How to Detect Heavy Higgs Bosons of the MSSM

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Outline of the talk

- Supersymmetric (SUSY) Higgs spectra (masses and couplings)
- Colliders phenomenology
  1. Current limits from LEP, Tevatron
  2. Future searches at LHC
- Outlook

MSSM

• MSSM based upon: 1. minimal particle content; 2. Poincare invariance; 3. SM gauge invariance; 4. SUSY.

• MSSM particle content:

Gauge bosons $S=1$	Gauginos $S=1/2$
gluon, $W^{\pm}, Z, \gamma$	gluino, $\widetilde{W}, \widetilde{Z}, \widetilde{\gamma}$
Fermions $S=1/2$	Sfermions $S=0$
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix}$	$\begin{pmatrix} \widetilde{u}_L \\ \widetilde{d}_L \end{pmatrix} \begin{pmatrix} \widetilde{\nu}_L^e \\ \widetilde{e}_L \end{pmatrix}$
u_R, d_R, e_R	$\widetilde{u}_R, \widetilde{d}_R, \widetilde{e}_R$
Higgs	Higgsinos
$\begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$	$\begin{pmatrix} \widetilde{H}_2^0 \\ \widetilde{H}_2^- \end{pmatrix} \begin{pmatrix} \widetilde{H}_1^+ \\ \widetilde{H}_1^0 \end{pmatrix}$

• Charged and neutral higgsinos mix with non-coloured gauginos to form physical mass eigenstates, so-called charginos $\widetilde{\chi}_{1,2}^{\pm}$ neutralinos $\widetilde{\chi}_{1,\ldots 4}^{0}$.

• Mixing also expected in b, t and τ sfermion sector.

- Introduce additional discrete symmetry, R-parity:

$\longrightarrow$ forbid $B - L$ violating interactions (i.e., no proton decay).

- SM particles are R-even while SUSY ones are R-odd !

- MSSM with R-parity conservation:

$\longrightarrow$ SUSY in pairs and Lightest SUSY Particle (LSP) is stable (DM candidate).

- Sparticles interactions fixed by gauge symmetries and SUSY:

$\longrightarrow$ no adjustable parameters, i.e. predictive !

- *However*, SUSY is <u>non-exact symmetry of nature</u>:

$\longrightarrow$ SM particle and SUSY sparticles non-degenerate masses !

- Mechanism of SUSY breaking not understood:

$$\mathcal{L} = \mathcal{L}(\text{SUSY}) + \mathcal{L}(\text{SUSY-breaking}).$$

- (<u>Soft-breaking terms terms</u> are consistent with Poincare and SM gauge invariance) and <u>do not reintroduce</u> quadratic divergences for scalar particles !)
- $>$ 100 free parameters to parametrise SUSY breaking.
- Models exist that assume universality of parameters at Plank/GUT scale (not treated here)

- Two-doublet Higgs models are anomaly-free, e.g. MSSM.

- SUSY structure also requires (at least) two Higgs doublets to generate masses for both "up"-type and "down"-type quarks and charged leptons.

- MSSM Higgs sector consists of five physical Higgs particles:

→ two CP-even neutral Higgses, h^0 and H^0 ($M_{h^0} \leq M_{H^0}$)
→ one CP-odd neutral Higgs boson, A^0
→ a charged Higgs boson pair, $H^\pm$.

- AT LO, $\tan\beta$ (ratio of VEVs) and one Higgs mass (e.g., M_{A^0}) completely determine MSSM Higgs sector.

- At LO: $M_{h^0} < M_Z$, $M_{A^0} < M_{H^0}$ and $M_W < M_{H^\pm}$!

- Particle/Sparticle (virtual) effects enter in higher orders via

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2} \frac{M_t^4}{\sin^2\beta} \log\left(1 + \frac{M_S^2}{M_t^2}\right) .$$

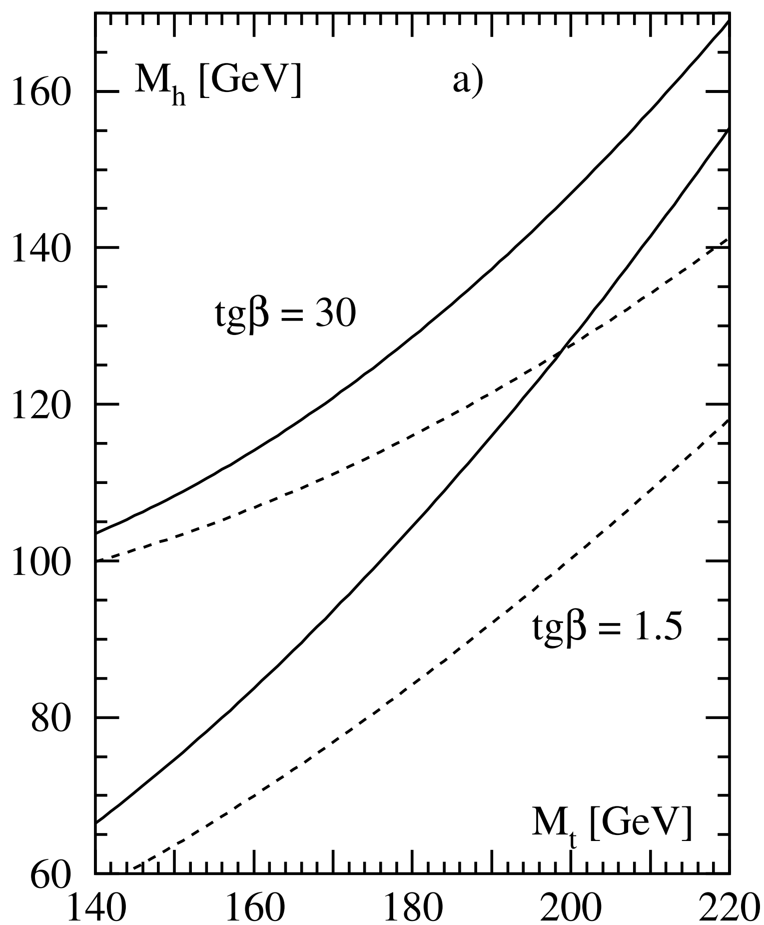
- When radiative corrections are included (NLO): $M_{h^0}^2 \leq M_Z^2 \cos^2 2\beta + \epsilon \sin^2\beta$.

- NNLO (almost complete): → fig

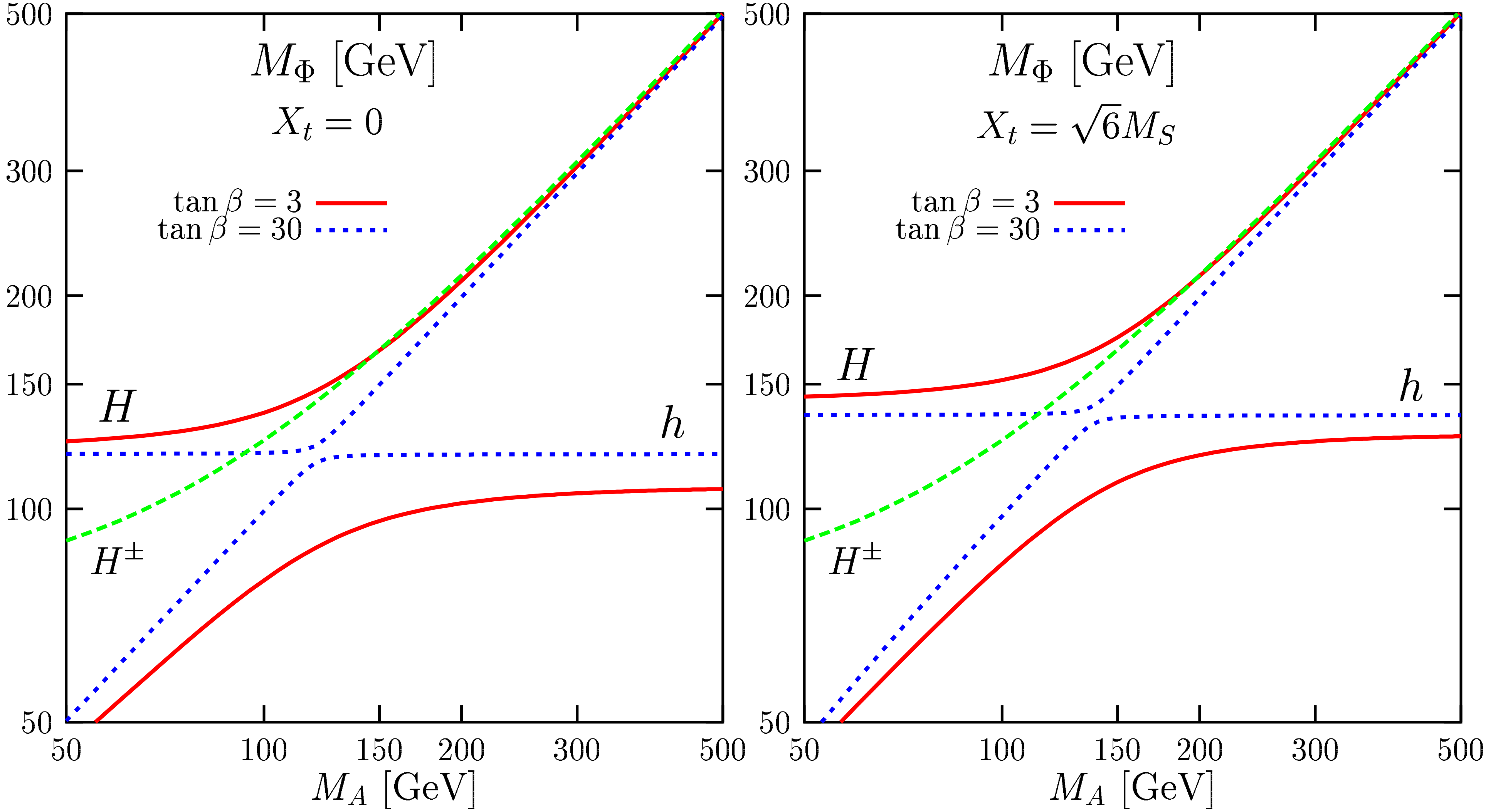
$M_{h^0} \lesssim 130$ GeV ! (absolute MSSM upper limit)

- Lightest Higgs mass (assume two scenarios):

  1. Minimal mixing $\mu = A_t = A_b = 0$ (dash);
  2. Maximal mixing $\mu = 0,\ A_b = 0,\ A_t = \sqrt{6} M_{\rm SUSY}$ (solid).



- M_{h^0} very sensitive to top mass !
- What about heavy Higgses ? $\longrightarrow$ next figure



M_Φ [GeV]
$X_t = 0$
$\tan\beta = 3$
$\tan\beta = 30$
H
h
$H^\pm$
500
300
200
150
100
50
50
100
150
200
300
500
M_A [GeV]
M_Φ [GeV]
$X_t = \sqrt{6} M_S$
$\tan\beta = 3$
$\tan\beta = 30$
H
h
$H^\pm$
500
300
200
150
100
50
50
100
150
200
300
500
M_A [GeV]

MSSM Higgs collider searches

- There exist limits from LEP2 and Tevatron, again assume:

1. Minimal mining scenario (i.e., no mixing in stop sector)
2. Maximal mixing scenario (i.e., $\tilde{t}_1$ & $\tilde{t}_2$ maximally mixed)

- MSSM parameter space available is reducing !

- LHC prospects from ATLAS and CMS for the MSSM

→ no-lose theorem but large decoupling SM-like area !

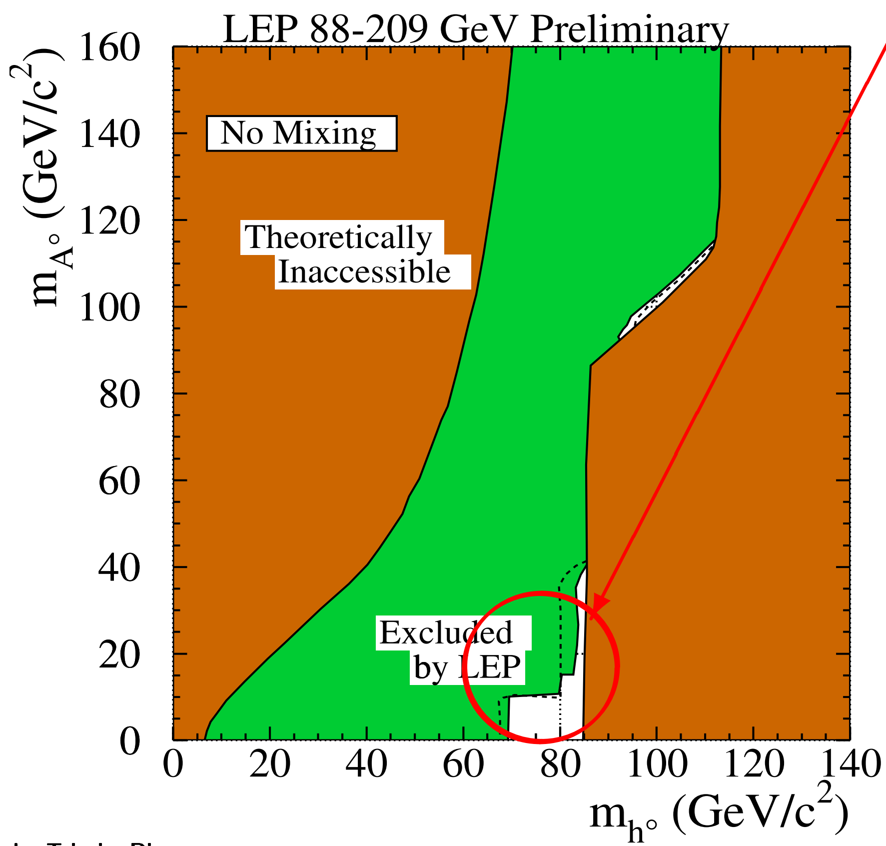
- Ought to observe second Higgs state or make precision measurements of BRs, Γs, etc.

- Ought to include interaction between Higgs/SUSY sectors:

→ Higgs → SUSY and SUSY → Higgs signatures !

MSSM: no-mixing benchmark

(m_h, m_A) 95% CL exclusion:



- $e^+e^- \to hZ \to AAZ$, but no $A \to b\bar{b}$!

  occurs for

  $\tan\beta < 0.7$ & $m_{H^\pm} < 74$ GeV

- Use $H^\pm$ direct searches to exclude this .

  ... but: $B(H^\pm \to W^\pm A) \neq 0$

  $\Rightarrow$ under investigation

excluded at 95% CL (for $\tan\beta > 0.7$):

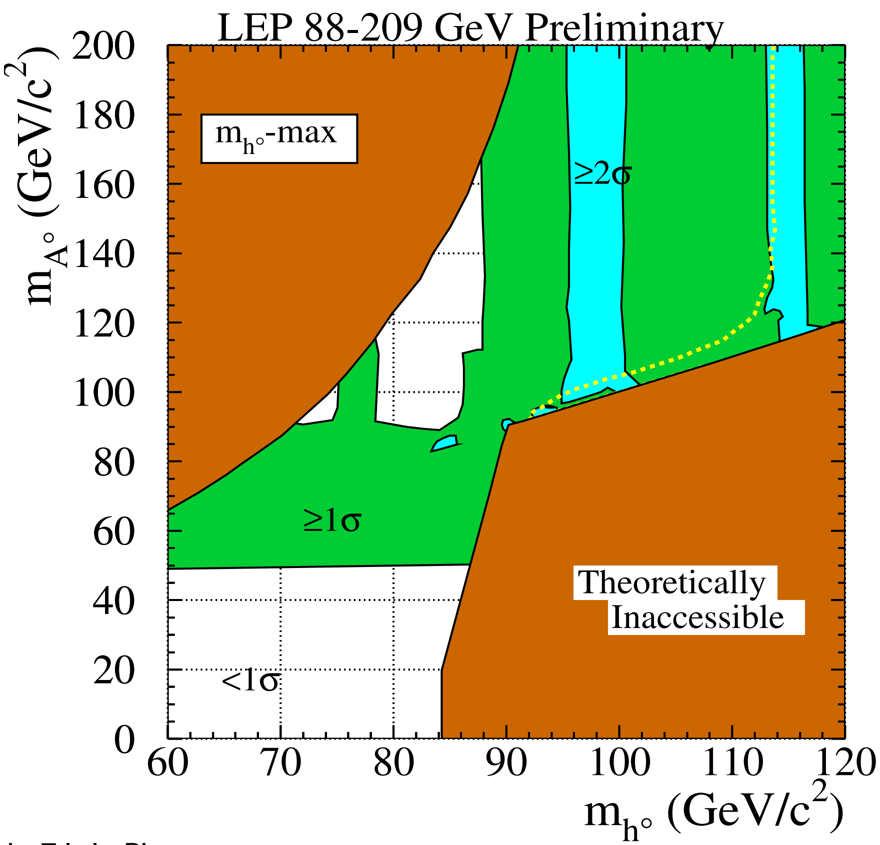
$m_h < 91.5$ (95.0 exp.) GeV

$m_A < 92.2$ (95.3 exp.) GeV

$0.7 < \tan\beta < 10.5$

MSSM: m_{h}-max benchmark

$1 - \mathbf{CL}_{\mathrm{b}}$ **in** $(m_{\mathsf{h}}, m_{\mathsf{A}})$**:**



➜ $e^+e^- \rightarrow$ hA **searches:**

$\sim 2\sigma$ **excess for**

$(m_{\mathsf{h}}, m_{\mathsf{A}}) \approx$ **(83,83), (93,93) G**

➜ $e^+e^- \rightarrow$ hZ **searches:**

$\geq 2\sigma$ **excess for**

$m_{\mathsf{h}} =$ **97 & 115 GeV**

excluded at 95% CL (- - -):

$m_{\mathsf{h}} <$ **91.0 (95.0 exp.) GeV**

$m_{\mathsf{A}} <$ **91.9 (94.6 exp.) GeV**

0.5 $< \tan\beta <$ **2.4**

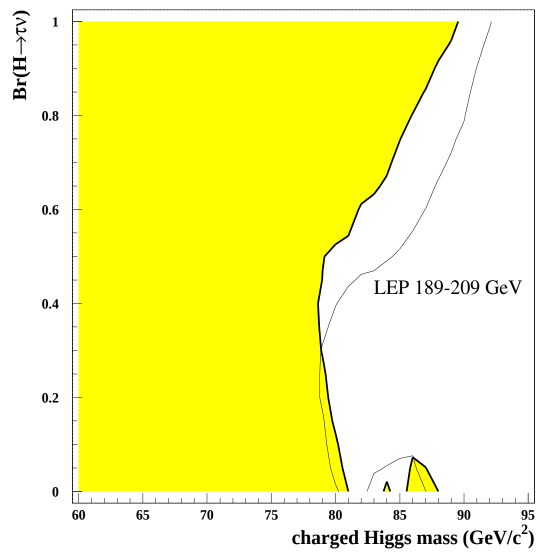
Charged Higgs, $H^{\pm}$

Assume $B(H^+ \to c\bar{s}) + B(H^+ \to \tau^+\nu) \doteq 1$

➜ $e^+e^- \to H^+H^- \to c\bar{s}s\bar{c},\ c\bar{s}\tau^-\bar{\nu},\ \tau^+\nu\tau^-\bar{\nu}$

- L3 observe a large excess in the 4-jets channel

➜ compatibility with ALEPH, DELPHI, OPAL is being investigated.



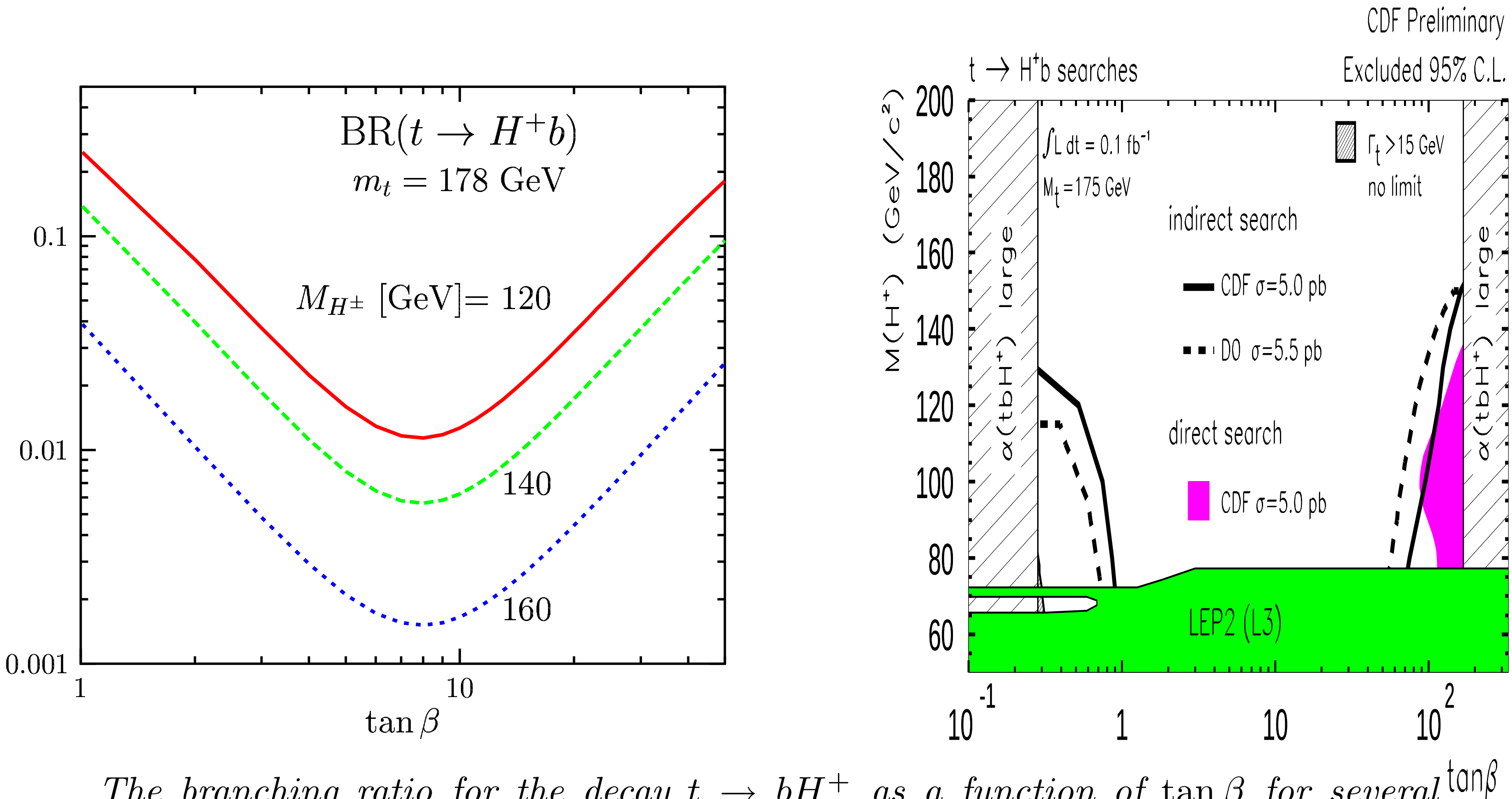
LEP combined search excludes (95%CL)

$m_{H^{\pm}} <$ 78.6 (78.8 exp.) GeV

for any $B(H^+ \to \tau^+\nu)$

$H^{\pm}$ at Tevatron (no updates on LEP's results for neutrals)

- In the MSSM, $M_{H^{\pm}} = \sqrt{M_{h^0}^2 + M_W^2}$.



The branching ratio for the decay $t \to bH^+$ as a function of $\tan\beta$ for several values of $M_{H^{\pm}}$ and for $m_t = 178$ GeV (left) and the $\tan\beta$–$M_{H^{\pm}}$ parameter space excluded by the CDF and D0 collaborations from the non–observation of these decays (right).

LHC search channels for MSSM Higgses

Typical discovery channels are:

- $h \to \gamma\gamma$, inclusive production and production in association with an isolated lepton in Wh^0 and $t\bar{t}h^0$ final states

- $h \to b\bar{b}$ in association with an isolated lepton and b-jets in Wh^0 and $t\bar{t}h^0$

- $A^0, H^0 \to \mu\mu$, inclusive and in $b\bar{b}H^0/A^0$ final states

- $A^0, H^0 \to \tau\tau$ with 2ℓ, $\ell + \tau$-jet and 2τ-jet final states

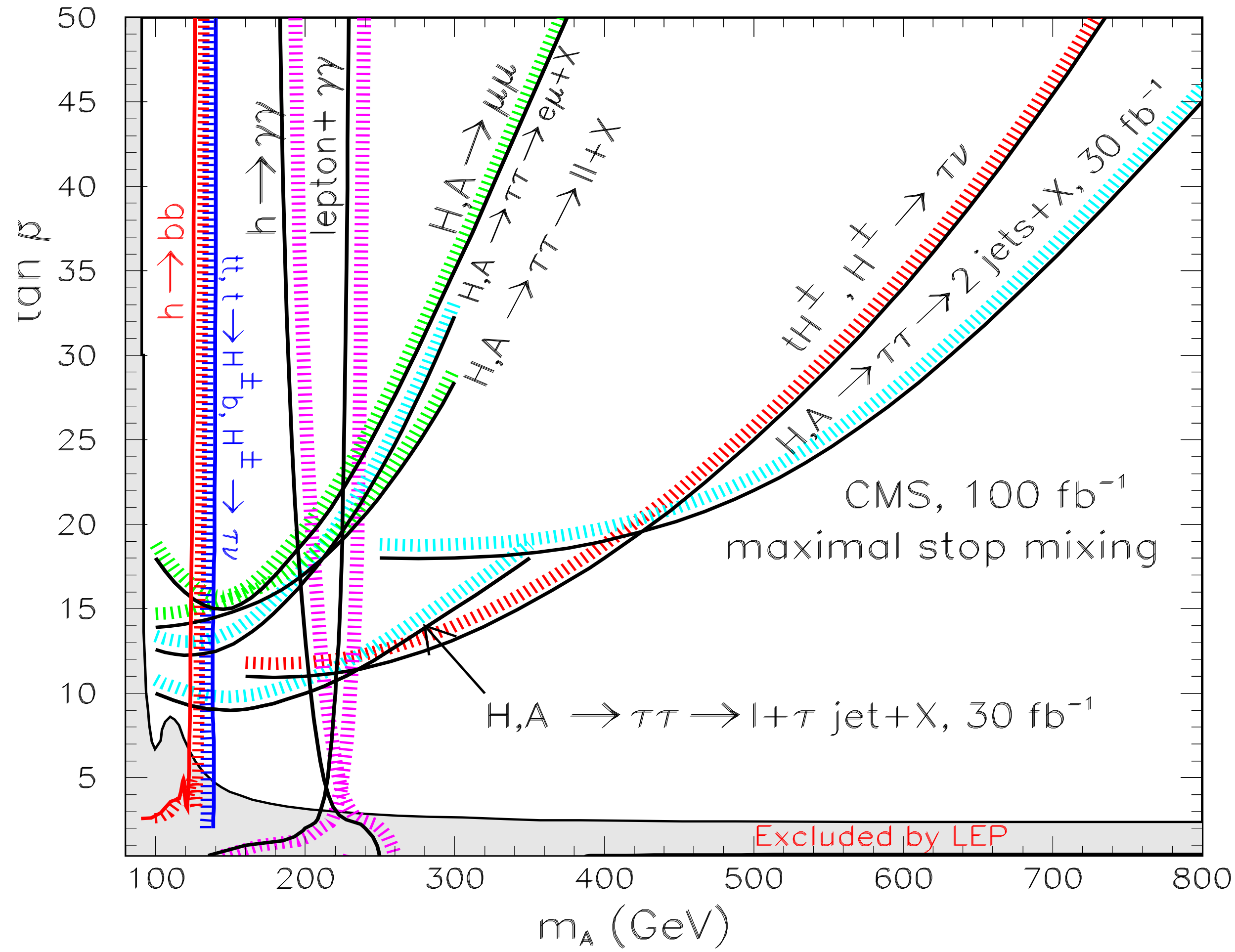
- $H^\pm \to \tau\nu$ in $gg \to tbH^\pm$ and in $q\bar{q}' \to H^\pm$

- $H^\pm \to tb$ in $gg \to tbH^\pm$

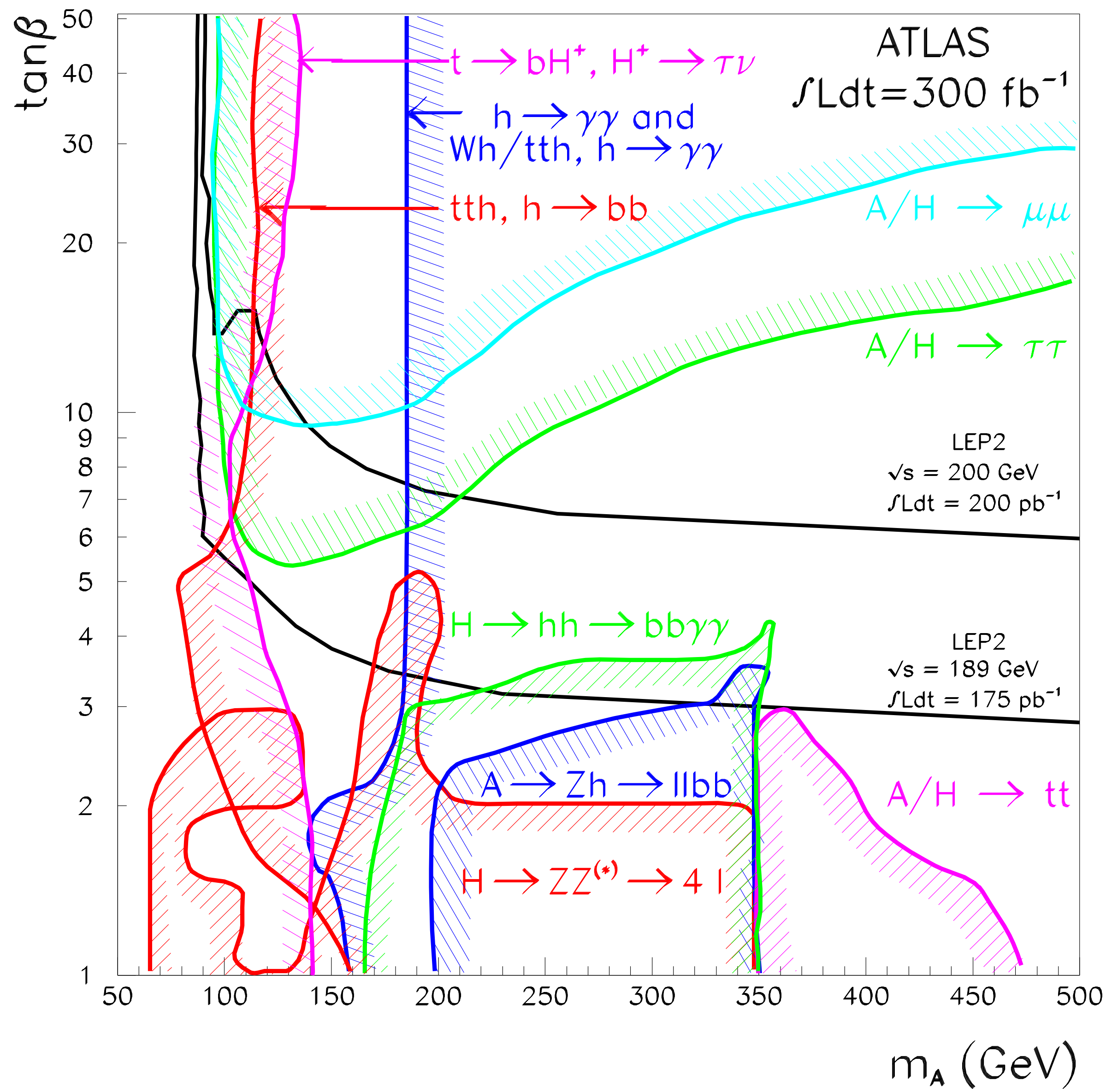
Note:

- They only include SM-particle to Higgs interactions

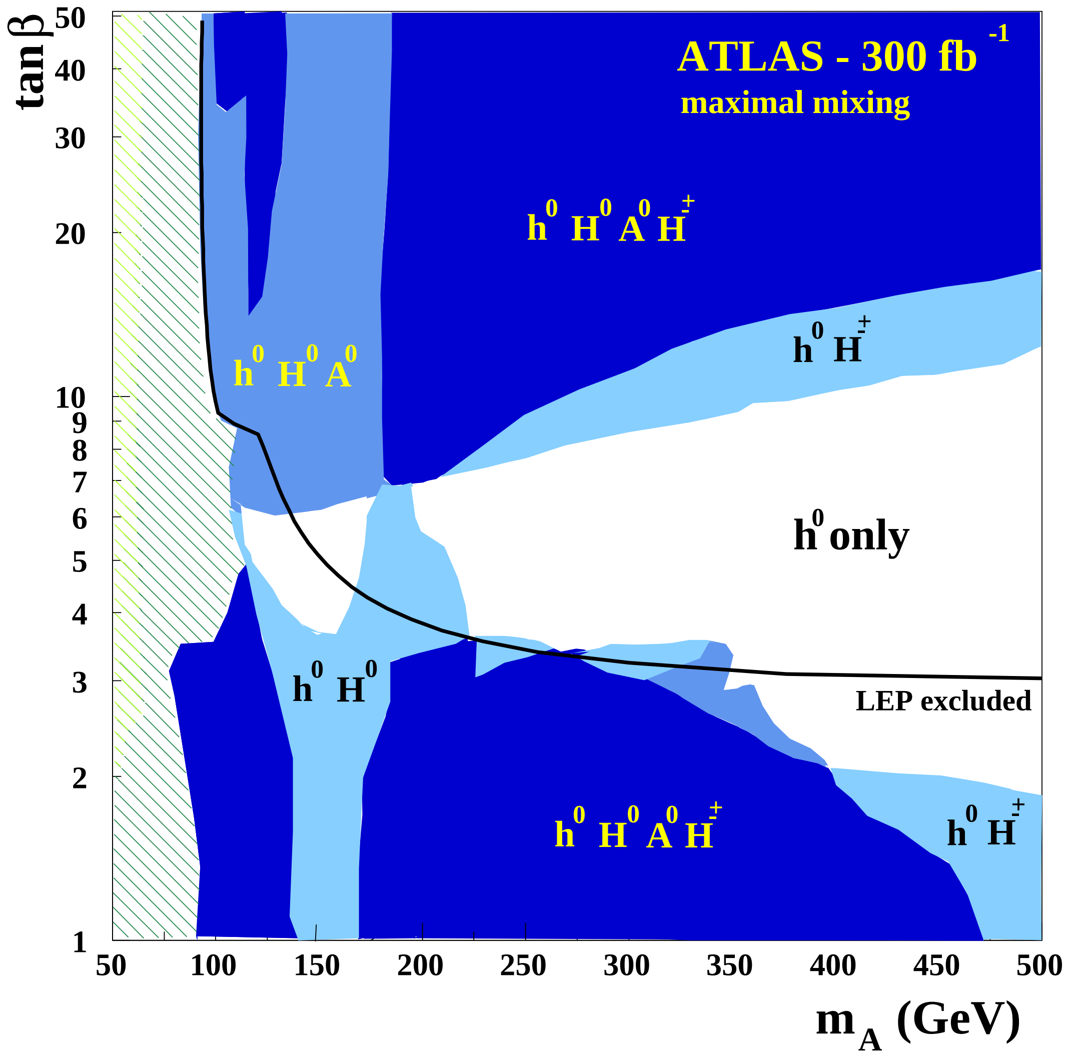
- This assumes no interaction between Higgs & sparticle sectors: i.e., SUSY mass scales all heavy (except $M_{\tilde{\chi}_1^0}$ and possibly $m_{\tilde{t}_1}$)



CMS after 100 fb^{-1} of luminosity (MaxMix)



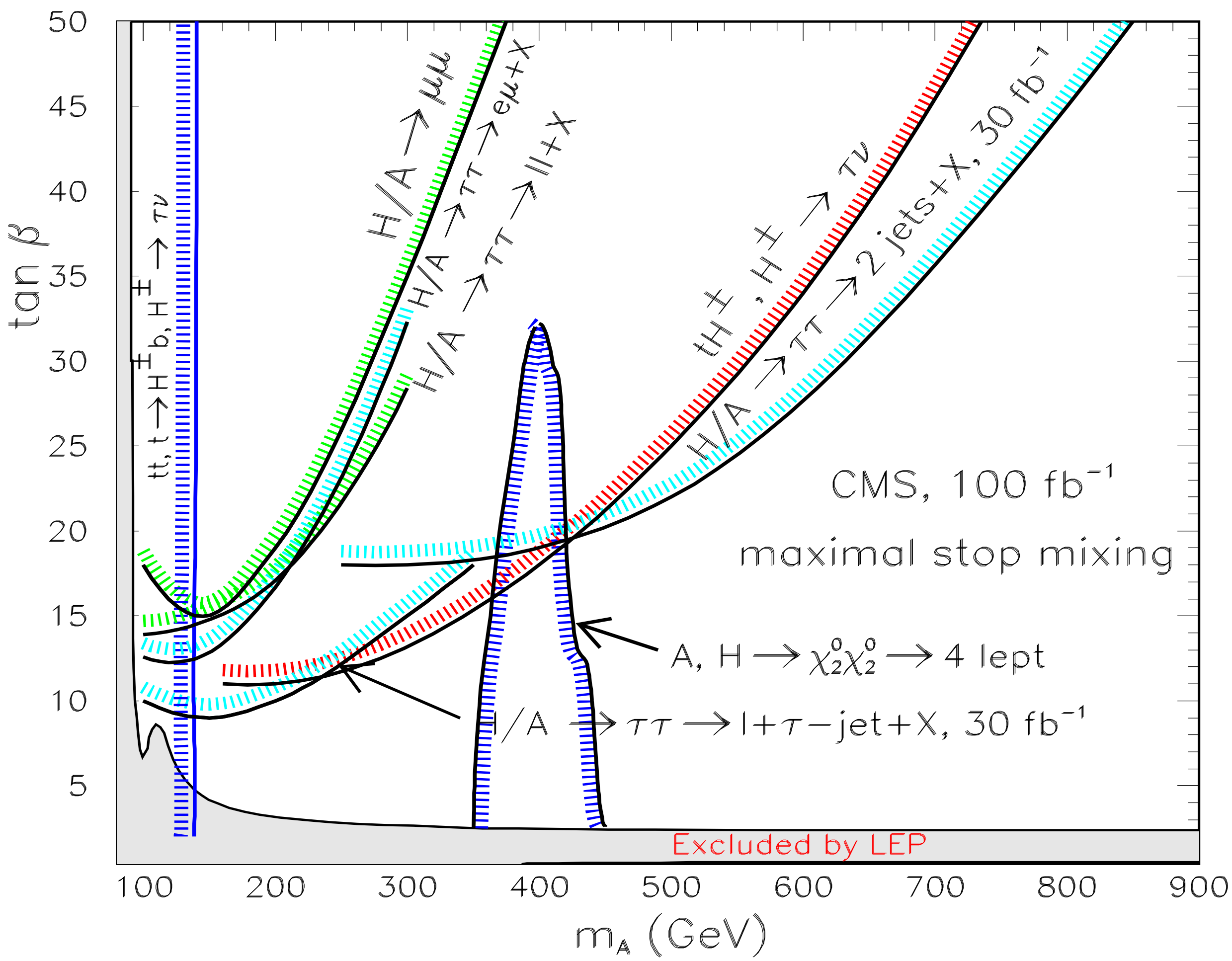
ATLAS after 300 fb^{-1} of luminosity (MaxMix)



ATLAS after 300 fb^{-1} of luminosity (MaxMix)

- Why do not reduce the SUSY mass spectrum ? To sub-TeV scales.
- (Preferred scenario for SUSY couplings unification)

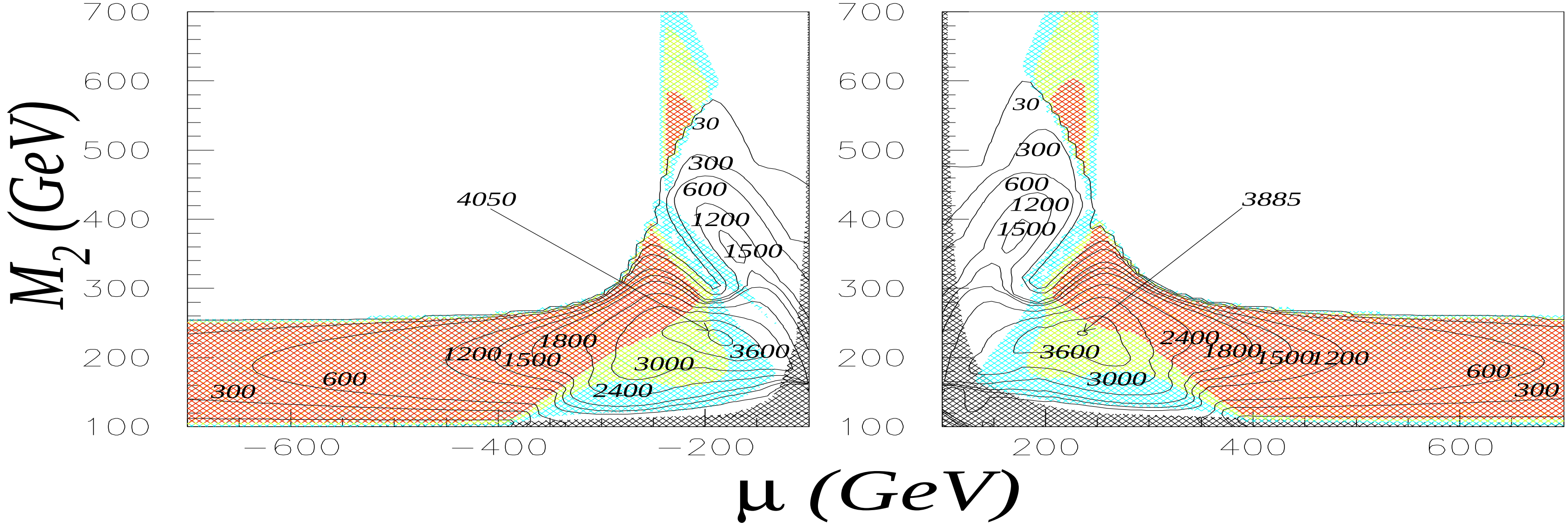
- Clean channel: $A, H \to \chi_2^0\chi_2^0 \to 4\ell^\pm + E_T^{\text{miss}}$ $(\chi_2^0 \to \chi_1^0\ell^+\ell^-,\ \ell = e,\mu)$ via $Z^{(*)}$ or sleptons (F Moortgat et al., hep-ph/0112045 & hep-ph/0105081)



CMS after 100 fb^{-1} assuming $M_1 = 90$ GeV, $M_2 = 180$ GeV, $\mu = 500$ GeV, $M_{\tilde{\ell}} = 250$ GeV, $M_{\tilde{q},\tilde{g}} = 1000$ GeV.

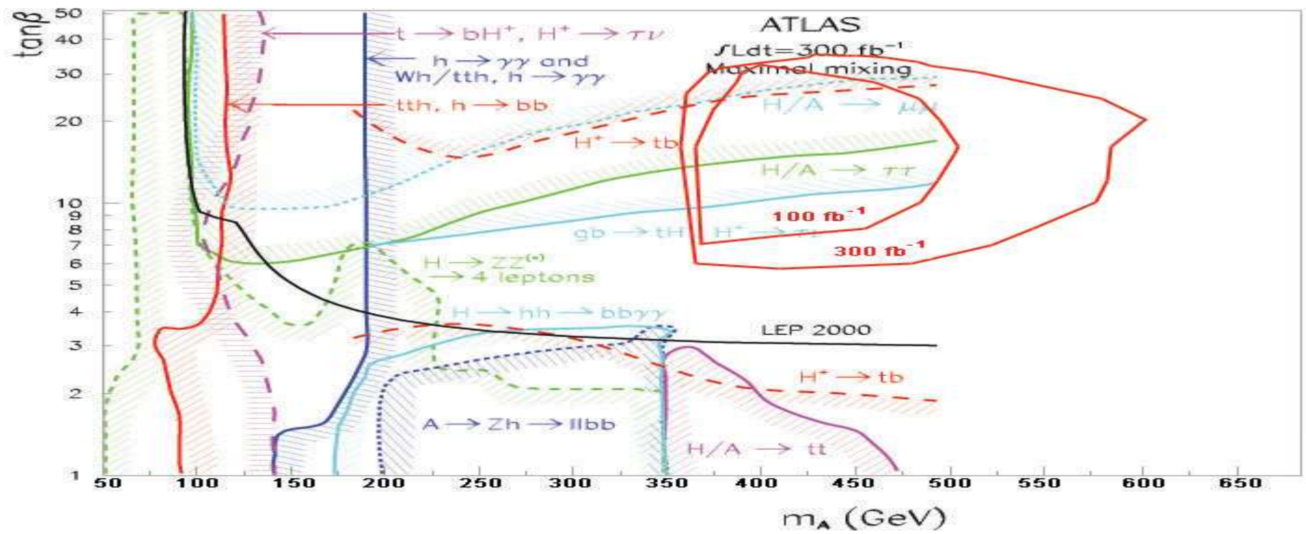
- Can supplement with heavier -inos: $A, H \rightarrow \tilde{\chi}_a^+ \tilde{\chi}_b^-, \tilde{\chi}_i^0 \tilde{\chi}_j^0 \rightarrow 4\ell^\pm + E_T^{\rm miss}$
  $(a, b = 1, 2, \;\; i, j = 1, 2, 3, 4)$
  (M Bisset, N Kersting, F Moortgat, S Moretti, in progress)

- Heavier -inos onset heavy Higgs decays



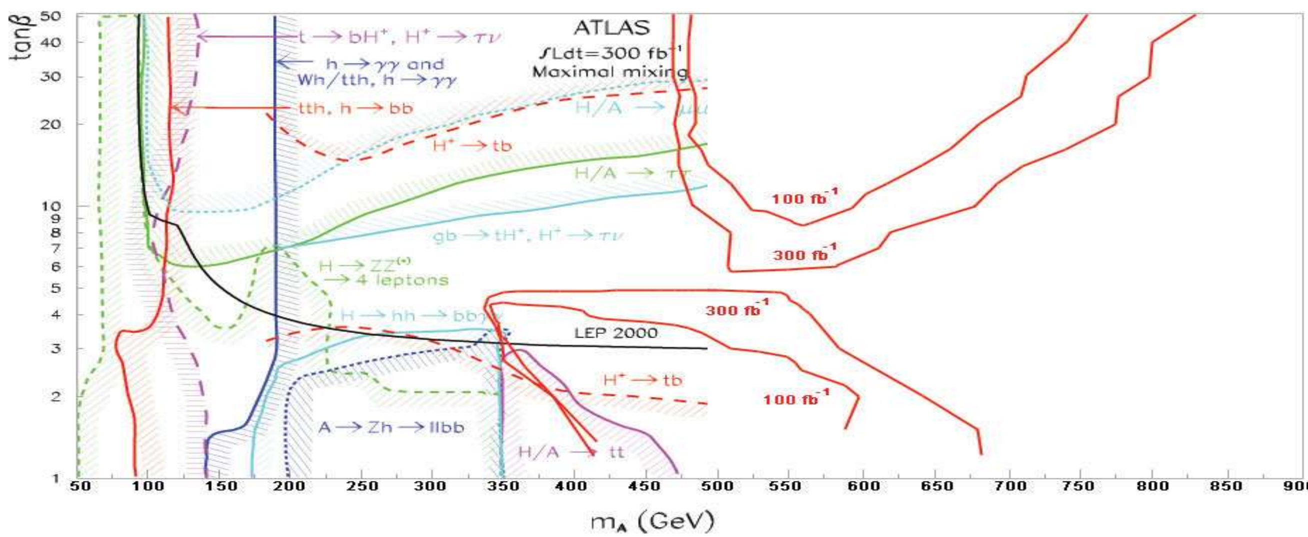
Number of $pp \rightarrow H^0, A^0 \rightarrow 4\ell N$ events, where $\ell = e^\pm$ or $\mu^\pm$ and N represents invisible final state particles, for $100\,\text{fb}^{-1}$, with $\tan\beta = 10$ and $M_A = 500\,\text{GeV}$. Also shown is the percentage from $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$: $> 90\%$ (red), $50\% - 90\%$ (yellow), $10\% - 50\%$ (light blue), $< 10\%$ (white). Optimized slepton masses (with stau inputs raised 100 GeV) are used, $m_t = 175\,\text{GeV}$, $m_b = 4.25\,\text{GeV}$, $m_{\tilde{q}} = 1\,\text{TeV}$, $m_{\tilde{g}} = 800\,\text{GeV}$, $A_\tau = A_\ell = 0$. The cross-hatch shaded areas are excluded by LEP.

PRELIMINARY !!!



$\tilde{\chi}_2^0 \tilde{\chi}_2^0$ dominated: $M_2 = 180\,\mathrm{GeV}$, $M_1 = 90\,\mathrm{GeV}$, $\mu = -500\,\mathrm{GeV}$, $m_{\tilde{\ell}_{soft}} = m_{\tilde{\tau}_{soft}} = 250\,\mathrm{GeV}$

AND NOT ATLAS !!!

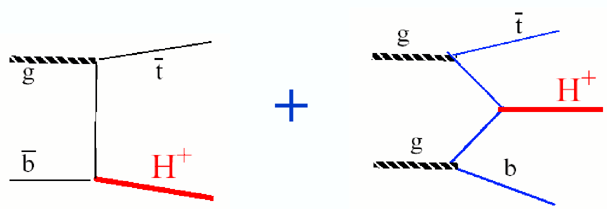


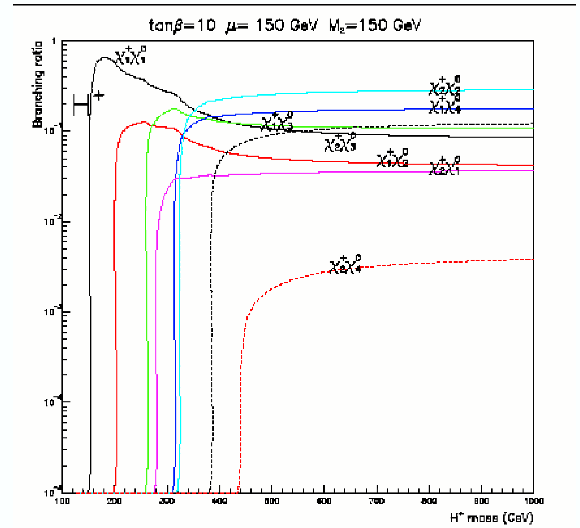
Heavier -inos dominated: $M_2 = 200\,\mathrm{GeV}$, $M_1 = 100\,\mathrm{GeV}$, $\mu = -200\,\mathrm{GeV}$, $m_{\tilde{\ell}_{soft}} = 150\,\mathrm{GeV}$, $m_{\tilde{\tau}_{soft}} = 25$

(M Bisset, M Guchait, S Moretti, Eur.Phys.J.C19:143-154,2001;
M Bisset, F Moortgat, S Moretti, Eur.Phys.J.C30:419-434,2003)

Charged Higgs to sparticles

Analogue production mechanism for $H^{\pm}$:



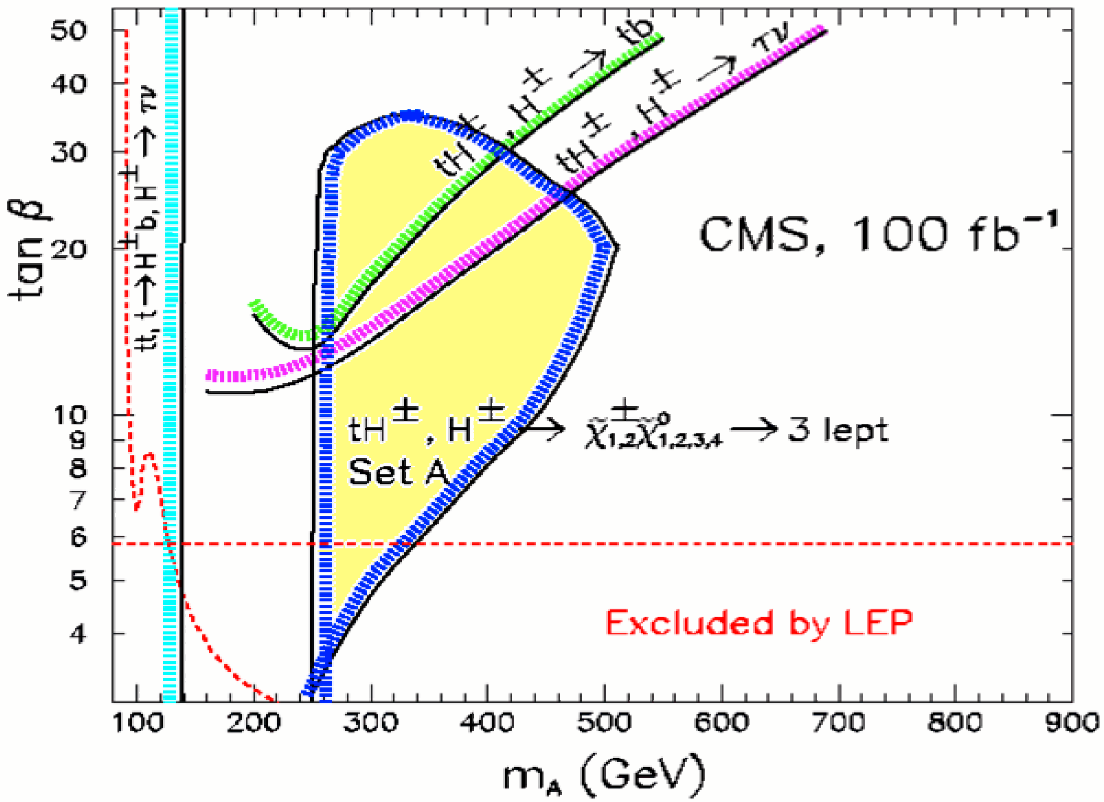


Analogue decay mode:

$H^{\pm} \rightarrow \chi_{2,3}^{0}\, \chi_{1,2}^{\pm} \rightarrow 3l + E_T^{miss}$

→ only 3 leptons, need to reconstruct additional top (t→bjj)

Discovery Reach



MSSM parameters:

$M_2 = 210$ GeV,
$\mu = 135$ GeV,
$M_{sleptons} = 110$ GeV,
$M_{squark,\ gluino} = 1$TeV

SUSY → Higgses

- Possible production & decay channels:

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} \quad \to \quad \chi_2^\pm, \chi_3^0, \chi_4^0 X$$
$$\to \quad \chi_1^\pm, \chi_2^0, \chi_1^0 h^0, H^0, A^0, H^\pm \;\; X$$

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} \quad \to \quad \chi_1^\pm, \chi_2^0 X$$
$$\to \quad \chi_1^0 H^\pm, h^0, H^0, A^0 \;\; X$$

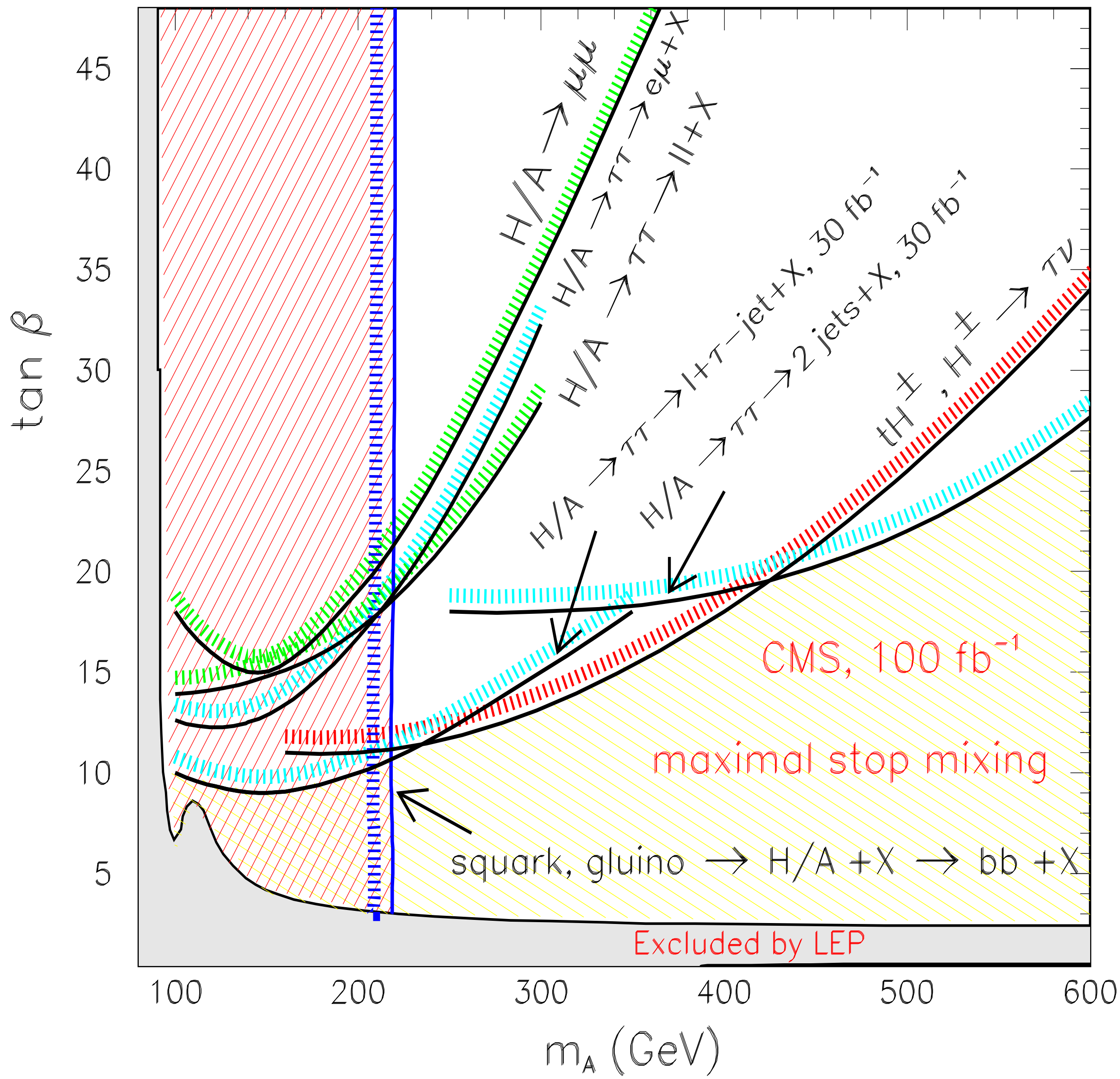
$$pp \quad \to \quad \tilde{t}_2\tilde{t}_2^*, \tilde{b}_2\tilde{b}_2^* \;\; \text{with} \;\; \tilde{t}_2(\tilde{b}_2) \to \tilde{t}_1(\tilde{b}_1)h^0, H^0, A^0 \text{ or } \tilde{b}_1(\tilde{t}_1)H^\pm$$

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} \quad \to \quad t/\bar{t}X \to H^\pm X$$

- Signatures:

$h^0, H^0, A^0 \to b\bar{b}$ and $H^\pm \to \tau\nu \to$ hadronic in a multi-jet environment + E_T^{miss}

(A Datta, A Djouadi, M Guchait, F Moortgat, Nucl.Phys.B681:31-64,2004)



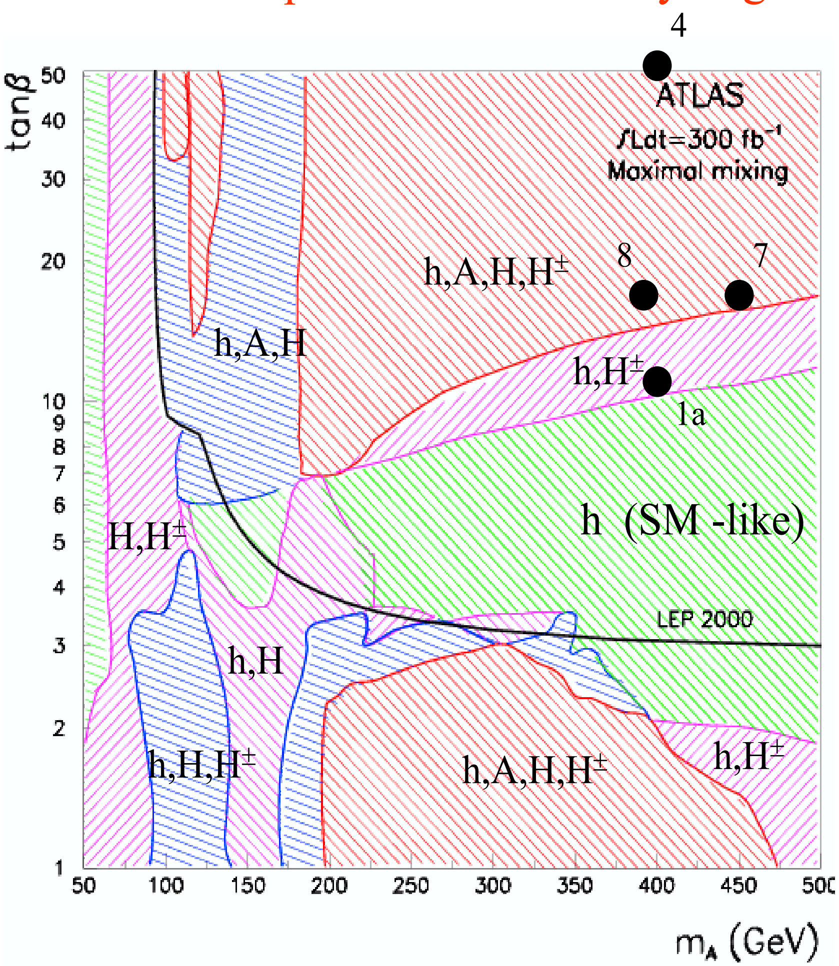
CMS after 100 fb^{-1} assuming $M_2 = 175$ GeV, $M_2 = 350$ GeV, $\mu = 150$ GeV, $M_{\tilde{\ell}} = 175$ GeV, $M_{\tilde{q},\tilde{g}} = 800$ GeV

Outlook

- A no-lose theorem exists for MSSM Higgs bosons: we are guarantueed to find at least one state at the LHC
- However, over a sizable region of the MSSM parameter space, this state (the lightest MSSM Higgs field) is degenerate with the SM field: we may not be able to distinguish a standard from a SUSY Higgs model at the LHC !
- These conclusions are however based on a decoupled MSSM, wherein SUSY objects are much heavier that the Higgs states (and SM matter)
- This is no longer true if the mass scale of SUSY is low (≤ 1 TeV)
- If Higgs-sparticle interactions are allowed, a rich phenomenology emerges
- Under these conditions all MSSM Higgs bosons can *potentially* be observed (some rescaling of SM-like channels may be needed)
- Approach so far: optmise yield of clean signatures implies discovery contours not overlayable (i.e., different MSSMs) on usual plane $(M_A, \tan\beta)$
- Need to define SUSY Higgs benchmarks $\longrightarrow$ figure
  (K Jacobs, S Moretti, P Osland et al., in progress)

SUSY benchmark points in m_A tan β plane

⇒Require dedicated study to give suitable set of benchmark points



Snowmass points and slopes: SPS
hep-ph/0202233

Chosen with SUSY space rather than Higgs space in mind.

9 points: 5+1 mSugra, 2 GSMB,
1 AMSB

Only 4 points feature in usual Higgs plane. 1a, 4 (mSUGRA) 7,8 GMSB.

Benchmarks from Carena et al.
Eur. Phys. J. C 26 601 (2003) not designed to take light SUSY particle effects into account, except in stop loops (gluo-phobic Higgs scenario)