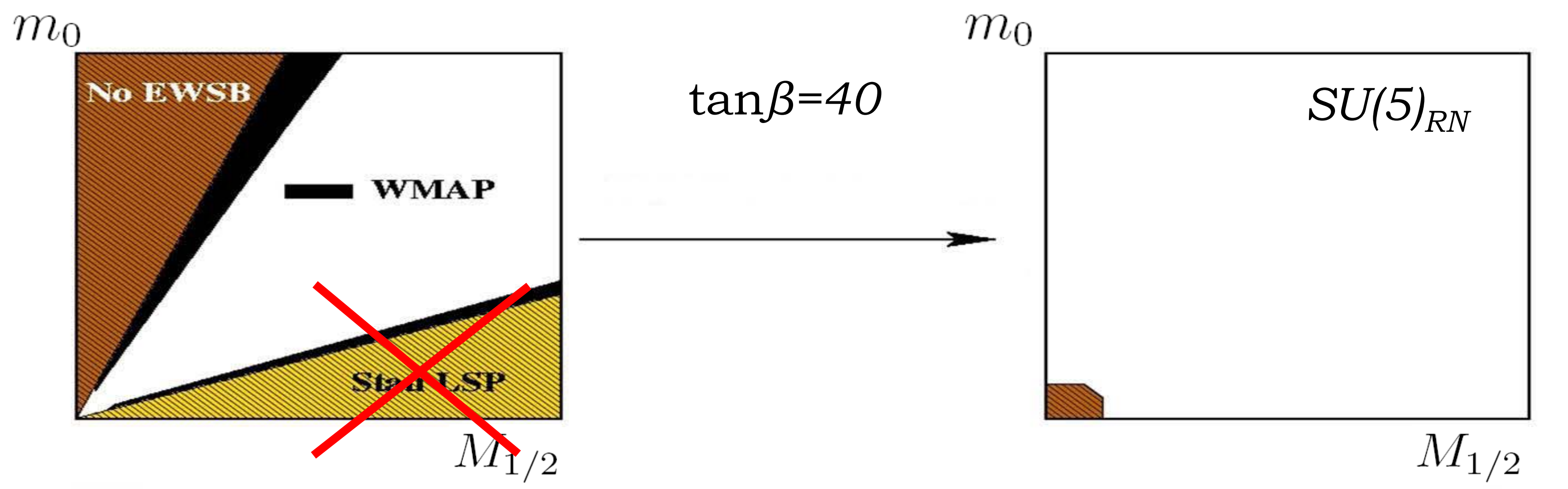
(right stau mass for $m_0 = 0$)

II) $$|\mu|^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}m_Z^2$$

$$\sin 2\beta = \frac{2B\mu}{m^2_{H_u} + m^2_{H_d} + 2\mu^2},$$



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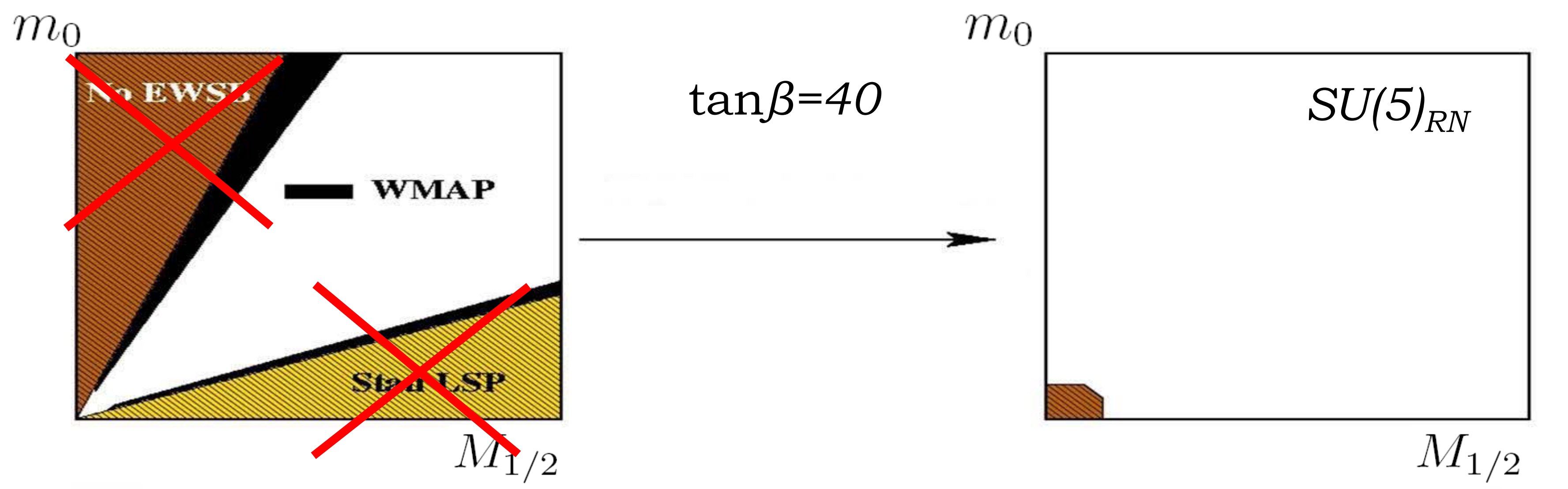
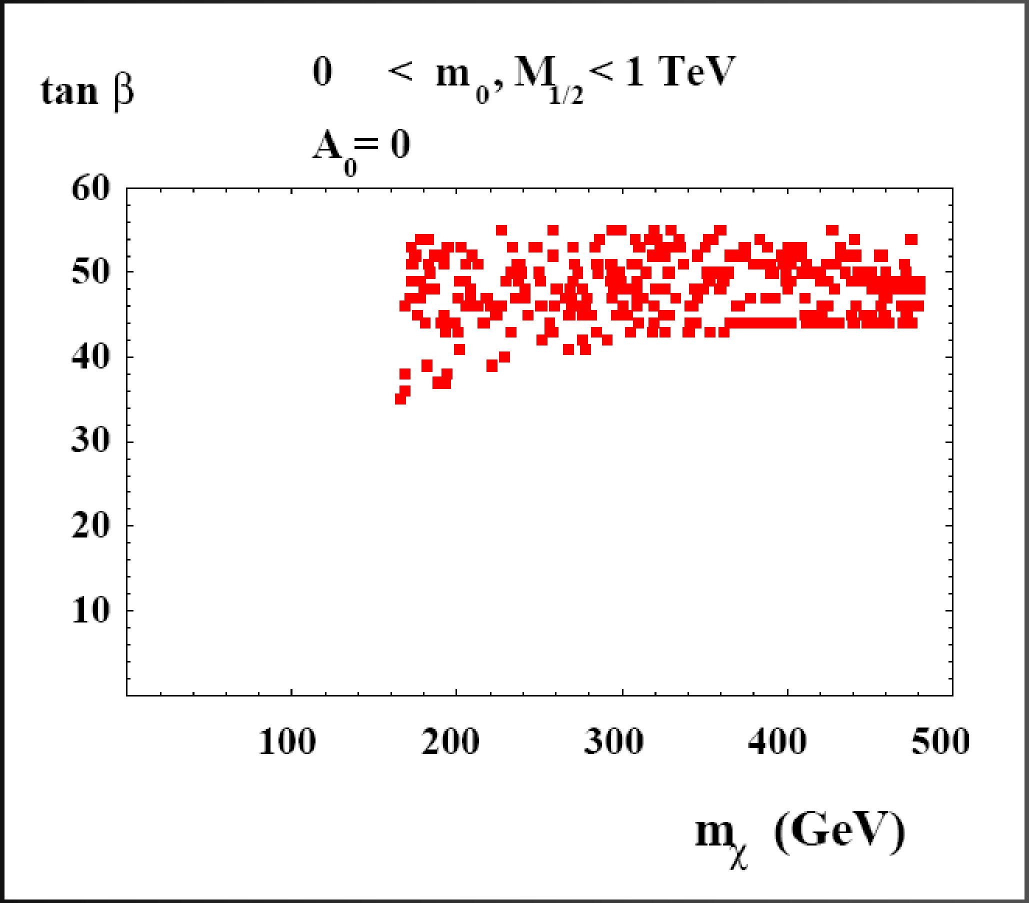
(right stau mass for $m_0 = 0$)

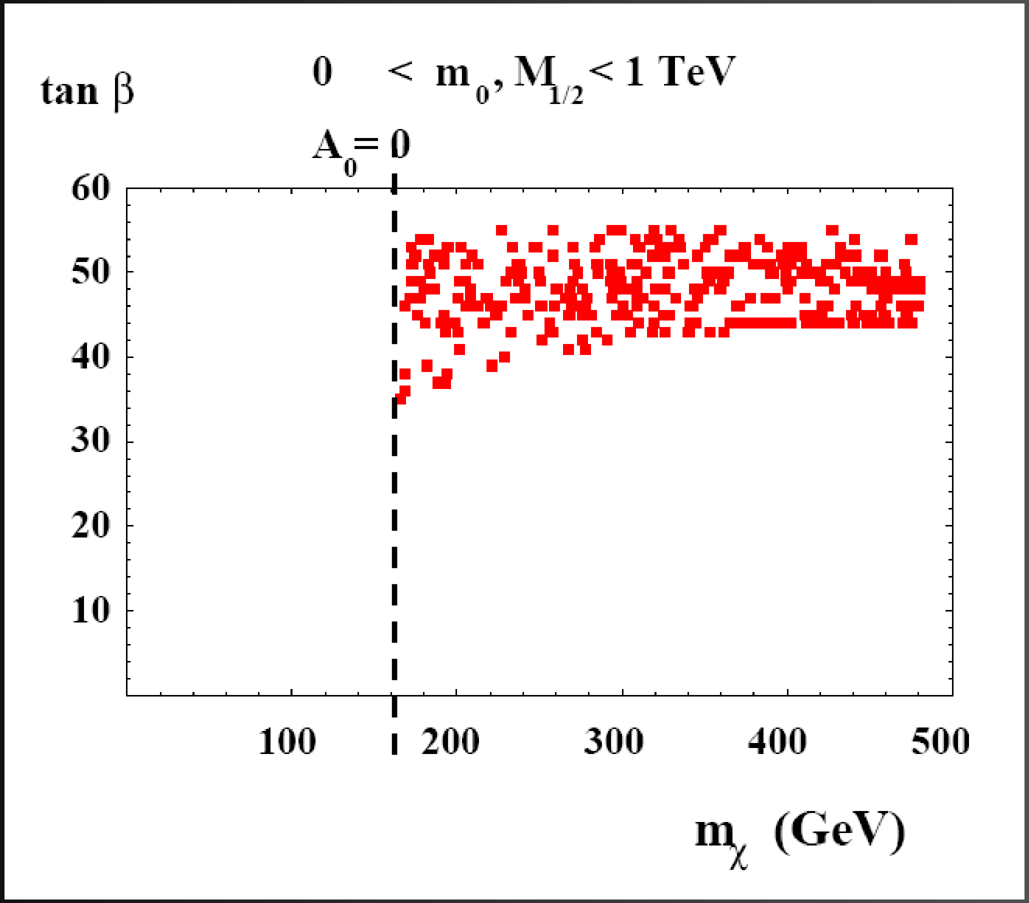
II)

$$(4\pi)^2\frac{\partial m^2_{H_u}}{\partial \ln(\tilde{\mu}/M_X)} \simeq 6y_t^2(m^2_{H_u} + m^2_{\tilde{U}_3} + m^2_{\tilde{Q}_3} + A_t^2) + 2y_\nu^2(m^2_{H_u} + m^2_{\tilde{N}} + m^2_{\tilde{L}_3} + A_\nu^2)$$



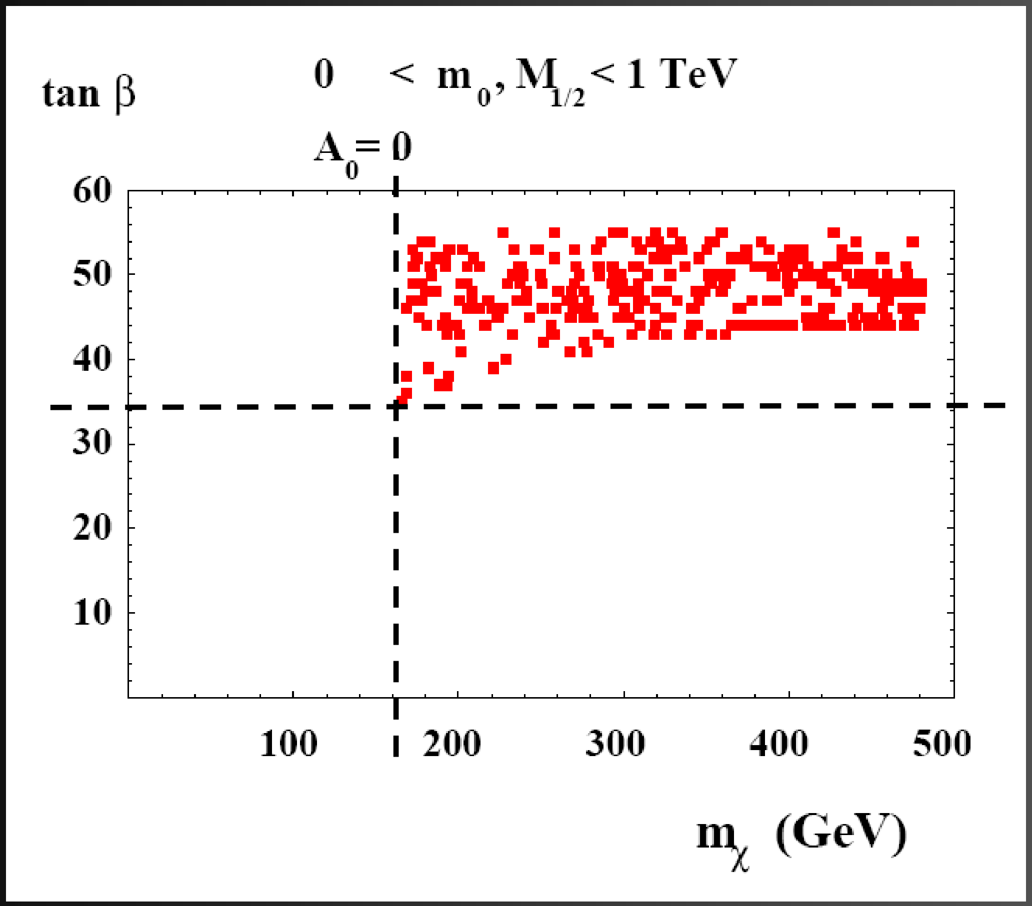


WMAP allowed points



WMAP allowed points

$$m_{\tilde{\chi}_1^0} \gtrsim 160\,\mathrm{GeV}$$



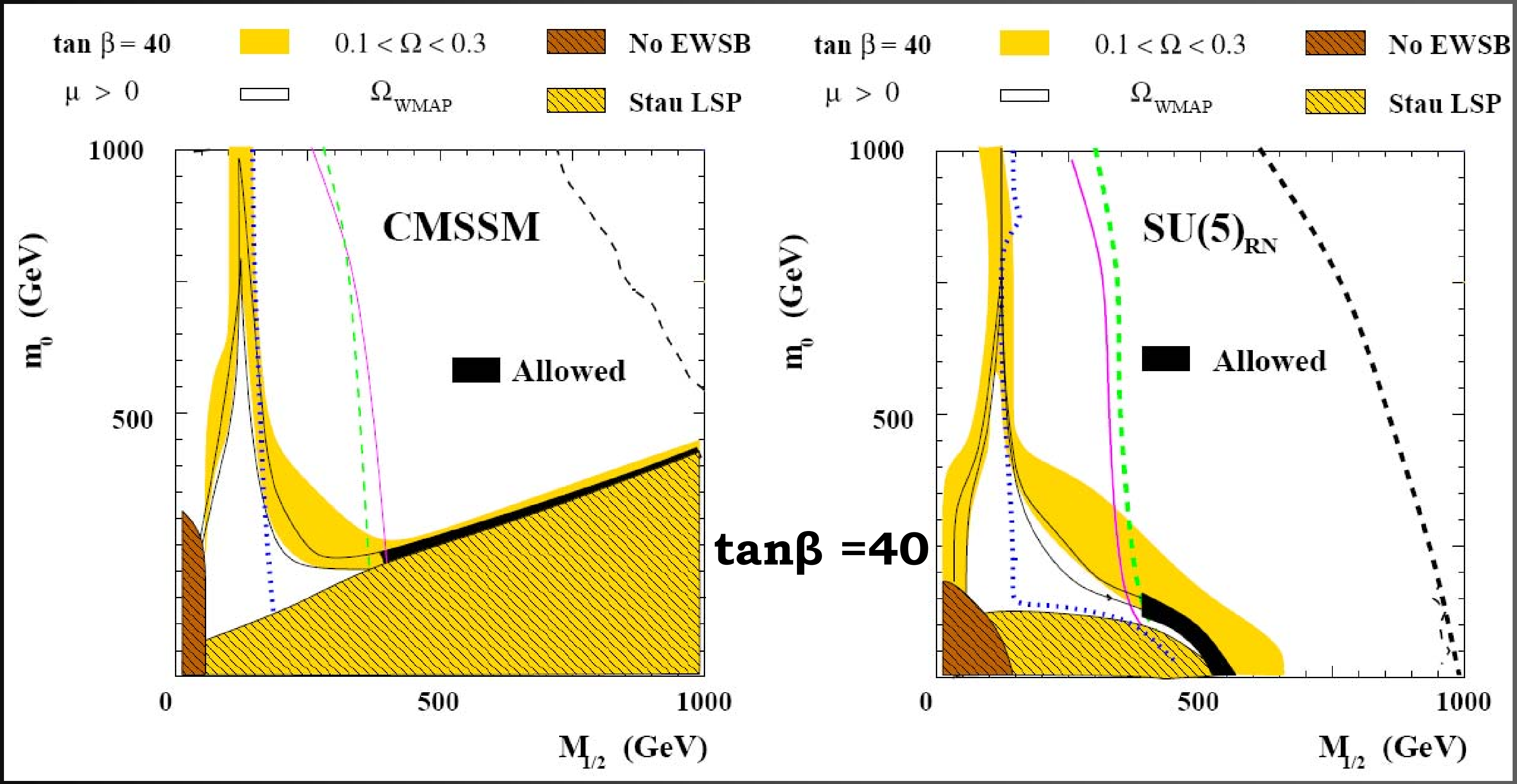
WMAP allowed points

$\rightarrow$ $\tan\beta \gtrsim 34$

$\downarrow$

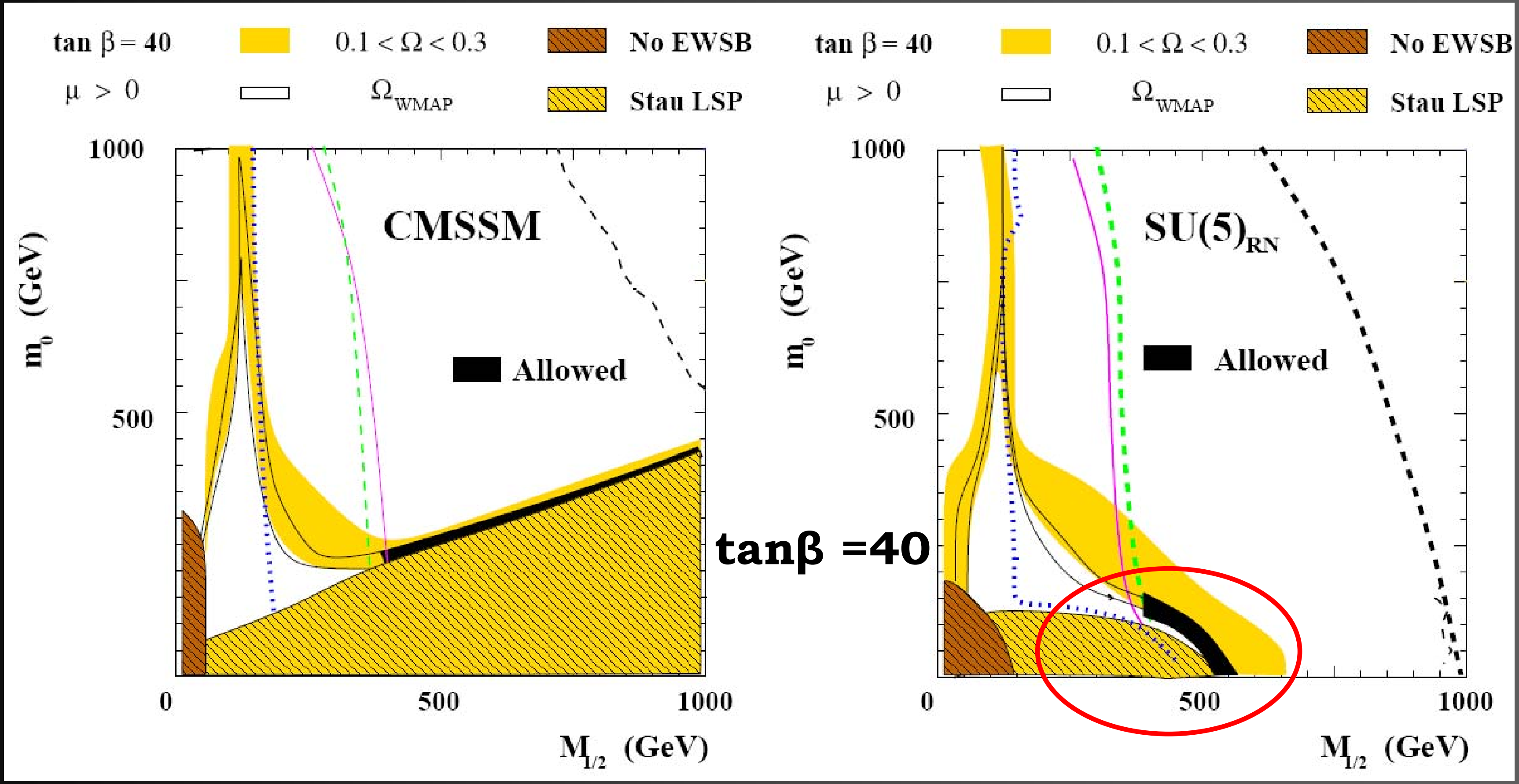
$m_{\tilde{\chi}^0_1} \gtrsim 160\,\mathrm{GeV}$

DM phenomenology in *SU(5)*$_{RN}$



tanβ =40

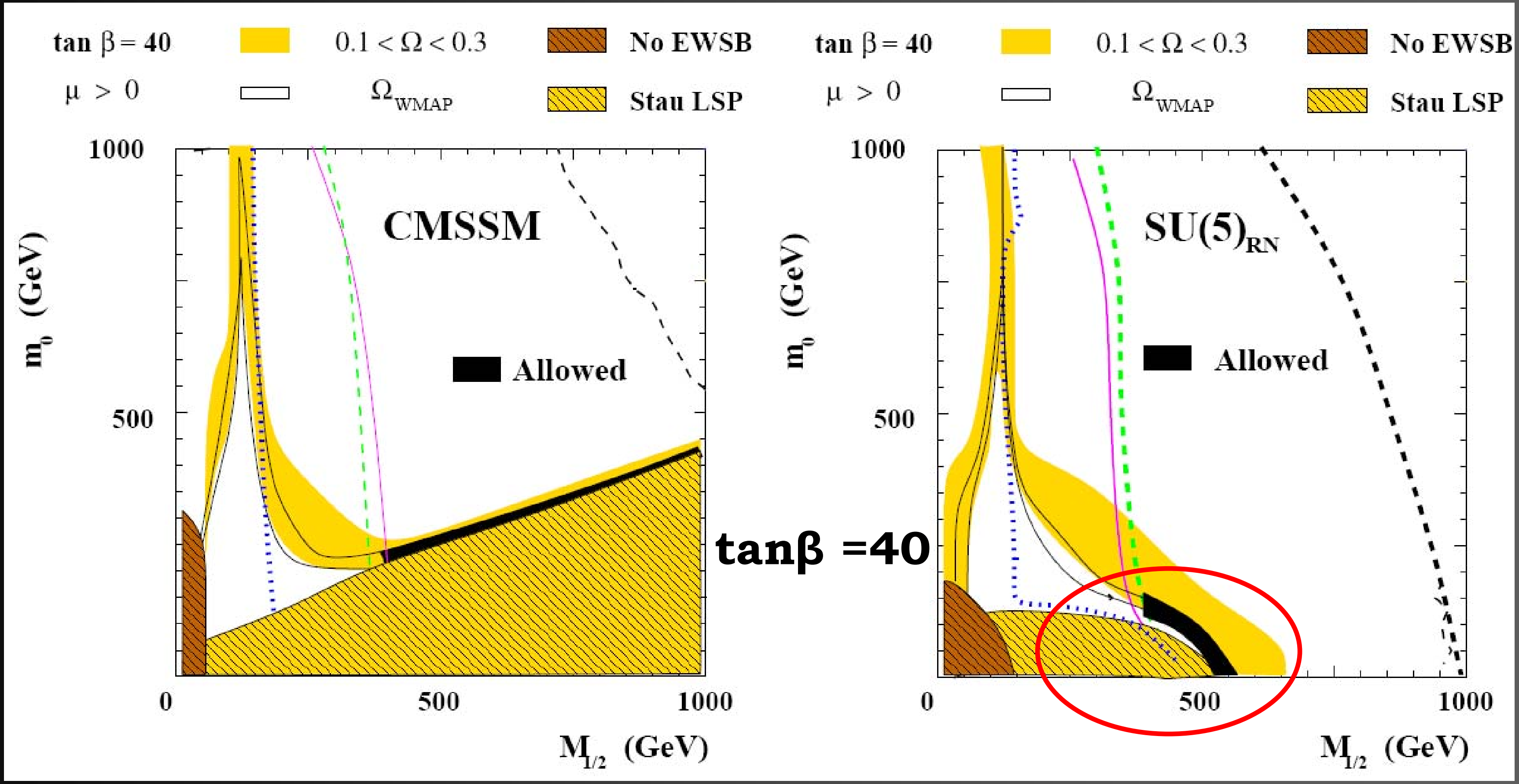
DM phenomenology in $SU(5)_{RN}$



Stau coannihilation:

$$m^2_{\tilde{\tau}_1} \simeq m^2_{\tilde{\tau}_{RR}} - m_\tau \, \mu \tan\beta$$

DM phenomenology in $SU(5)_{RN}$



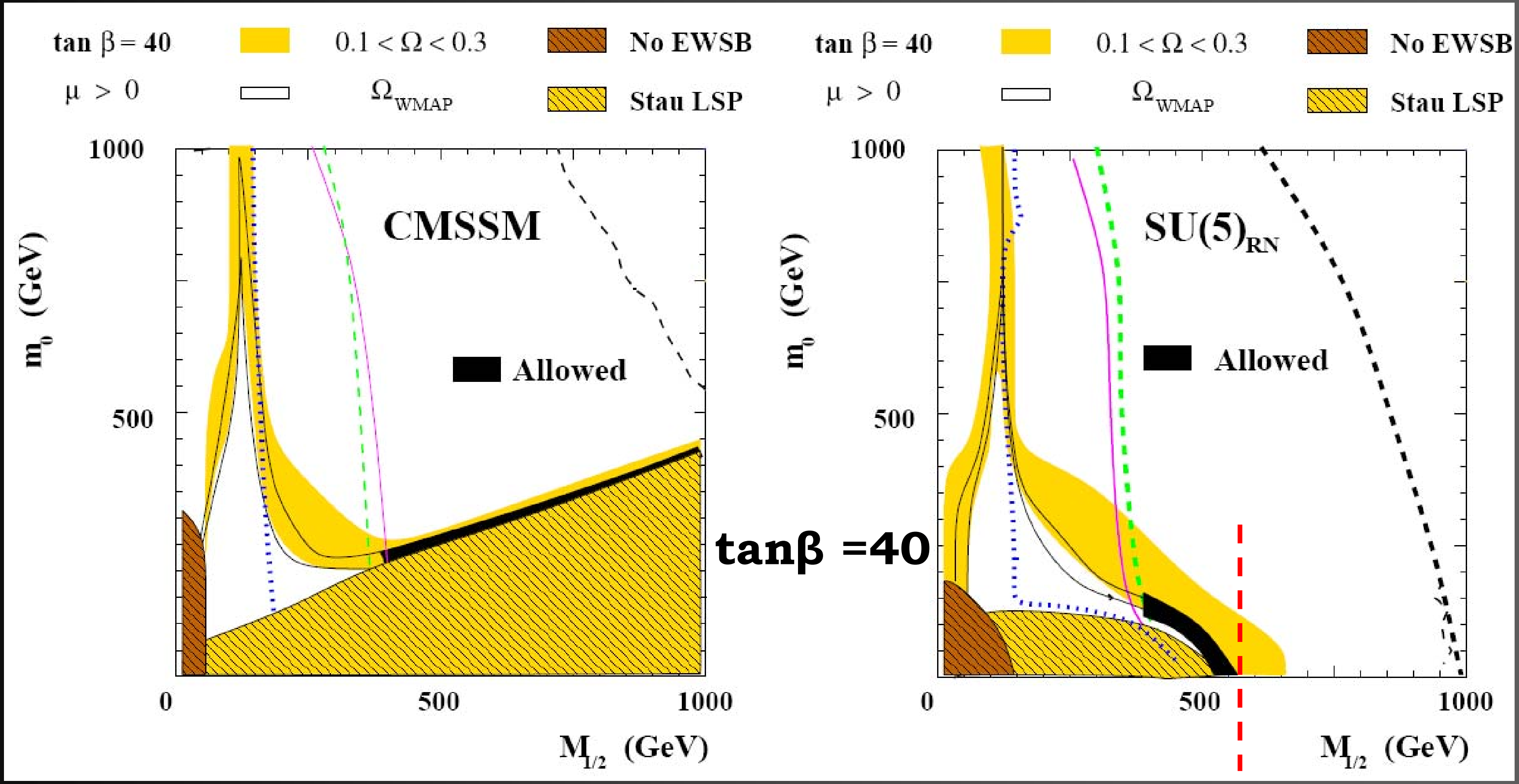
Stau coannihilation:

$$m^2_{\tilde{\tau}_1} \simeq m^2_{\tilde{\tau}_{RR}} - m_\tau \, \mu \tan\beta$$

→ lower limit on tanβ

$$\tan\beta \gtrsim 34$$

DM phenomenology in $SU(5)_{RN}$



Stau coannihilation: $m^2_{\tilde{\tau}_1} \simeq m^2_{\tilde{\tau}_{RR}} - m_\tau \, \mu \tan\beta$

→ upper limit on the LSP mass $m_{\tilde{\chi}^0_1} \simeq 240 \text{ GeV}$ $(\tan\beta = 40, \; A_0 = 0)$

The other CMSSM "corridors" ?

- A-pole funnel

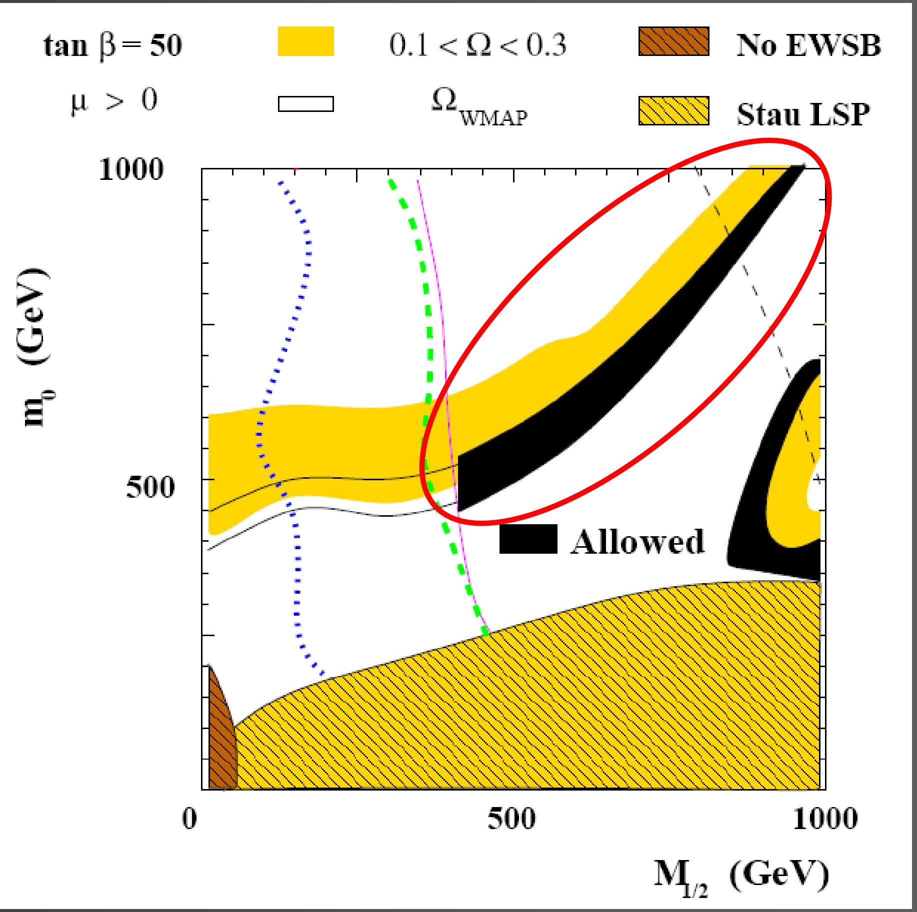
$$\tan\beta \simeq 45 - 50$$

no more upper bound on the LSP mass

- Focus point

not present up to 5 TeV

tanβ =50



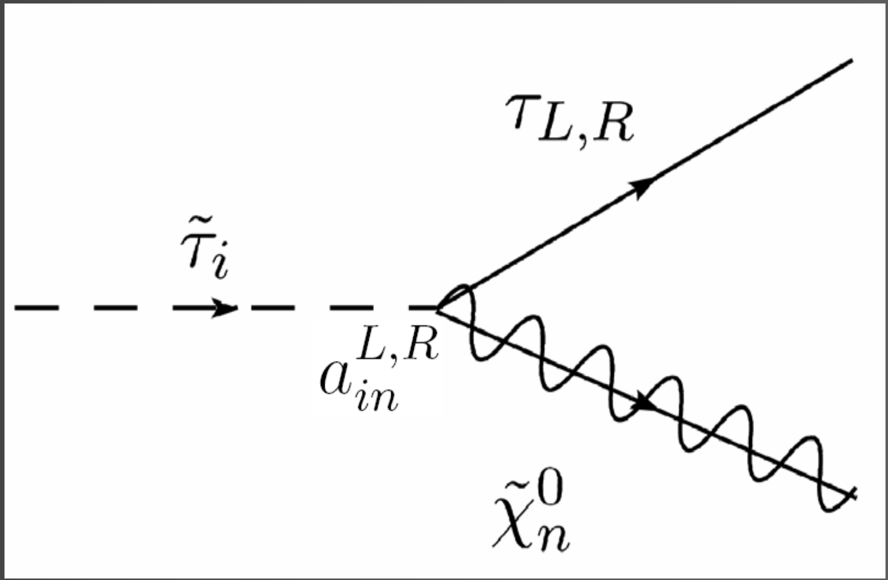
Second part:
τ polarization

Tau polarization:

$$\mathcal{P}_\tau = \frac{\mathrm{Br}(\tilde{\tau}_i \to \tilde{\chi}^0_n \tau_R) - \mathrm{Br}(\tilde{\tau}_i \to \tilde{\chi}^0_n \tau_L)}{\mathrm{Br}(\tilde{\tau}_i \to \tilde{\chi}^0_n \tau_R) + \mathrm{Br}(\tilde{\tau}_i \to \tilde{\chi}^0_n \tau_L)}$$

If $m_\tau \ll m_{\tilde{\tau}_1}$

$$\mathcal{P}_\tau = \frac{(a^R_{in})^2 - (a^L_{in})^2}{(a^R_{in})^2 + (a^L_{in})^2}$$



M. Nojiri, PRD **51** (1995) 6281 [hep/ph/9412374]

Tau polarization in stau decays

$$\tilde{\chi}_n^0 = Z_{n1}\tilde{B} + Z_{n2}\tilde{W}_3 + Z_{n3}\tilde{H}_d^0 + Z_{n4}\tilde{H}_u^0$$

$$m_{\tilde{\tau}}^2 = \begin{pmatrix} m_{\rm LL}^2 & m_{\rm LR}^2 \\ m_{\rm LR}^2 & m_{\rm RR}^2 \end{pmatrix} = \mathcal{R}^T \begin{pmatrix} m_{\tilde{\tau}_1}^2 & 0 \\ 0 & m_{\tilde{\tau}_2}^2 \end{pmatrix} \mathcal{R}\,; \quad \mathcal{R} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix}$$

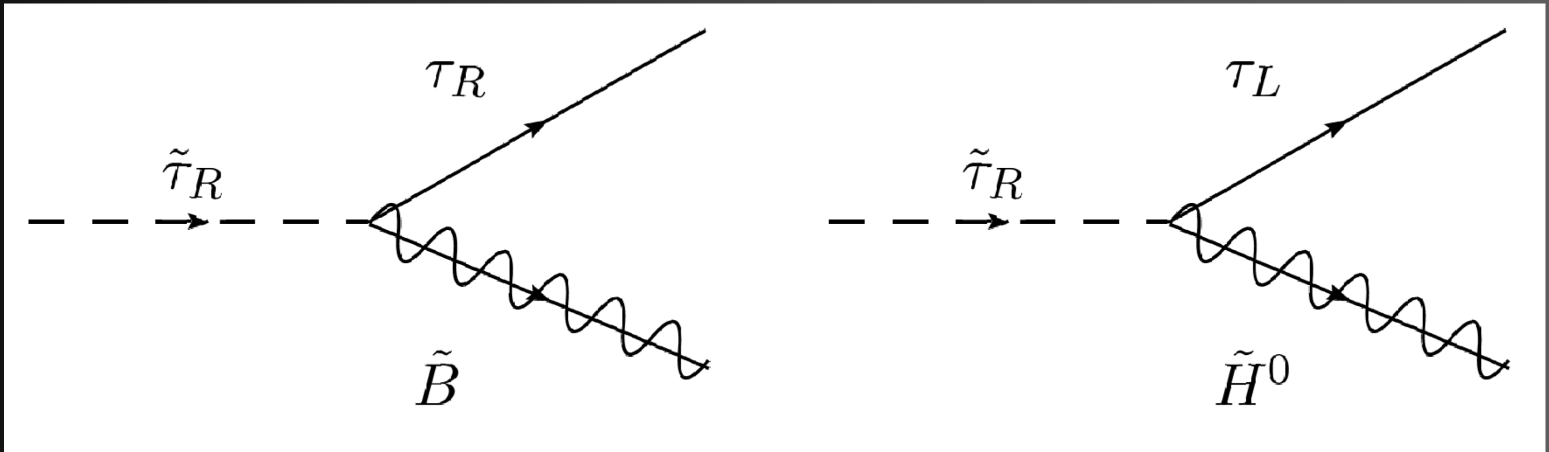
$\Longrightarrow$

$$\begin{aligned} \tilde{\tau}_1 &= \tilde{\tau}_R \sin\theta_\tau + \tilde{\tau}_L \cos\theta_L \\ \tilde{\tau}_2 &= \tilde{\tau}_R \cos\theta_\tau - \tilde{\tau}_L \sin\theta_L \end{aligned}$$

$$\begin{aligned} m_{\rm LL}^2 &\approx (1-\rho_L) m_0^2 + c_L M_{1/2}^2 \\ m_{\rm RR}^2 &\approx (1-\rho_R) m_0^2 + c_R M_{1/2}^2 \\ m_{\rm LR}^2 &= m_\tau (A_\tau - \mu \tan\beta) \approx -m_\tau \mu \tan\beta \end{aligned}$$

The same parameters which are crucial for coannihilation

Tau polarization in stau decays



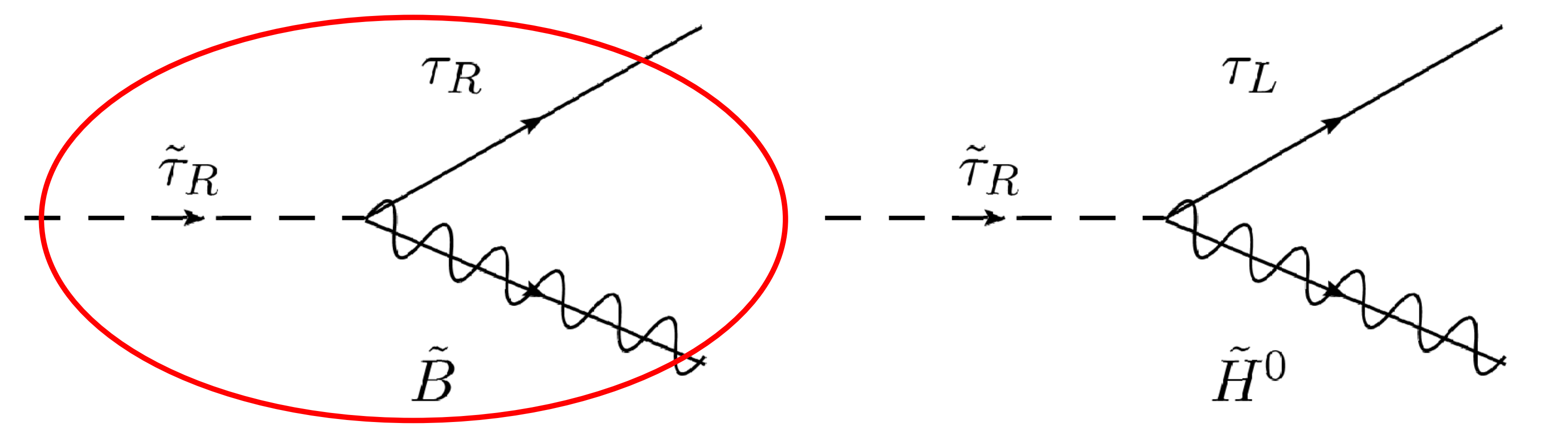
$$\tilde{\tau}_1 \longrightarrow \tilde{\chi}_1^0 \tau$$

$$\mathcal{P}_\tau = \frac{(a_{11}^R)^2 - (a_{11}^L)^2}{(a_{11}^R)^2 + (a_{11}^L)^2}$$

$$a_{11}^R = -\frac{2g}{\sqrt{2}} Z_{11} \tan\theta_W \sin\theta_\tau - \frac{g m_\tau}{\sqrt{2} m_W \cos\beta} Z_{12} \cos\theta_\tau$$

$$a_{11}^L = \frac{g}{\sqrt{2}} [Z_{12} + Z_{11} \tan\theta_W] \cos\theta_\tau - \frac{g m_\tau}{\sqrt{2} m_W \cos\beta} Z_{13} \sin\theta_\tau$$

Tau polarization in stau decays



$$\tilde{\tau}_1 \longrightarrow \tilde{\chi}_1^0 \tau$$

CMSSM

$$\mathcal{P}_\tau = \frac{(a_{11}^R)^2 - (a_{11}^L)^2}{(a_{11}^R)^2 + (a_{11}^L)^2} \longrightarrow \mathbf{1}$$

$$a_{11}^R = -\frac{2g}{\sqrt{2}} Z_{11} \tan\theta_W \sin\theta_\tau - \frac{g m_\tau}{\sqrt{2} m_W \cos\beta} Z_{12} \cos\theta_\tau$$

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Measuring τ polarization at the ILC

• τ has hadronic decay modes, such as $\tau \to \pi\, \nu_\tau$, $\rho\, \nu_\tau$, $a_1\, \nu_\tau$. The CM angular distribution of decay meson (π ; v = ρ, a_1) depends on τ polarization:

$$\frac{1}{\Gamma_\pi}\frac{d\Gamma_\pi}{d\cos\theta} = \frac{1}{2}(1 + P_\tau \cos\theta)$$
$$\frac{1}{\Gamma_v}\frac{d\Gamma_{vL,T}}{d\cos\theta} = \frac{\frac{1}{2}m_\tau^2, m_v^2}{m_\tau^2 + 2m_v^2}(1 \pm P_\tau \cos\theta),$$

Hagiwara, Martin, Zeppenfeld '90

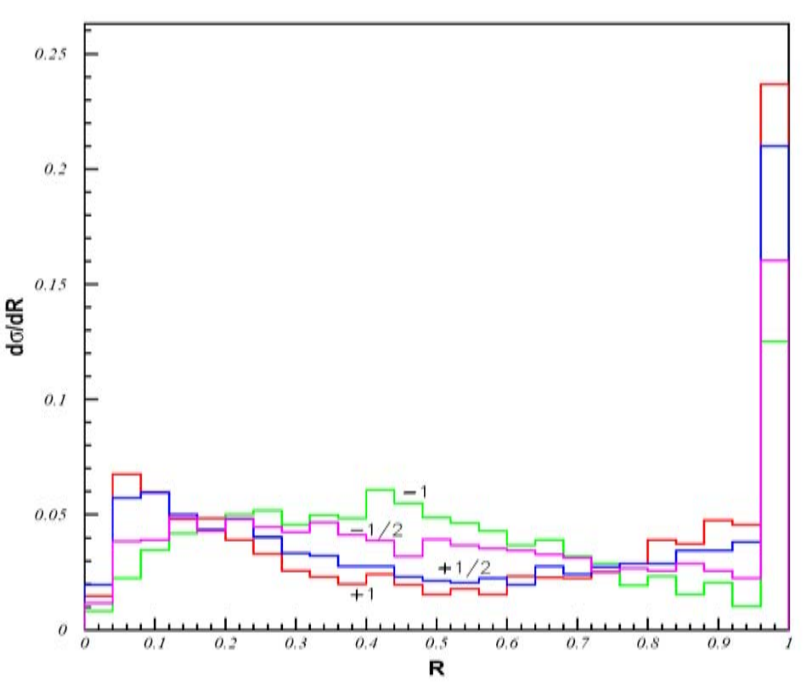
Bullock, Hagiwara, Martin '91

D.P. Roy '92

• ILC can determine τ polarization, using inclusive 1-prong channel.

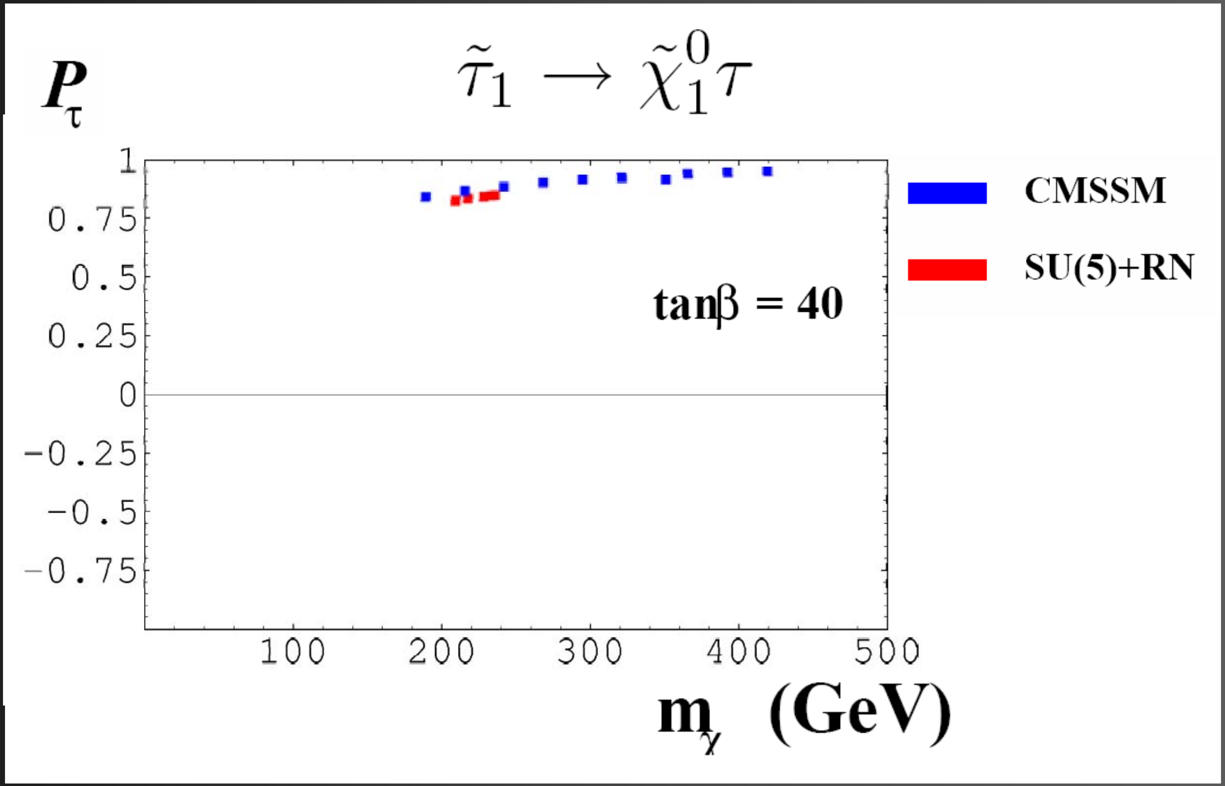
Useful variable: $R = p_{\pi^\pm}/p_{\tau-\mathrm{jet}}$

$$\sqrt{s} = 350\,\mathrm{GeV},\ m_{\tilde\tau_1} = 150\,\mathrm{GeV},\ m_{\tilde\chi_1^0} = 100\,\mathrm{GeV}$$
$$p^T_{\tau-\mathrm{jet}} > 25\,\mathrm{GeV},\ \cos\theta_{\tau-\mathrm{jet}} < 0.75$$



R. Godbole, M. Guchait, D.P. Roy, PLB **618**, 193, 2005.

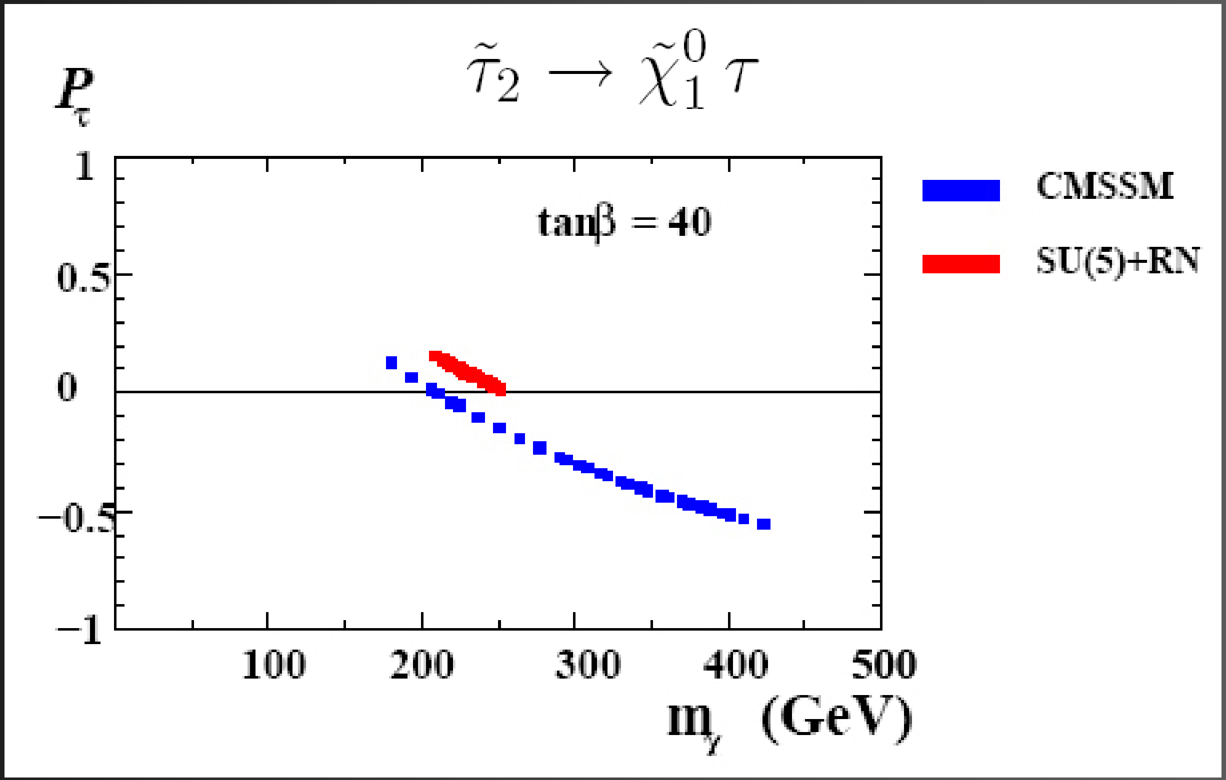
Distinguishing $SU(5)_{RN}$ from CMSSM



- τ polarization for the points lying in the stau coannihilation region
- Polarization not able to distinguish the two models
- Only possibility perhaps the upper limit on the neutralino-stau masses

L.C., R. Godbole, Y. Mambrini, S. Vempati in preparation

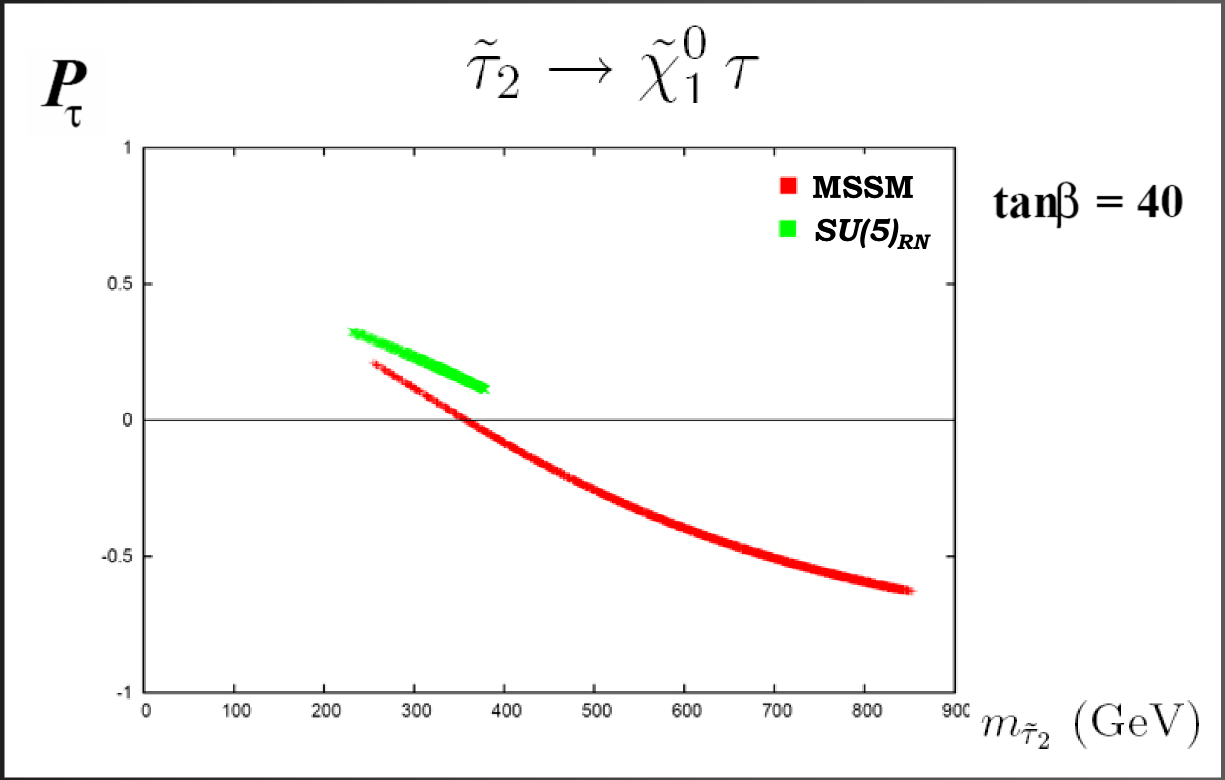
Distinguishing *SU(5)*$_{RN}$ from CMSSM



- τ polarization changes sign in CMSSM, while in *SU(5)*$_{RN}$ is always positive
- This is due to a small enhancement of the polarization in *SU(5)*$_{RN}$, together with the upper bound on the neutralino mass
- At least, it is possible to exclude *SU(5)*$_{RN}$ if negative polarization is measured

L.C., R. Godbole, Y. Mambrini, S. Vempati in preparation

Distinguishing $SU(5)_{RN}$ from CMSSM



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L.C., R. Godbole, Y. Mambrini, S. Vempati in preparation

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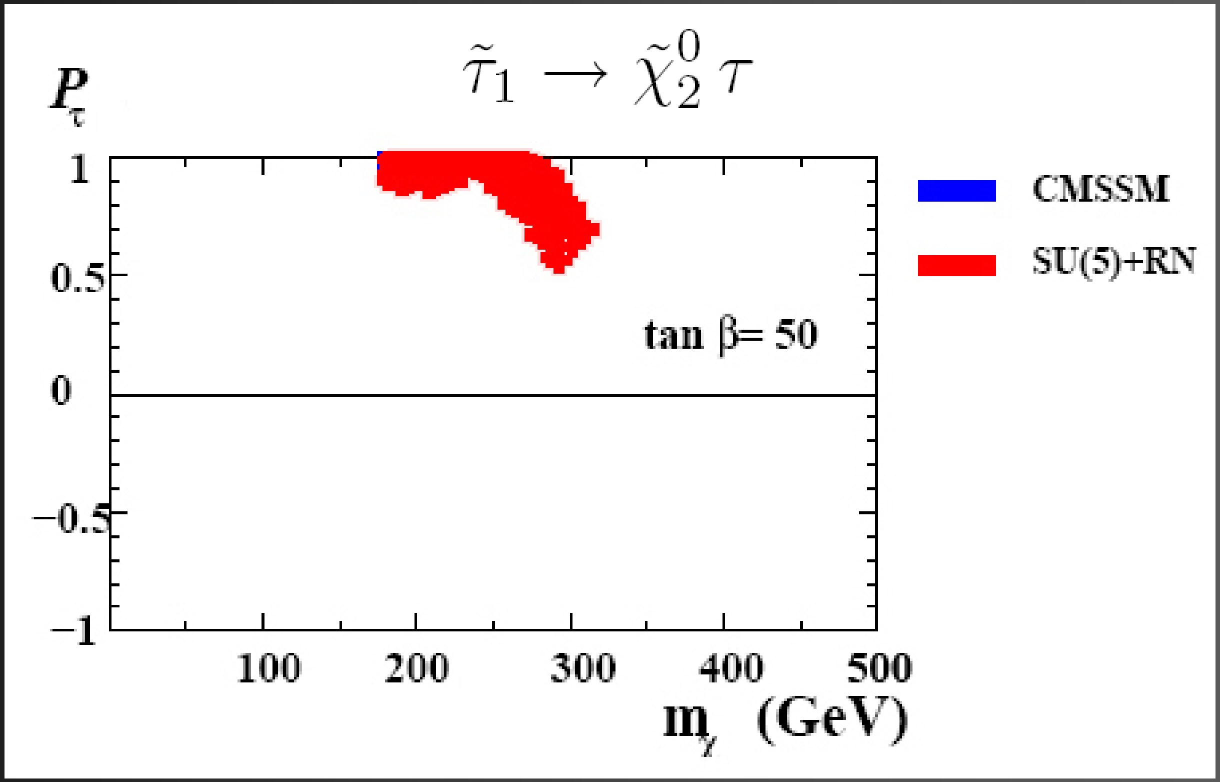

• A-pole funnel region: we cannot distinguish CMSSM and $SU(5)_{RN}$ using the channels above

• In $SU(5)_{RN}$ a channel forbidden in CMSSM is open: lightest stau decaying in the second neutralino. This is again a consequence of the GUT enhancement of the stau mass

L.C., R. Godbole, Y. Mambrini, S. Vempati in preparation

Summary

• In CMSSM, some peculiar relations among parameters are needed to have the correct relic density

• GUT running and/or presence of RH neutrinos can destabilize such relations

• In $SU(5)_{RN}$ relic density requirements put severe constraints on the allowed range of tanβ (> 35); coannihilations branch shows a peculiar phenomenology and upper bound on the LSP mass in some regions of the parameter space

• The polarization of the τ from the decay of the staus can be measured at the ILC

• In the stau coannihilation region τ polarization can distinguish between CMSSM and $SU(5)_{RN}$. The difference is a pure GUT effect

• In the A-funnel region of $SU(5)_{RN}$, the decay $\tilde{\tau}_1 \longrightarrow \tilde{\chi}_2^0 \, \tau$ is possible, while it is kinematically forbidden in CMSSM.