

# MSSM Higgs Bosons at the Tevatron

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P. D., Tao Liu, and Carlos E.M. Wagner, arXiv:0905.xxxx

# Introduction

- The Tevatron reach for the Standard Model Higgs is getting stronger.
- Current exclusion at 95% C.L for  
 $160 \text{ GeV} < m_h < 170 \text{ GeV}$
- Current data set is  $\approx 6 \text{ fb}^{-1}$ /experiment
- May run for two more years, gaining  
 $\approx 2 \text{ fb}^{-1}$ /experiment/year
- May be able to improve signal efficiencies in some channels.

# Goal

What efficiency and luminosity improvements are necessary to constrain large regions of the MSSM Higgs parameter space?

# Constraints on $m_h$ in the SM

- Tevatron searches produce constraints on the signal relative to the signal predicted by the SM:

$$\frac{\sigma \times \text{Br}}{\sigma_{SM} \times \text{Br}_{SM}} \leq R_{SM}^{95}$$

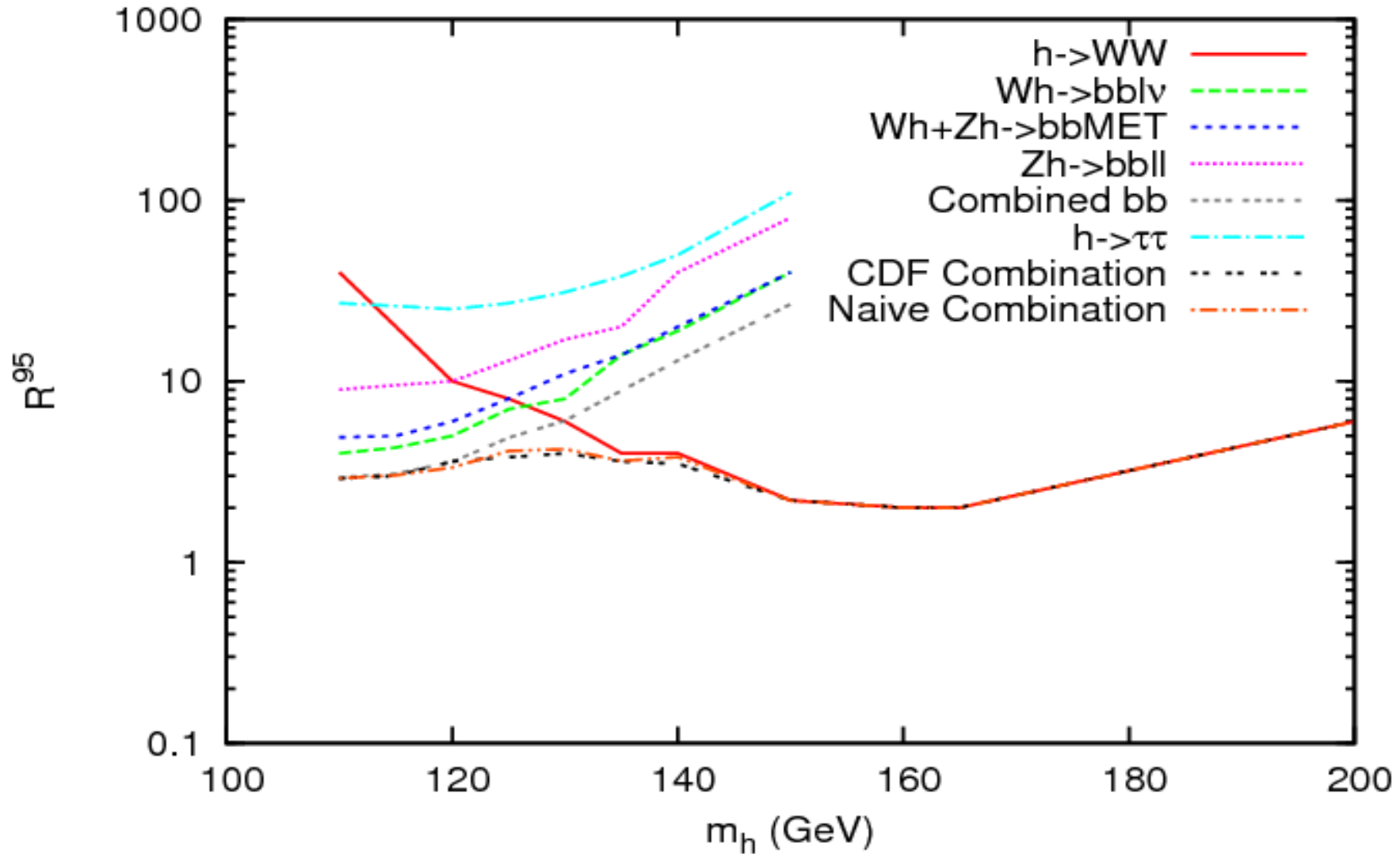
- Can compute naïve expected limits in each channel  $i$  at 95% C.L. (statistical errors + no signal):

$$R_{SM,i}^{95} = 2 \times \sqrt{b_i/s_i}$$

- → Combined expected limit:

$$\frac{1}{(R_{SM}^{95})^2} = \sum_i \frac{1}{(R_{SM,i}^{95})^2}$$

# Naïve Combined Limit vs CDF



# Translating Limits into the MSSM

- Rescale limits from individual channels

$$R_{MSSM,i}^{95} = R_{SM,i}^{95} \times \frac{\sigma_{SM,i} \times \text{Br}_{SM,i}}{\sigma_{MSSM,i} \times \text{Br}_{MSSM,i}}$$

- Allow each channel to go through any MSSM Higgs state:

$$gg \rightarrow h \rightarrow WW, \quad gg \rightarrow H \rightarrow WW$$

- Recombine. Limit is a function of MSSM parameters.
- Initially, keep separate combined limits from SM-like Higgs search channels and MSSM direct searches to see complementarity.

# MSSM Higgs Sector

- Two Higgs Doublets  $H_1$  and  $H_2$  coupling to down-type and up-type fermions, respectively
- Neutral components get vevs

$$\sqrt{v_1^2 + v_2^2} = 174 \text{ GeV} \quad v_2/v_1 \equiv \tan \beta$$

- 1 CP-odd mass eigenstate  $A$ , mass  $m_A$
- 2 CP-even states: 
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -\sin \alpha & \cos \alpha \\ \cos \alpha & \sin \alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$\frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2} \cdot (\cot \alpha - \tan \alpha) = (\cot \beta - \tan \beta)$$

# Properties of Lightest CP-even $h$

- Tree level:  $m_h = \frac{1}{2} \left( m_A^2 + m_Z^2 - \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta} \right)$
- $\rightarrow$  bounded:  $m_h \leq m_Z$
- Large radiative corrections:  $m_h \lesssim 130$  GeV
- Couplings to fermions rescaled relative to the SM:

$$g_{hdd} = -(m_d/v) \frac{\sin \alpha}{\cos \beta} \quad g_{huu} = (m_u/v) \frac{\cos \alpha}{\sin \beta}$$

- Couplings to gauge bosons rescaled by  $\sin^2(\beta - \alpha)$
- Typically up-type, but can be down-type for small  $m_A$
- SM-like gauge and fermion couplings for large  $m_A$



# MSSM Benchmark Scenarios

- At tree level,  $m_A$  and  $\tan\beta$  determine the Higgs spectrum and couplings to the SM.
- At loop level, more parameters enter  $A_t, \mu, M_S\dots$
- Choose 3 sets of benchmark values representative of different effects of the radiative corrections
- Scan over  $(m_A, \tan\beta)$  plane, compute combined  $R_{MSSM}^{95}$
- Plot 95% C.L. exclusions for various increases in luminosity and signal efficiency

# Scenario 1: Maximal Mixing

- Off-diagonal component  $X_t \equiv A_t - \mu/\tan\beta$  of  $\tilde{t}$  mass matrix chosen so that  $m_h$  maximized

$$M_S = 1 \text{ TeV}$$

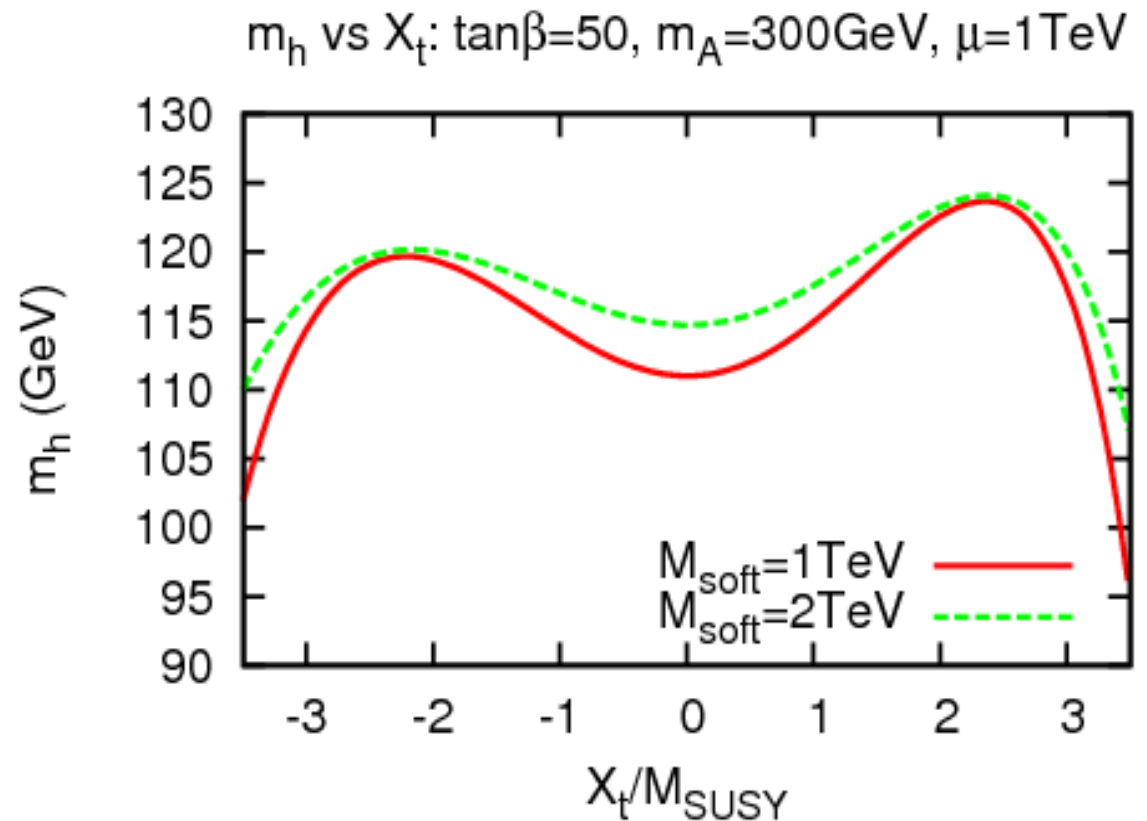
$$\mu = 1 \text{ TeV}$$

$$X_t = \sqrt{6}M_S$$

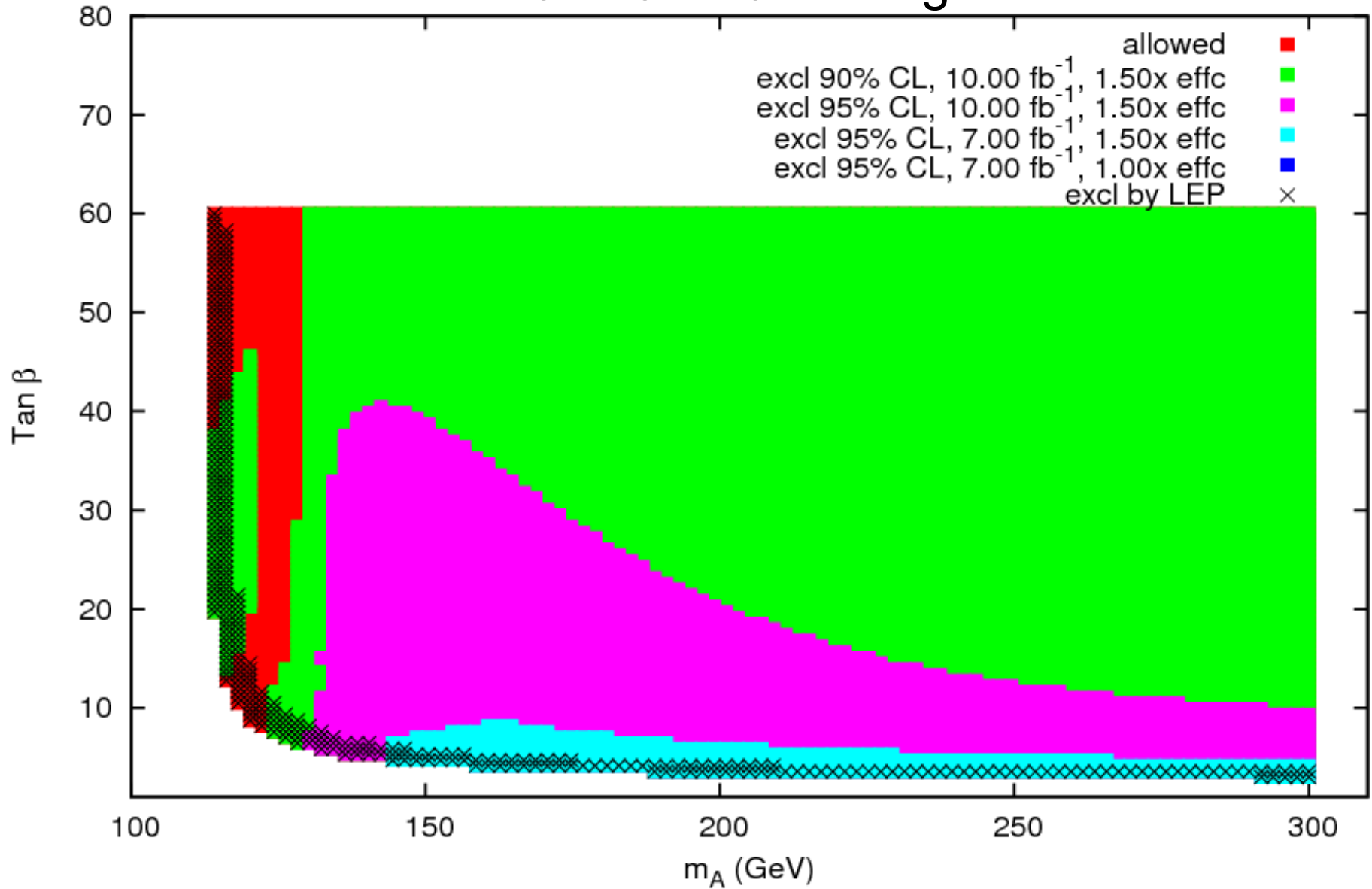
- Typically

$$120 \text{ GeV} \lesssim m_h \lesssim 125 \text{ GeV}$$

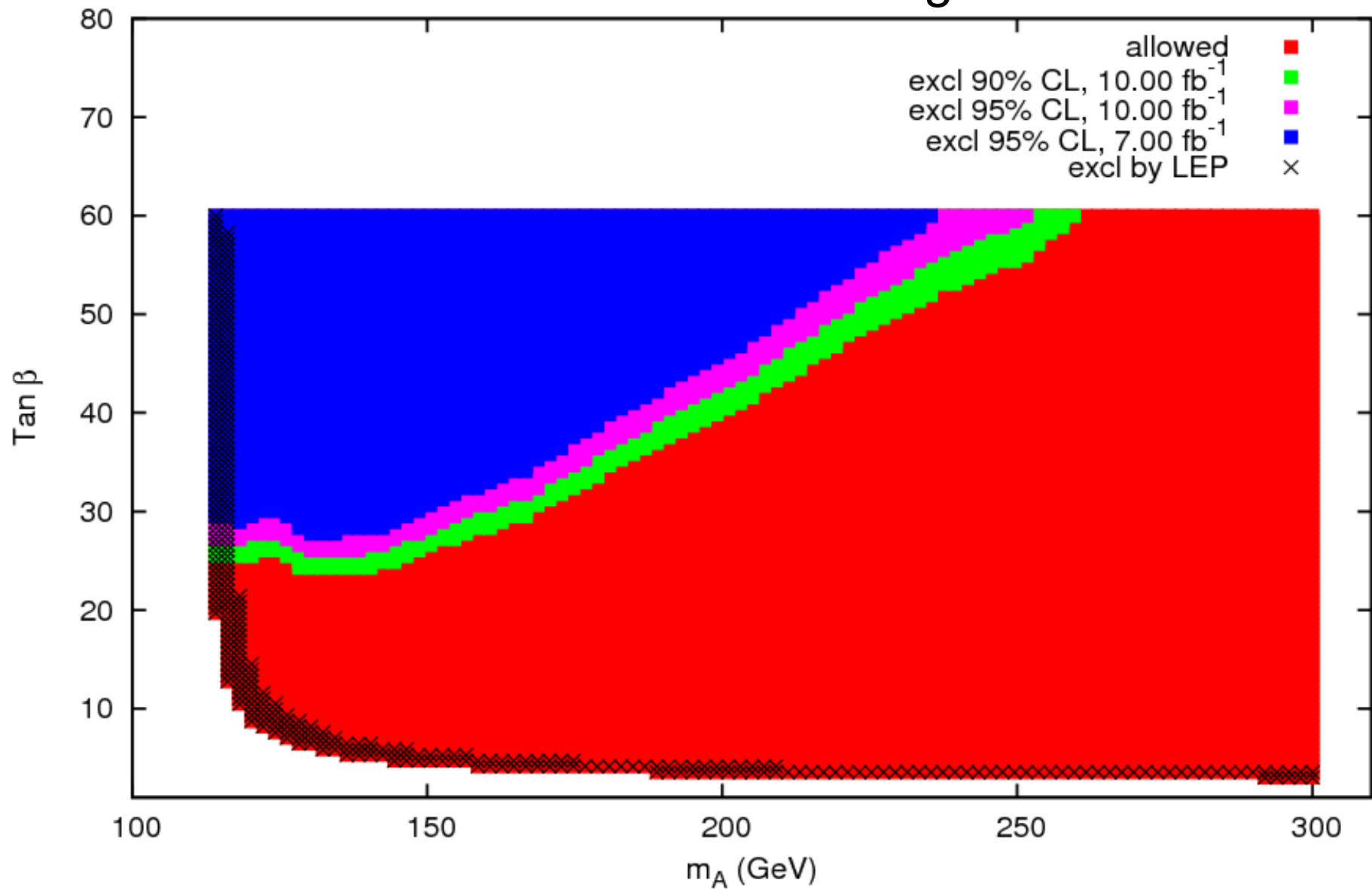
$$\text{for } m_t = 172.6 \text{ GeV}$$



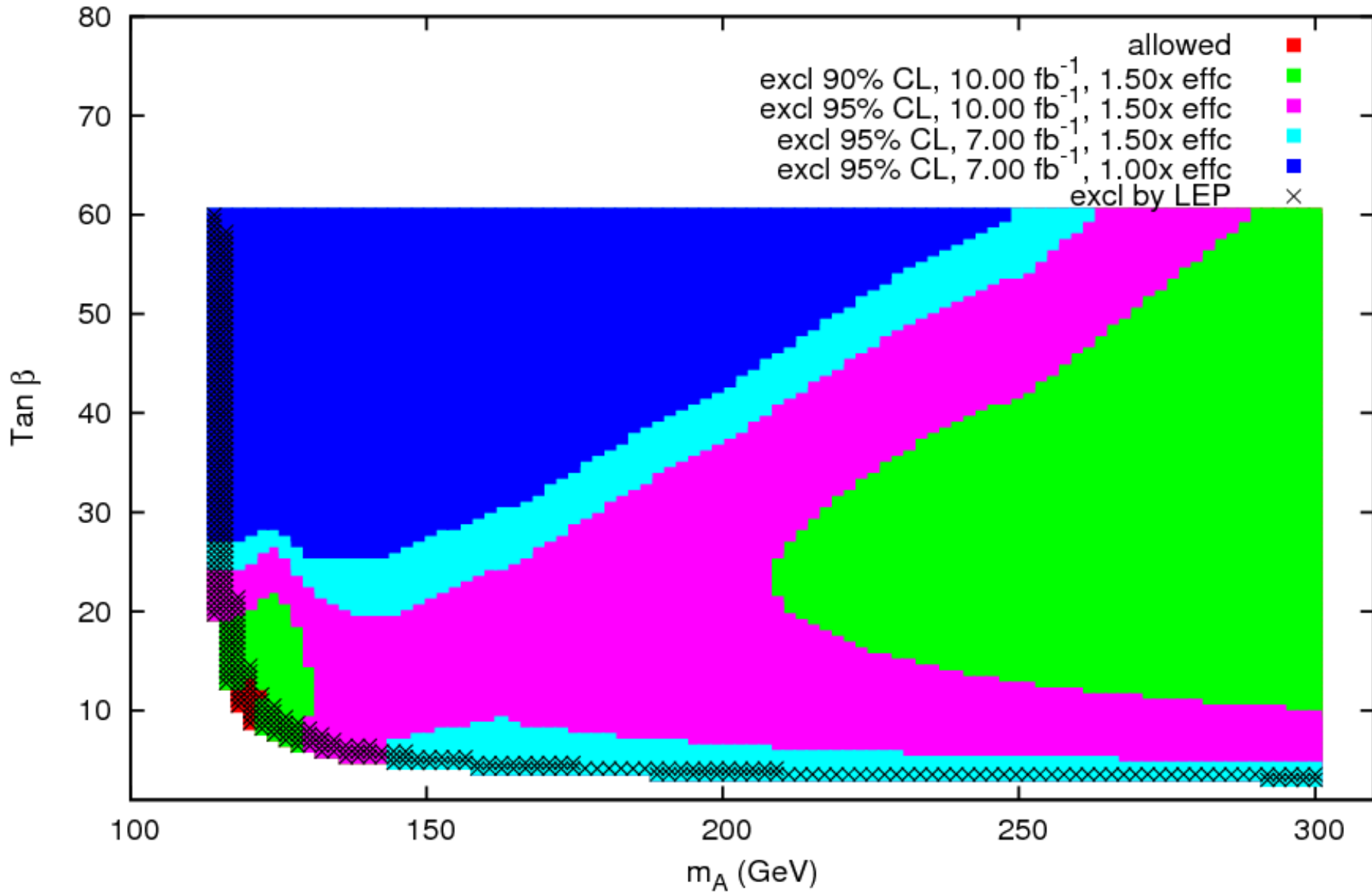
# Constraints from SM-like Higgs Searches for Maximal Mixing



# Constraints from Nonstandard Higgs Searches for Maximal Mixing



# Combined Constraints for Maximal Mixing



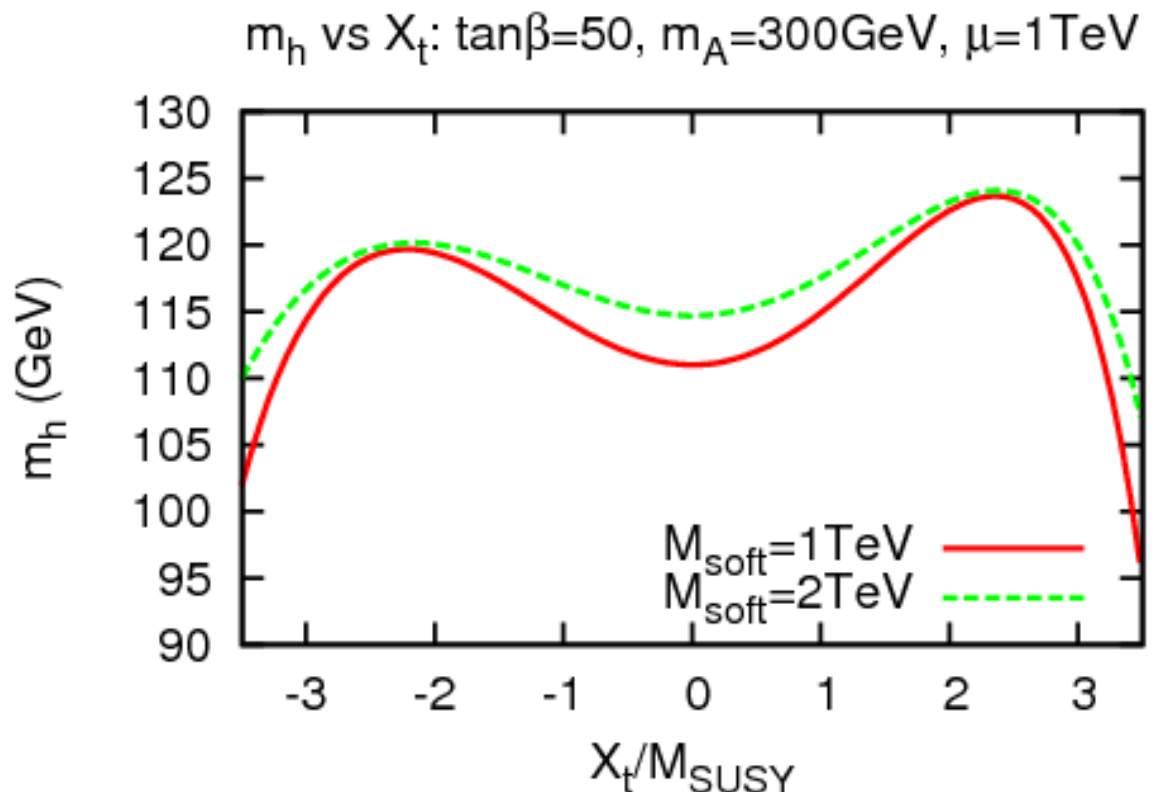
# Scenario 2: No Mixing

- No mixing in the stop sector minimizes  $m_h$ ,  
 $m_h \sim 110 - 115$  GeV
- Soft mass scale raised to (partially) avoid LEP bounds
- Lighter Higgs  $\rightarrow$   
constraints stronger  
vs. Maximal Mixing

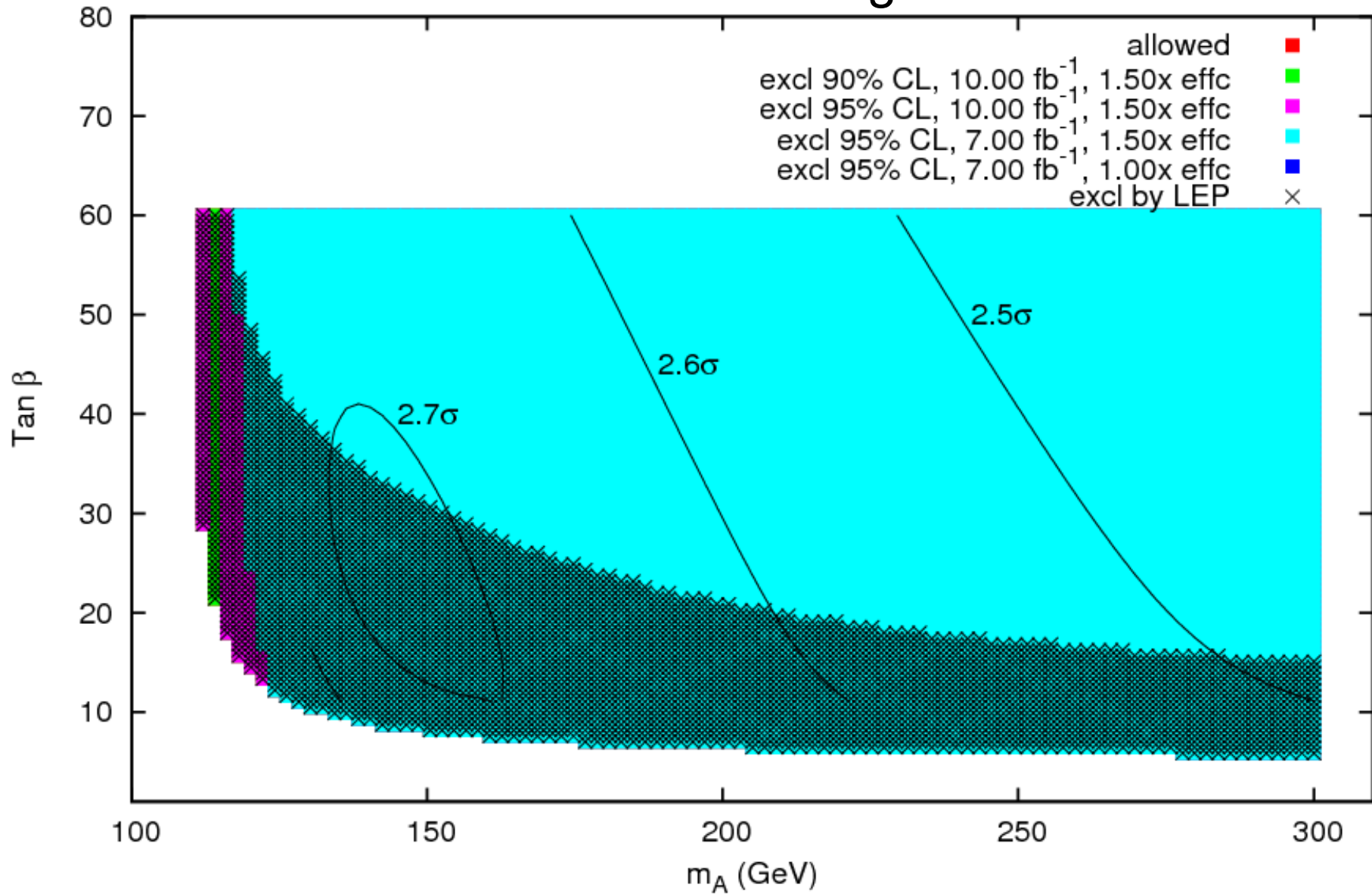
$$M_S = 2 \text{ TeV}$$

$$\mu = 1 \text{ TeV}$$

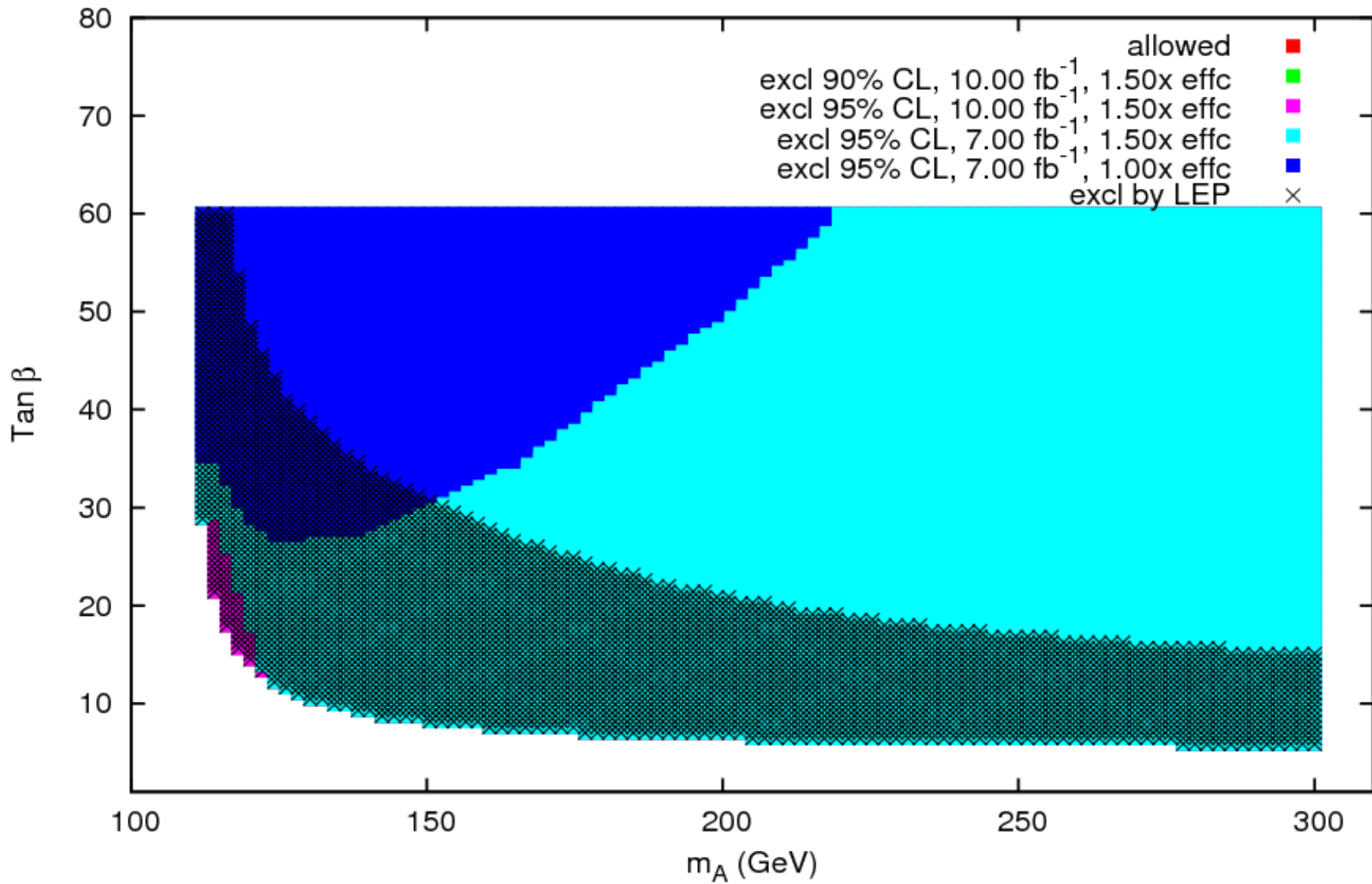
$$X_t \approx 0$$



# Constraints from SM-like Higgs Searches for No-Mixing



# Combined Constraints for No-Mixing





# Scenario 3: Small $\alpha_{eff}$

- Higgs mixing angle  $\rightarrow 0$  in a region of the  $(m_A, \tan \beta)$  plane because of cancellation between tree level and loop corrections to off-diagonal term in the mass matrix:

$$\mathcal{M}_{12} \simeq -(m_A^2 + m_Z^2) / \tan \beta + \frac{h_t^4 v^2}{16\pi^2} \bar{\mu} \bar{A}_t (\bar{A}_t^2 - 6)$$

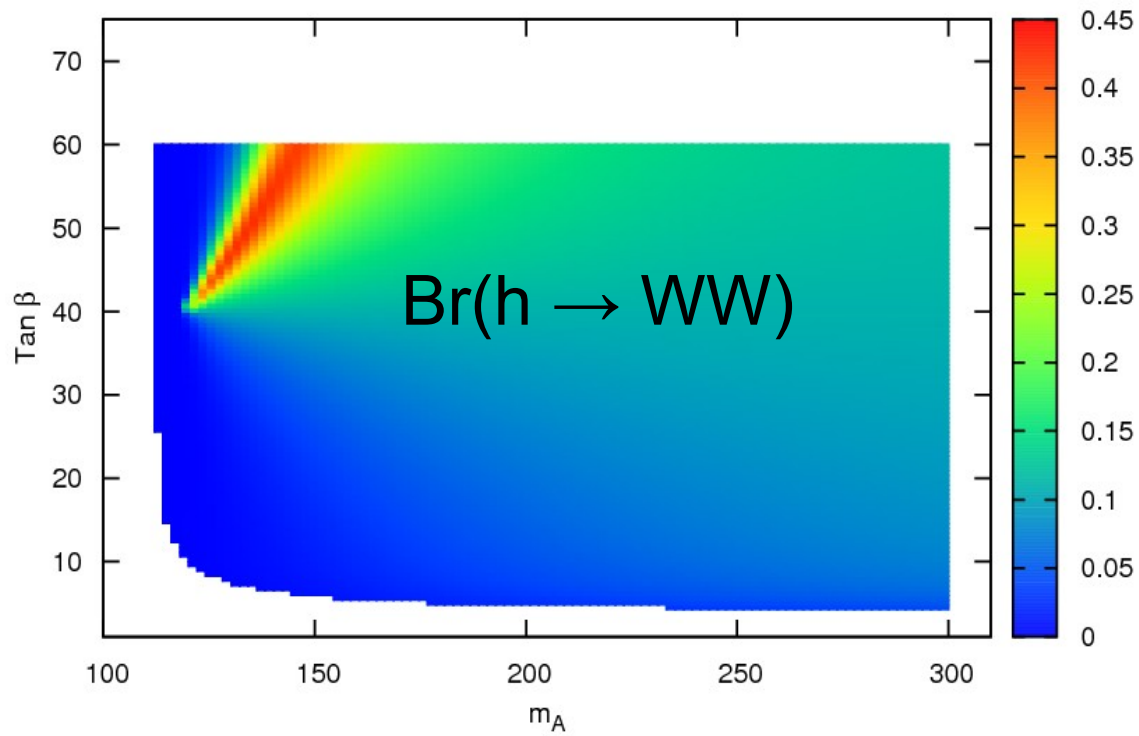
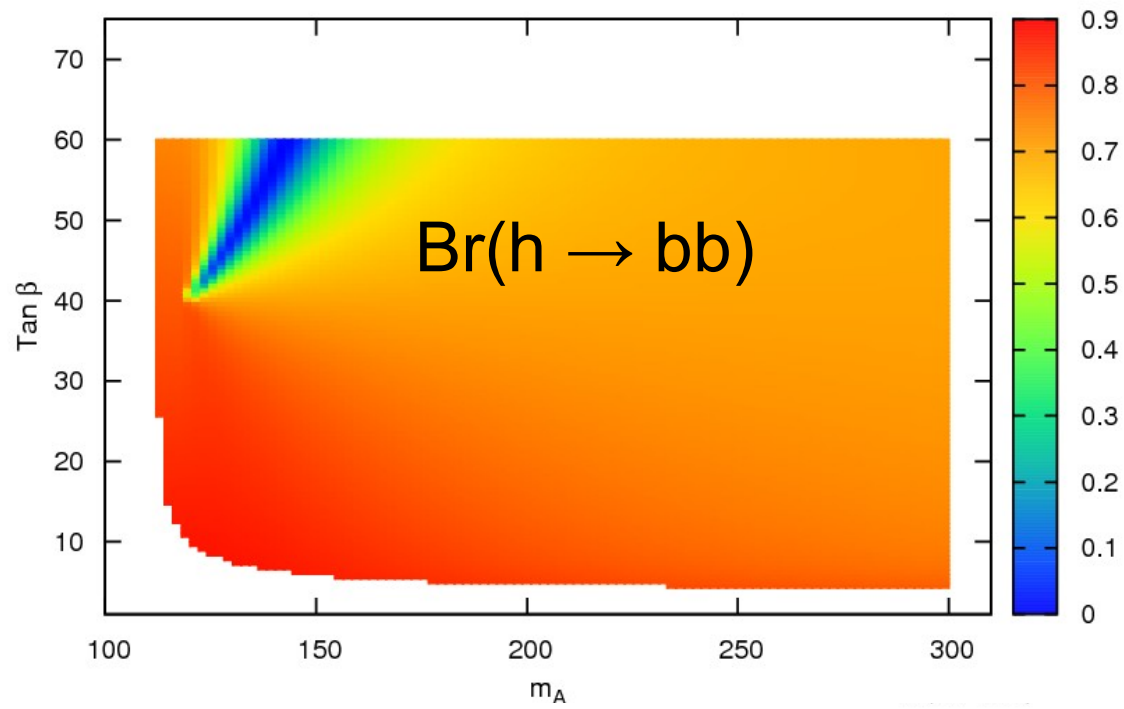
$$\bar{A}_t \equiv A_t / M_S, \quad \bar{\mu} \equiv \mu / M_S$$

- $\rightarrow$  need moderate, opposite-signed  $A_t, \mu$

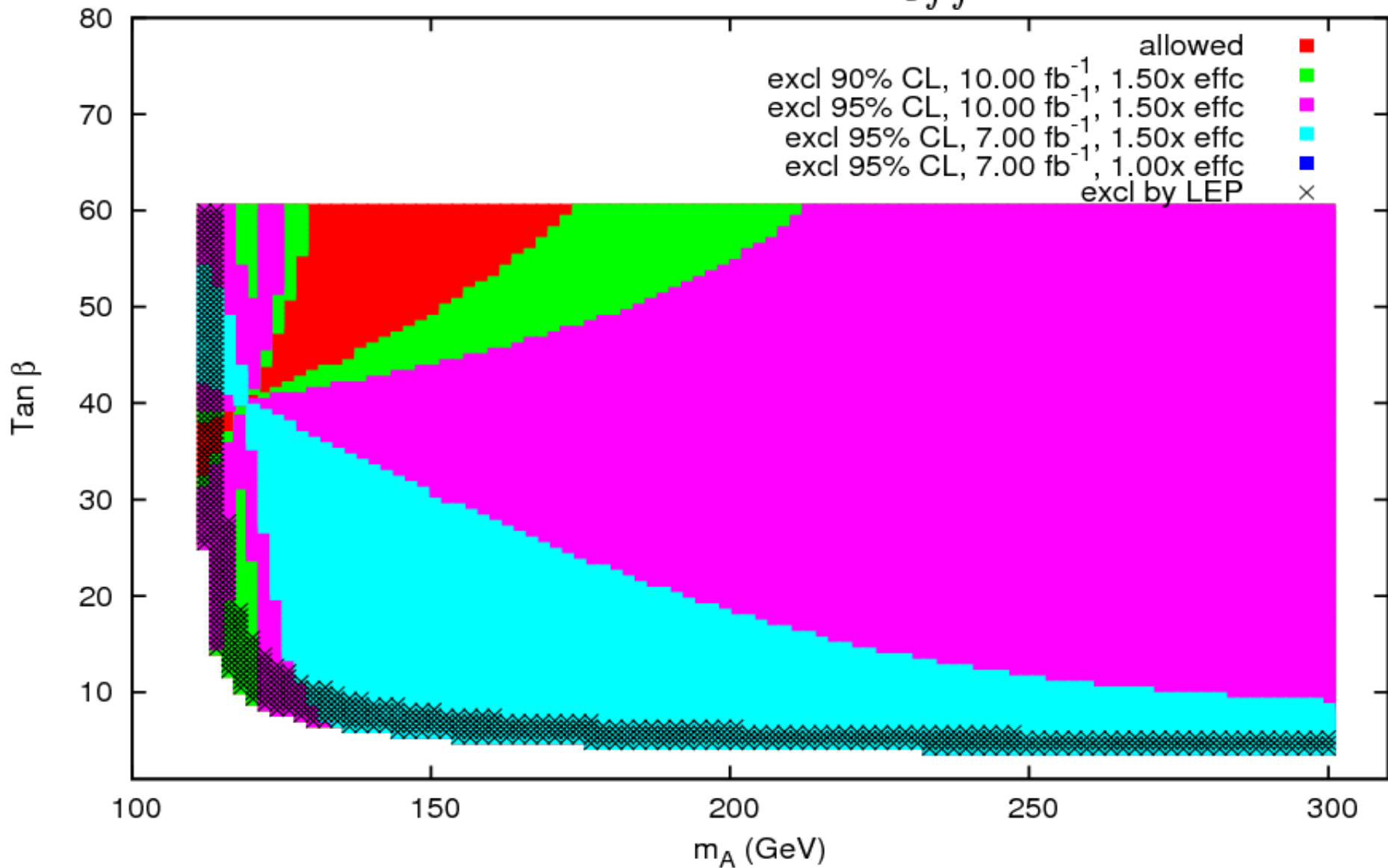
# Scenario 3: Small $\alpha_{eff}$

- Strongly suppresses  $h \rightarrow b\bar{b}$  search channels, enhances  $h \rightarrow WW$
- Demonstrates utility of WW in low-mass region

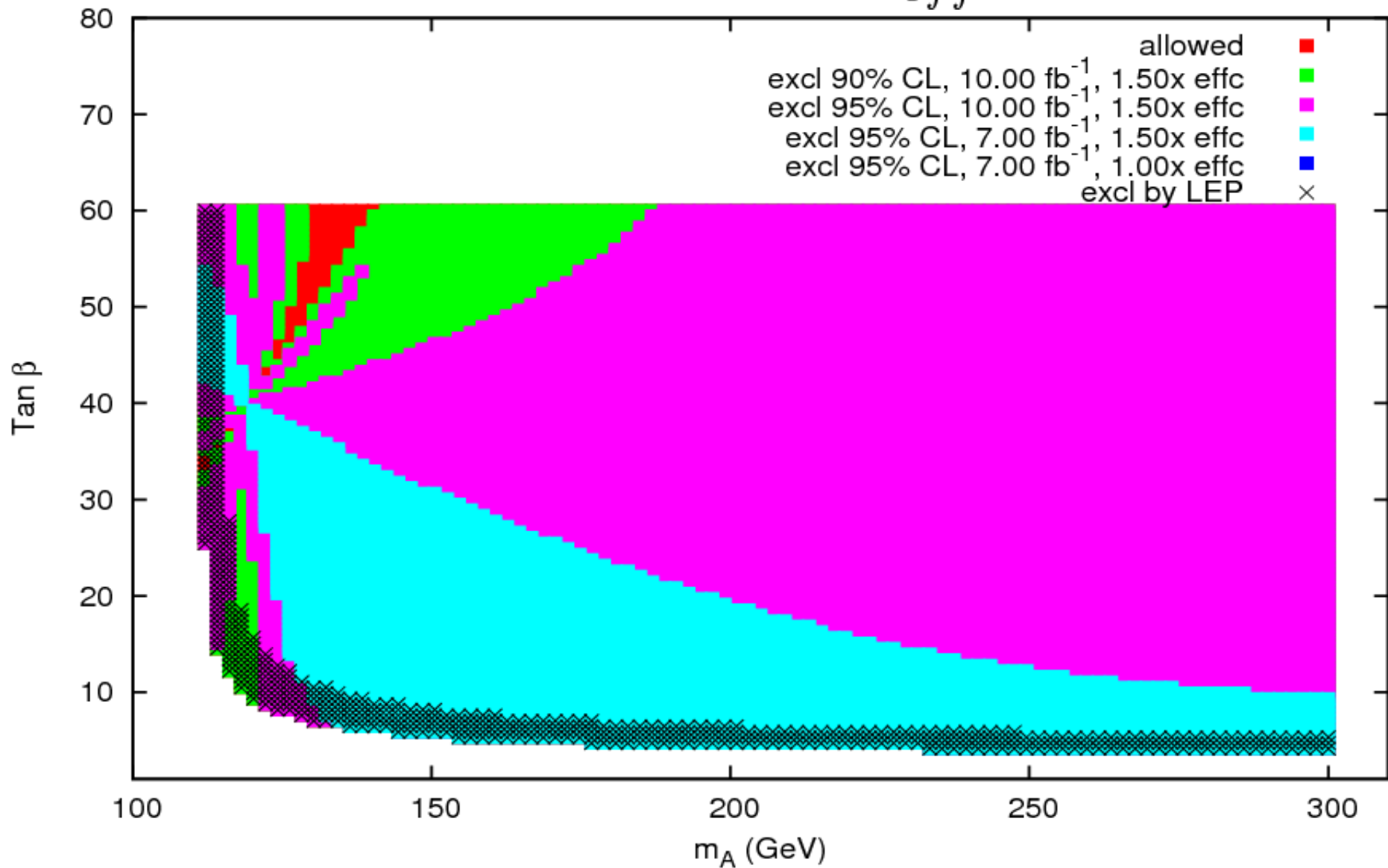
$$\begin{aligned}M_S &= 1 \text{ TeV} \\ \mu &= 1.5 \text{ TeV} \\ A_t &= -1.5 \text{ TeV}\end{aligned}$$



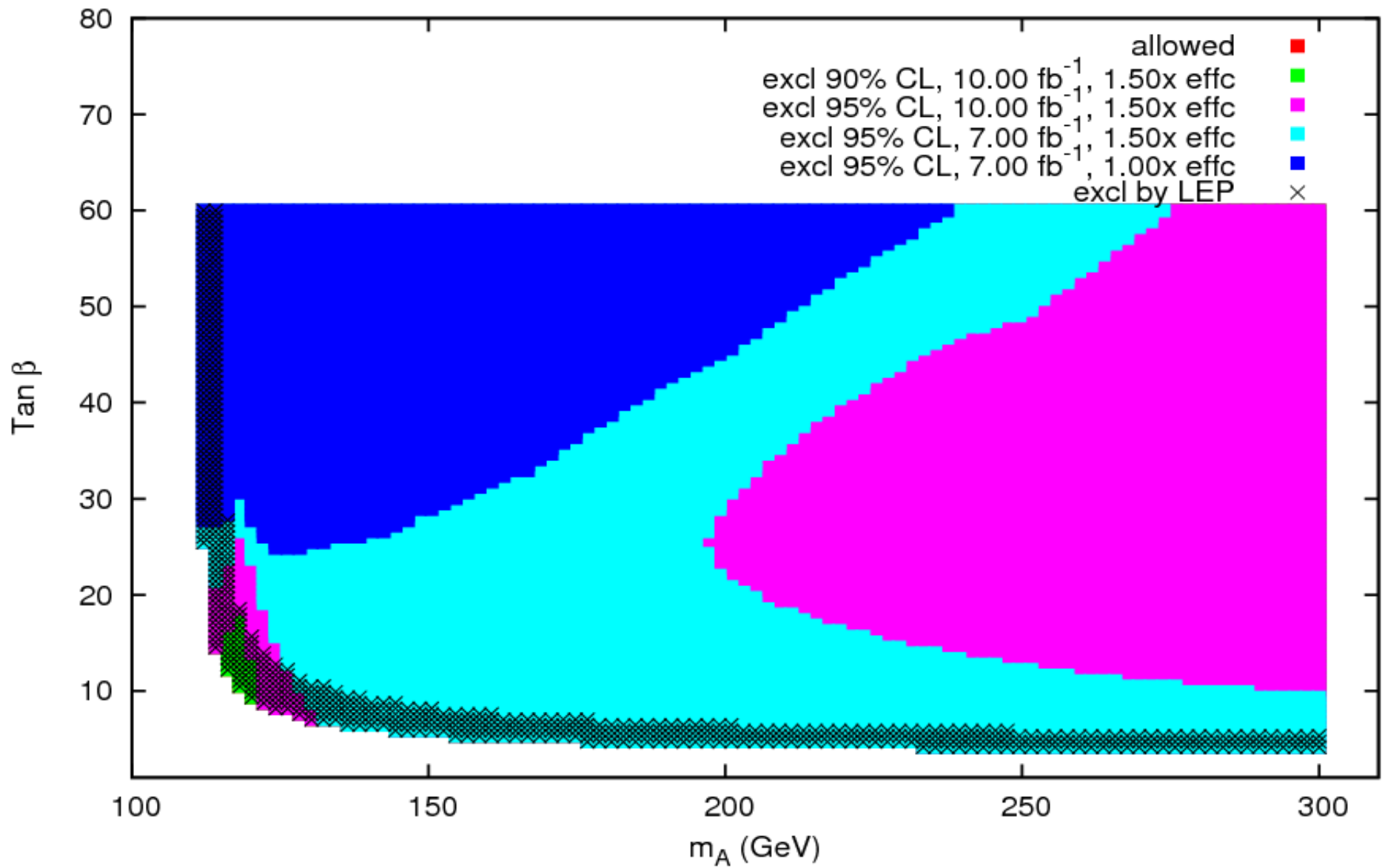
# $h \rightarrow bb$ search for SM-like Higgs for small $\alpha_{eff}$



# ( $h \rightarrow bb + h \rightarrow WW$ ) search for SM-like Higgs for small $\alpha_{eff}$



# Combined search for small $\alpha_{eff}$



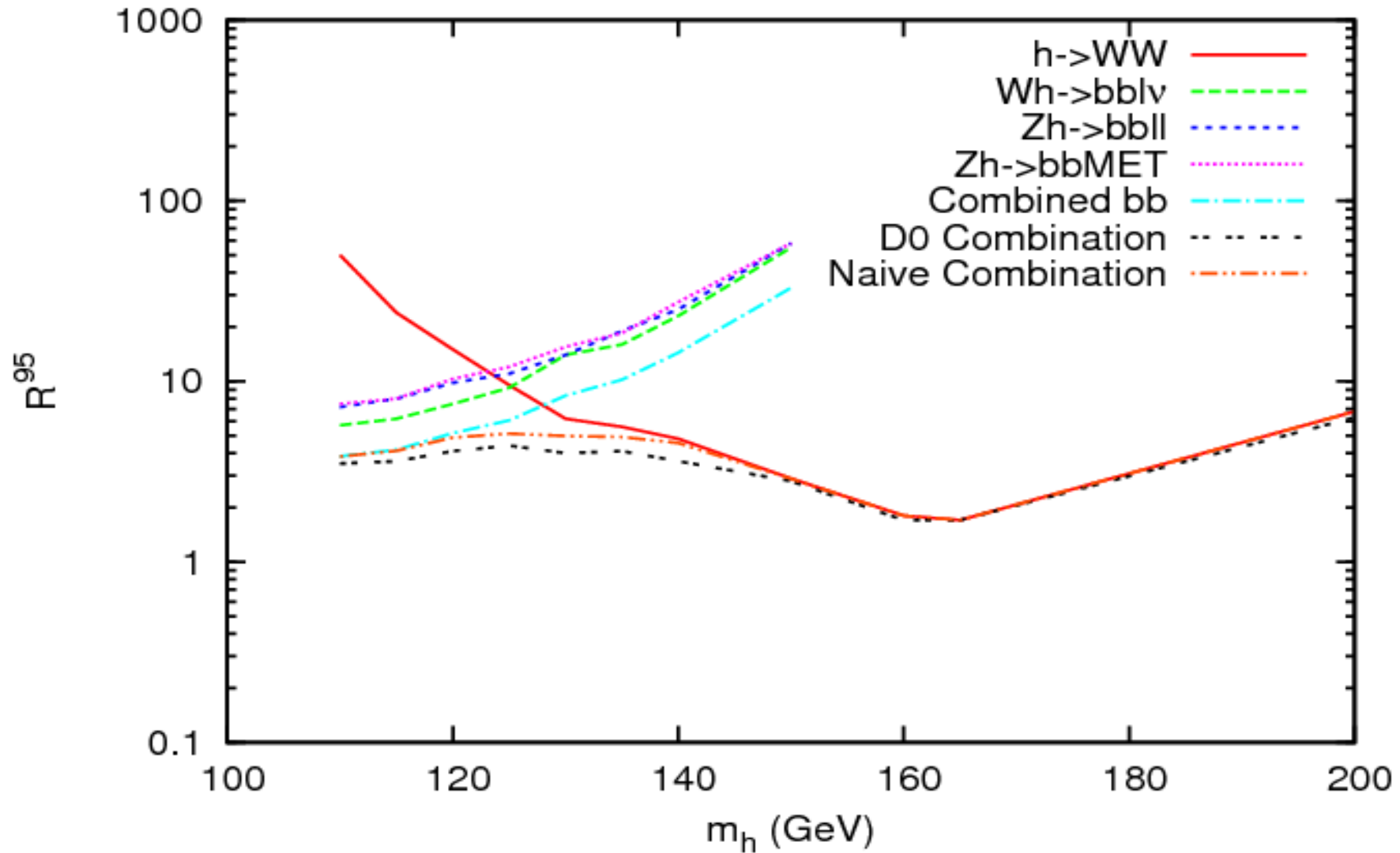
# Conclusions

- Tevatron has the potential to exclude almost all of MSSM Higgs parameter space at 95% C.L.
- 1.5x improvement in efficiency is necessary in all benchmark scenarios
- Wide coverage requires  $10 \text{ fb}^{-1}$  in all but the no-mixing scenario (reasonable if Tevatron runs through the end of 2011)
- Complementarity between  $bb$  and  $WW$  channels in SM-like Higgs searches can extend coverage when  $h$  is fermiophobic, even in the low-mass region
- Complementarity between SM-like and nonstandard Higgs searches can yield 95% exclusions everywhere except in the maximal-mixing decoupling limit
- $3\sigma$  evidence is not likely in any scenario

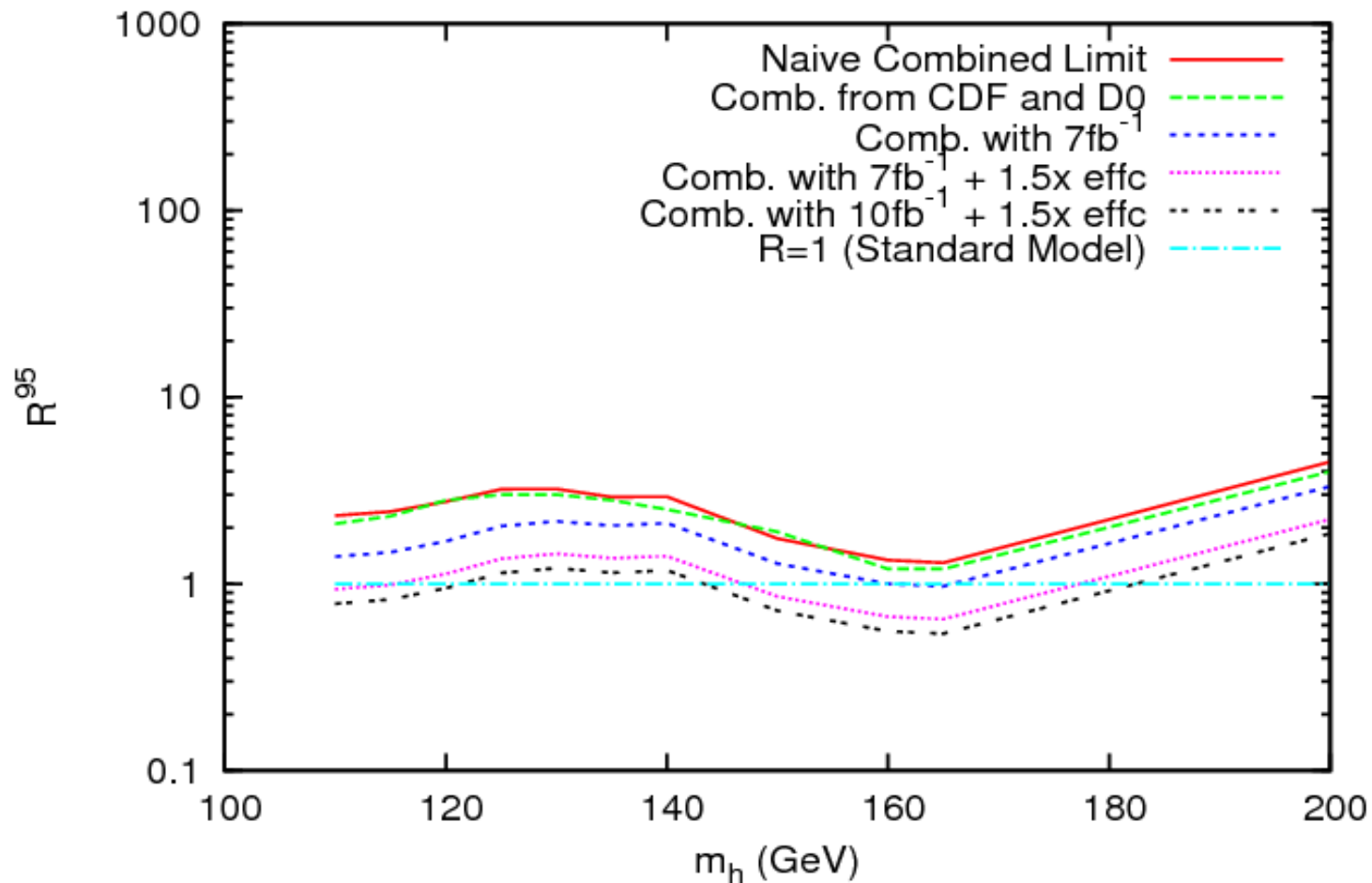
# Backup Slides



# Naïve Combined Limit vs D0

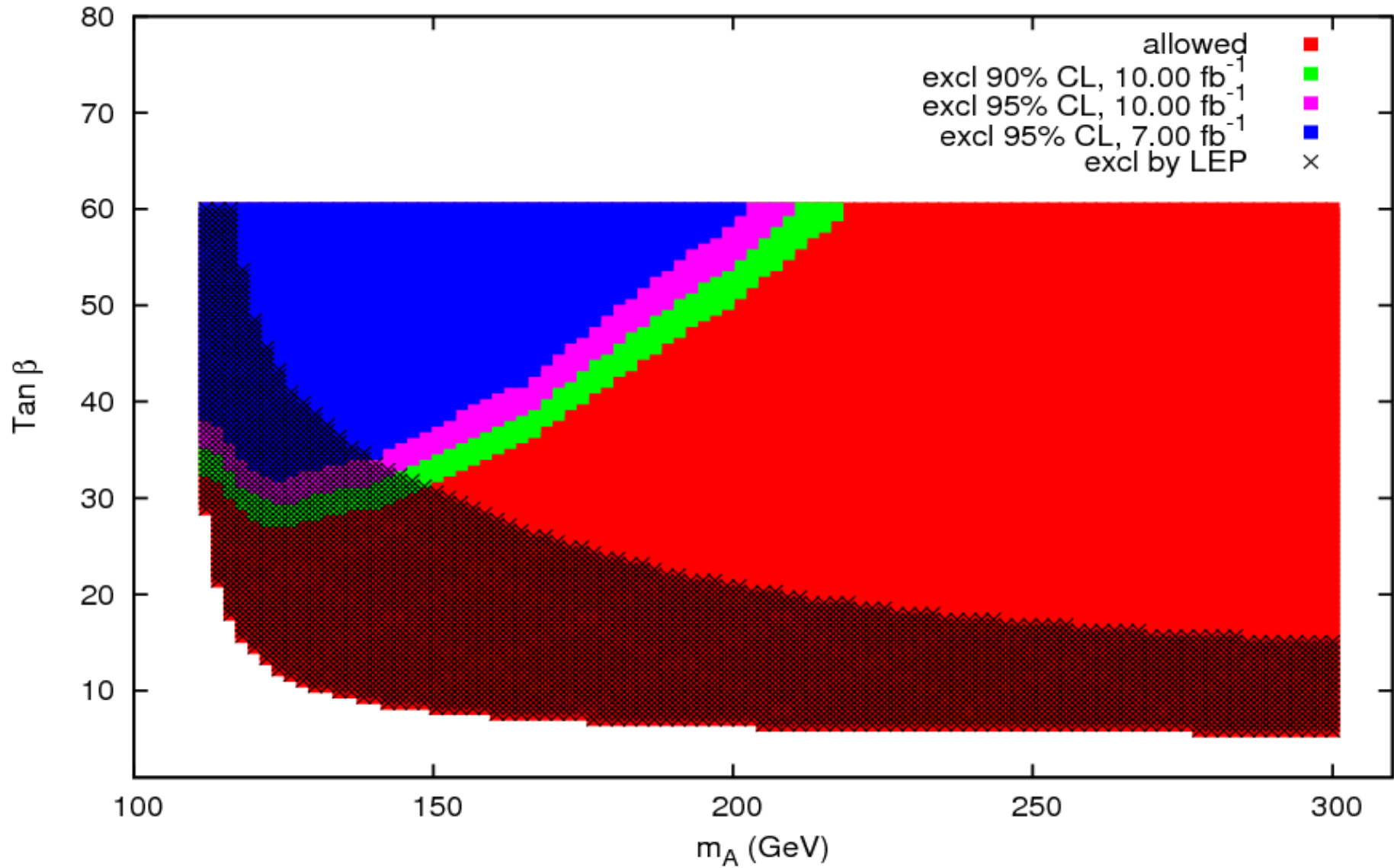


# Naïve Combined Limit vs Limit from CDF + D0



- $R_{SM}^{95}$  scales with luminosity as  $L^{-1/2}$  and signal efficiency as  $e^{-1}$

# Constraints from nonstandard Higgs Searches for No-Mixing



# Constraints from nonstandard Higgs Searches for small $\alpha_{eff}$

