# Supersymmetric extensions of the Standard Model

## (Lecture 2 of 4)

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Hadron Collider Physics Summer School
Fermilab, August 2010

## Outline

Lecture 1: Introducing SUSY

Lecture 2: SUSY Higgs sectors

Lecture 3: Superpartner spectra and detection

Lecture 4: Measuring couplings, spins, and masses

In the last lecture we saw the two key features of the MSSM that impact Higgs physics:

- There are two Higgs doublets.

- The scalar potential is constrained by the form of the supersymmetric Lagrangian.

Let's start with a closer look at each of these.

## The MSSM requires two Higgs doublets
## Reason #1: generating quark masses

The SM Higgs doublet is $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, with $\langle \phi^0 \rangle = v/\sqrt{2}$.

Generate the down-type quark masses:

$$\begin{aligned}
\mathcal{L}_{\text{Yuk}} &= -y_d \, \bar{d}_R \Phi^\dagger Q_L + \text{h.c.} \\
&= -y_d \, \bar{d}_R \left(\phi^-, \phi^{0*}\right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \text{h.c.} \\
&= -y_d \frac{v}{\sqrt{2}} \left(\bar{d}_R d_L + \bar{d}_L d_R\right) + \text{interactions} \\
&= -m_d \, \bar{d} d + \text{interactions}
\end{aligned}$$

Generate the up-type quark masses:

$$\mathcal{L}_{\text{Yuk}} = -y_u \, \bar{u}_R \Phi^\dagger Q_L + \text{h.c.?}$$

Does not work! Need to put the vev in the upper component of the Higgs doublet.

Can sort this out by using the conjugate doublet $\tilde{\Phi}$:

[not to be confused with a superpartner....]

$$\tilde{\Phi} \equiv i\sigma_2 \Phi^* = i \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} \phi^- \\ \phi^{0*} \end{pmatrix} = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= -y_u \bar{u}_R \tilde{\Phi}^\dagger Q_L + \text{h.c.} \\ &= -y_u \bar{u}_R \left(\phi^0, -\phi^+\right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \text{h.c.} \\ &= -y_u \frac{v}{\sqrt{2}} (\bar{u}_R u_L + \bar{u}_L u_R) + \text{interactions} \\ &= -m_u \bar{u} u + \text{interactions} \end{aligned}$$

Works fine in the SM!

But in SUSY we can't do this, because $\mathcal{L}_{\text{Yuk}}$ comes from $-\frac{1}{2} W^{ij} \psi_i \psi_j + \text{c.c.}$ with $W^{ij} = M^{ij} + y^{ijk} \phi_k$.

$W$ must be analytic in $\phi$
$\longrightarrow$ not allowed to use complex conjugates.

Instead, need a second Higgs doublet with opposite hypercharge:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= -y_d \, \bar{d}_R \, \epsilon_{ij} H_1^i Q_L^j - y_u \, \bar{u}_R \, \epsilon_{ij} H_2^i Q_L^j + \text{h.c.} \qquad \text{ok!} \\ &= -y_d \frac{v_1}{\sqrt{2}} \bar{d} d - y_u \frac{v_2}{\sqrt{2}} \bar{u} u + \text{interactions} \end{aligned}$$

[lepton masses work just like down-type quarks]

Two important features:

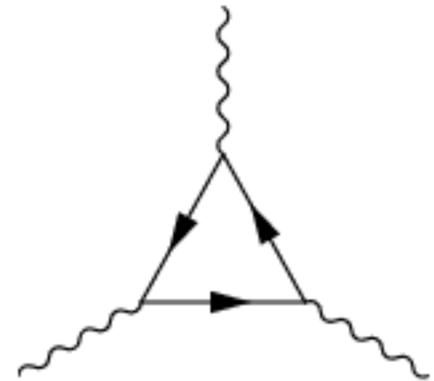
- Both doublets contribute to the $W$ mass, so need $v_1^2 + v_2^2 = v_{\text{SM}}^2$.
Ratio of vevs is not constrained; define parameter $\tan\beta \equiv v_2/v_1$.

- $\tan\beta$ shows up in couplings when $y_i$ are re-expressed in terms of fermion masses.

$$y_d = \frac{\sqrt{2} m_d}{v \cos\beta} \qquad y_u = \frac{\sqrt{2} m_u}{v \sin\beta} \qquad y_\ell = \frac{\sqrt{2} m_\ell}{v \cos\beta}$$

The MSSM requires two Higgs doublets
Reason #2: anomaly cancellation

Chiral fermions (where the left-handed and right-handed fermions have different couplings) can cause chiral anomalies. anomaly diagram $\rightarrow$



Breaks the gauge symmetry—generally very bad.

Standard Model: chiral anomalies all miraculously cancel within one fermion generation:

pure hypercharge : $\sum_{\text{all } f} Y_f^3 = 0$

hypercharge and QCD : $\sum_{\text{all } q} Y_q = 0$

hypercharge and SU(2) : $\sum_{\text{weak doublets}} Y_d = 0$

Higgs has no effect on this since it's not a chiral fermion.

Supersymmetric models: Higgs is now part of a chiral supermultiplet. Paired up with chiral fermions! (Higgsinos)

The Higgsinos contribute to the chiral anomalies.

One Higgs doublet: carries hypercharge and SU(2) quantum numbers; gives nonzero $Y_f^3$ and $Y_d$ anomalies.

To solve this, introduce a second Higgs doublet with opposite hypercharge: sum of anomalies cancels.

[This is exactly the same as the requirement from generating up and down quark masses.]

MSSM is the minimal supersymmetric extension of the SM.
- Minimal SUSY Higgs sector is 2 doublets.
- More complicated extensions can have larger Higgs content (but must contain an even number of doublets).

## Higgs content of the MSSM

**Standard Model:**

$$\Phi = \begin{pmatrix} \phi^+ \\ (v + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix}$$

- Goldstone bosons $G^+ = \phi^+$, $G^0 = \phi^{0,i}$ "eaten" by $W^+$ and $Z$.
- One physical Higgs state $H^0 = \phi^{0,r}$.

**MSSM:**

$$H_1 = \begin{pmatrix} (v_1 + \phi_1^{0,r} + i\phi_1^{0,i})/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \phi_2^{0,r} + i\phi_2^{0,i})/\sqrt{2} \end{pmatrix}$$

$\tan\beta \equiv v_2/v_1$

- Still have one charged and one neutral Goldstone boson:

$$G^+ = -\cos\beta\,\phi_1^{-*} + \sin\beta\,\phi_2^+ \qquad G^0 = -\cos\beta\,\phi_1^{0,i} + \sin\beta\,\phi_2^{0,i}$$

- Orthogonal combinations are physical particles: [mixing angle $\beta$]

$$H^+ = \sin\beta\,\phi_1^{-*} + \cos\beta\,\phi_2^+ \qquad A^0 = \sin\beta\,\phi_1^{0,i} + \cos\beta\,\phi_2^{0,i}$$

- Two CP-even neutral physical states mix: [mixing angle $\alpha$]

$$h^0 = -\sin\alpha\,\phi_1^{0,r} + \cos\alpha\,\phi_2^{0,r} \qquad H^0 = \cos\alpha\,\phi_1^{0,r} + \sin\alpha\,\phi_2^{0,r}$$

What are these physical states?

Masses and mixing angles are determined by the Higgs potential.

For the most general two-Higgs-doublet model:

$$\begin{aligned}\mathcal{V} \;=\; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] \\ & +\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},\end{aligned}$$

from Haber & Davidson, PRD72, 035004 (2005)

MSSM is much more constrained, because of supersymmetry.

Supersymmetric part:

$$\mathcal{L} \supset -W_i^* W_i - \frac{1}{2}\sum_a g_a^2(\phi^* T^a \phi)^2$$

recall $W^i = M^{ij}\phi_j + \frac{1}{2}y^{ijk}\phi_j\phi_k$

The only relevant part of the superpotential is $W = \mu H_1 H_2$.
The rest of the SUSY-obeying potential comes from the D (gauge) terms, $V \supset \frac{1}{2}\sum_a g_a^2(\phi^* T^a \phi)^2$.

$$V_{\rm SUSY} = |\mu|^2 H_1^\dagger H_1 + |\mu|^2 H_2^\dagger H_2 + \frac{1}{8} g'^2 \left(H_2^\dagger H_2 - H_1^\dagger H_1\right)^2 + \frac{1}{8} g^2 \left(H_1^\dagger \sigma^a H_1 + H_2^\dagger \sigma^a H_2\right)^2$$

Note only one unknown parameter, $|\mu|^2$! ($g$, $g'$ are measured.)

But there is also SUSY breaking, which contributes three new quadratic terms:

$$V_{\rm breaking} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + \left[b\,\epsilon_{ij} H_2^i H_1^j + \text{h.c.}\right]$$

Three more unknown parameters, $m_{H_1}^2$, $m_{H_2}^2$, and $b$.

Combining and multiplying everything out yields the MSSM Higgs potential, at tree level:

$$\begin{aligned} V &= (|\mu|^2 + m_{H_1}^2)\left(|H_1^0|^2 + |H_1^-|^2\right) + (|\mu|^2 + m_{H_2}^2)\left(|H_2^0|^2 + |H_2^+|^2\right) \\ &\quad + \left[b\,(H_2^+ H_1^- - H_2^0 H_1^0) + \text{h.c.}\right] \\ &\quad + \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_2^0|^2 + |H_2^+|^2 - |H_1^0|^2 - |H_1^-|^2\right)^2 \\ &\quad + \frac{1}{2} g^2 \left|H_2^+ H_1^{0*} + H_2^0 H_1^{-*}\right|^2 \end{aligned}$$

Dimensionful terms: $(|\mu|^2 + m_{H_{1,2}}^2)$, $b$ set the mass-squared scale.

$\mu$ terms come from F-terms: SUSY-preserving

$m_{H_{1,2}}^2$ and $b$ terms come directly from soft SUSY breaking

Dimensionless terms: fixed by the gauge couplings $g$ and $g'$

D-term contributions: SUSY-preserving

Three relevant unknown parameter combinations:
$(|\mu|^2 + m_{H_1}^2)$, $(|\mu|^2 + m_{H_2}^2)$, and $b$.

[All this is tree-level: it will get modified by radiative corrections.]

The scalar potential fixes the vacuum expectation values, mass eigenstates, and 3– and 4–Higgs couplings.

Step 1: Find the minimum of the potential using $\frac{\partial V}{\partial H_i} = 0$.
This lets you solve for $v_1$ and $v_2$ in terms of the Higgs potential parameters. Usually use these relations to eliminate $(|\mu|^2 + m_{H_1}^2)$ and $(|\mu|^2 + m_{H_2}^2)$ in favor of the vevs.

[Eliminate one unknown: $v_1^2 + v_2^2 = v_{\rm SM}^2$.]

Step 2: Plug in the vevs and collect terms quadratic in the fields. These are the mass terms (and generically include crossed terms like $H_1^+ H_2^-$). Write these as $M_{ij}^2 \phi_i \phi_j$ and diagonalize the mass-squared matrices to find the mass eigenstates.

## Results: Higgs masses and mixing angle

[Only 2 unknowns: $\tan\beta$ and $M_{A^0}$.]

$$M^2_{A^0} = \frac{2b}{\sin 2\beta} \qquad\qquad M^2_{H^\pm} = M^2_{A^0} + M^2_W$$

$$M^2_{h^0,H^0} = \frac{1}{2}\left(M^2_{A^0} + M^2_Z \mp \sqrt{(M^2_{A^0} + M^2_Z)^2 - 4M^2_Z M^2_{A^0}\cos^2 2\beta}\right)$$

[By convention, $h^0$ is lighter than $H^0$]

Mixing angle for $h^0$ and $H^0$:

$$\frac{\sin 2\alpha}{\sin 2\beta} = -\frac{M^2_{A^0} + M^2_Z}{M^2_{H^0} - M^2_{h^0}} \qquad\qquad \frac{\cos 2\alpha}{\cos 2\beta} = -\frac{M^2_{A^0} - M^2_Z}{M^2_{H^0} - M^2_{h^0}}$$

[Note $M^2_W = g^2v^2/4$ and $M^2_Z = (g^2 + g'^2)v^2/4$: these come from the $g^2$ and $g'^2$ terms in the scalar potential.]

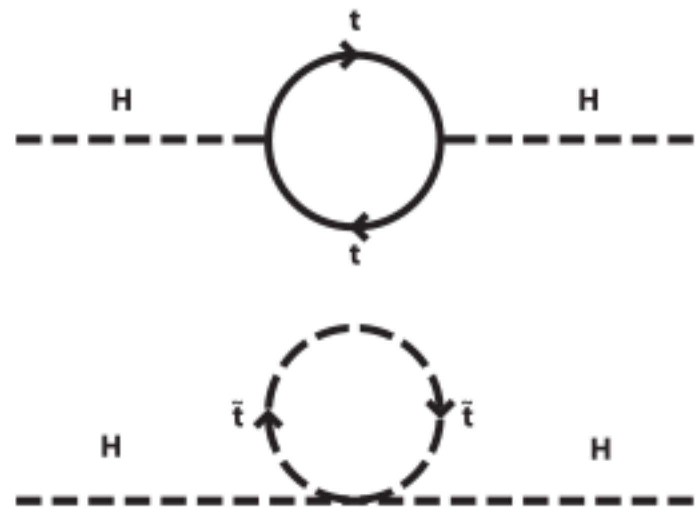
- $A^0$, $H^0$ and $H^\pm$ masses can be arbitrarily large: grow with $\frac{2b}{\sin 2\beta}$.
- $h^0$ mass is bounded from above: $M_{h^0} < |\cos 2\beta| M_Z \leq M_Z$ (!!)

This is already ruled out by LEP! The MSSM would be dead if not for the large radiative corrections to $M_{h^0}$.

Mass matrix for $\phi^{0,r}_{1,2}$:

$$\mathcal{M}^2 = \begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

Radiative corrections come mostly from the top and stop loops.




New mass matrix:

$$\mathcal{M}^2 = \mathcal{M}^2_{\text{tree}} + \begin{pmatrix} \Delta\mathcal{M}^2_{11} & \Delta\mathcal{M}^2_{12} \\ \Delta\mathcal{M}^2_{21} & \Delta\mathcal{M}^2_{22} \end{pmatrix}$$

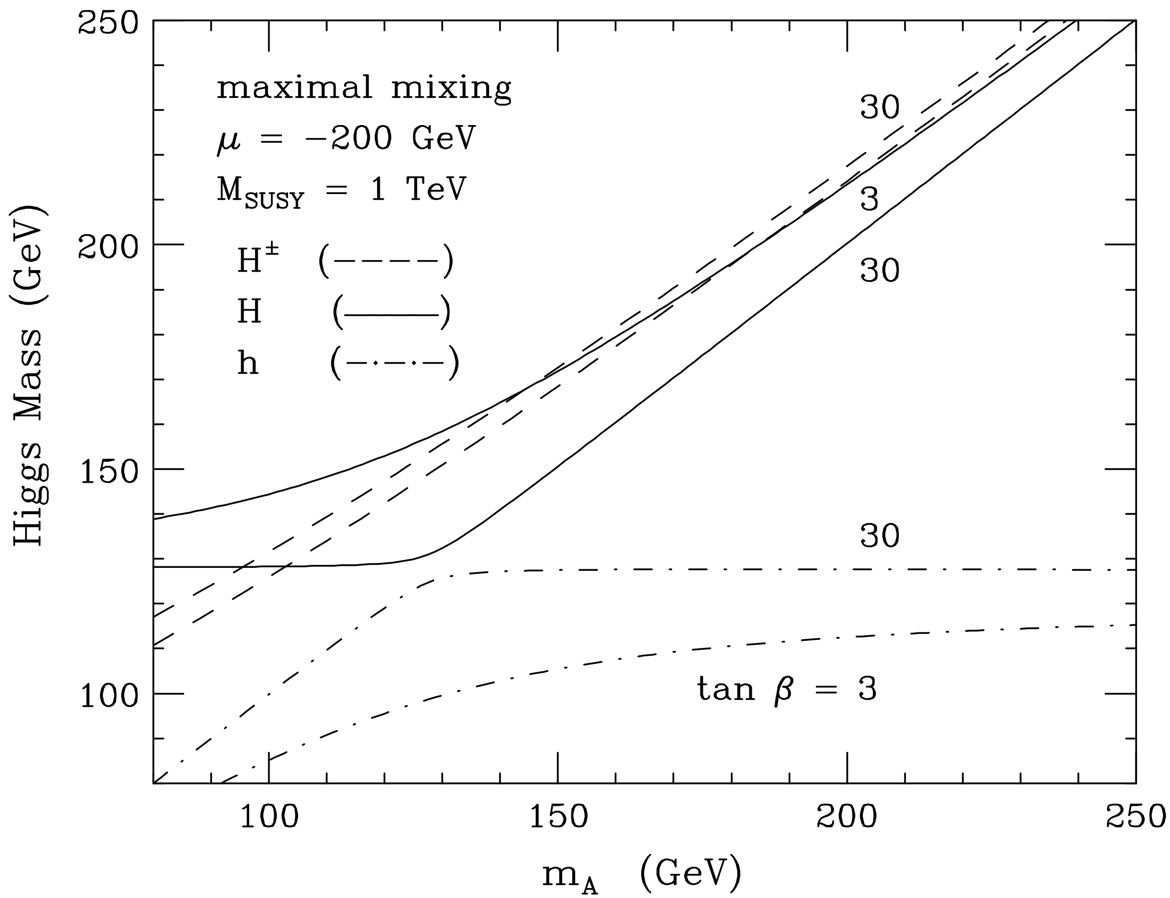
Have to re-diagonalize.

Leading correction to $M_{h^0}$:

$$\Delta M^2_{h^0} \simeq \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \; \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

Revised bound (full 1-loop + dominant 2-loop): $M_{h^0} \lesssim 135$ GeV.

Higgs masses as a function of $M_A$ [for $\tan\beta$ small (3) and large (30)]




from Carena & Haber, hep-ph/0208209

For large $M_A$:

- $M_h$ asymptotes
- $M_{H^0}$ and $M_{H^+}$ become increasingly degenerate with $M_A$

## Higgs couplings

Higgs couplings to fermions are controlled by the Yukawa Lagrangian,

$$\mathcal{L}_{\text{Yuk}} = -y_\ell \, \bar{e}_R \epsilon_{ij} H_1^i L_L^j - y_d \, \bar{d}_R \, \epsilon_{ij} H_1^i Q_L^j - y_u \, \bar{u}_R \, \epsilon_{ij} H_2^i Q_L^j + \text{h.c.}$$

$\tan\beta$-dependence shows up in couplings when $y_i$ are re-expressed in terms of fermion masses:

$$y_\ell = \frac{\sqrt{2} m_\ell}{v \cos\beta} \qquad y_d = \frac{\sqrt{2} m_d}{v \cos\beta} \qquad y_u = \frac{\sqrt{2} m_u}{v \sin\beta}$$

Higgs couplings to gauge bosons are controlled by the SU(2) structure.

Plugging in the mass eigenstates gives the actual couplings.

## Couplings of $h^0$ (the light Higgs)

$$\begin{aligned}
h^0W^+W^- &: \quad igM_W g_{\mu\nu} \sin(\beta-\alpha) \\
h^0ZZ &: \quad i\frac{gM_Z}{\cos\theta_W} g_{\mu\nu} \sin(\beta-\alpha) \\
h^0\bar{t}t &: \quad i\frac{gm_t}{2M_W}\left[\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\right] \\
h^0\bar{b}b &: \quad i\frac{gm_b}{2M_W}\left[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\right]
\end{aligned}$$

[$h^0\ell^+\ell^-$ coupling has same form as $h^0\bar{b}b$]

Controlled by $\tan\beta$ and the mixing angle $\alpha$.

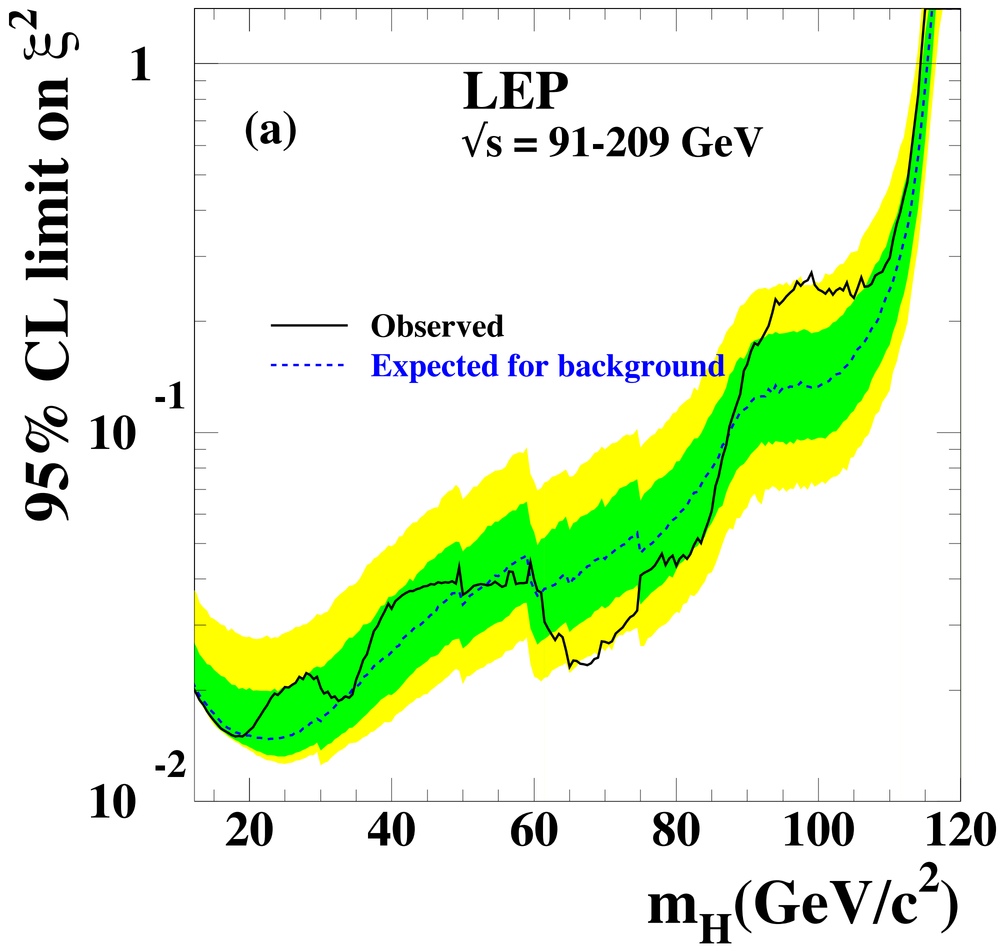
In the "decoupling limit" $M_{A^0} \gg M_Z$, $\cos(\beta-\alpha)$ goes to zero:

$$\cos(\beta-\alpha) \simeq \frac{1}{2}\sin 4\beta \frac{M_Z^2}{M_{A^0}^2}$$

Then all the $h^0$ couplings approach their SM values!

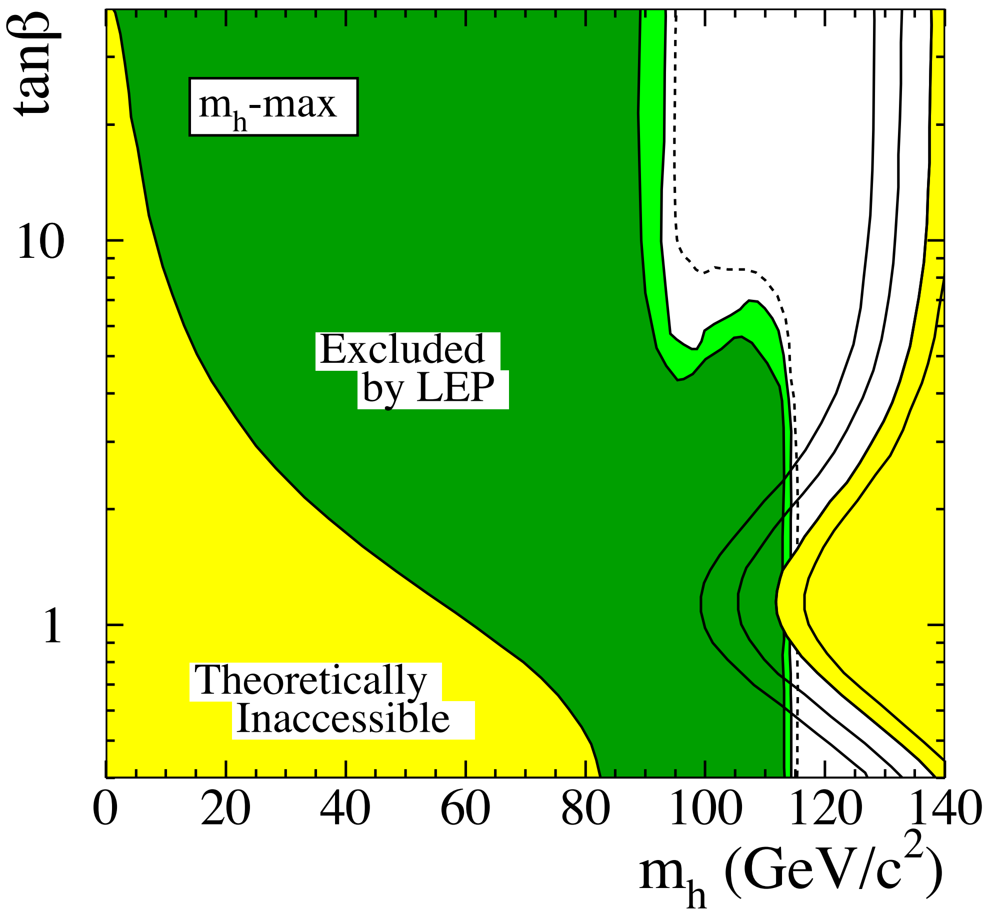
## LEP searches for $h^0$

$e^+e^- \to Z^* \to Zh^0$: coupling $\frac{igM_Z}{\cos\theta_W} g_{\mu\nu} \sin(\beta - \alpha)$
- Production can be suppressed compared to SM Higgs



# LEP searches for $h^0$

$e^+e^- \to Z^* \to h^0 A^0$: coupling $\propto \cos(\beta - \alpha)$
- Complementary to $Zh^0$
- Combine searches for overall MSSM exclusion



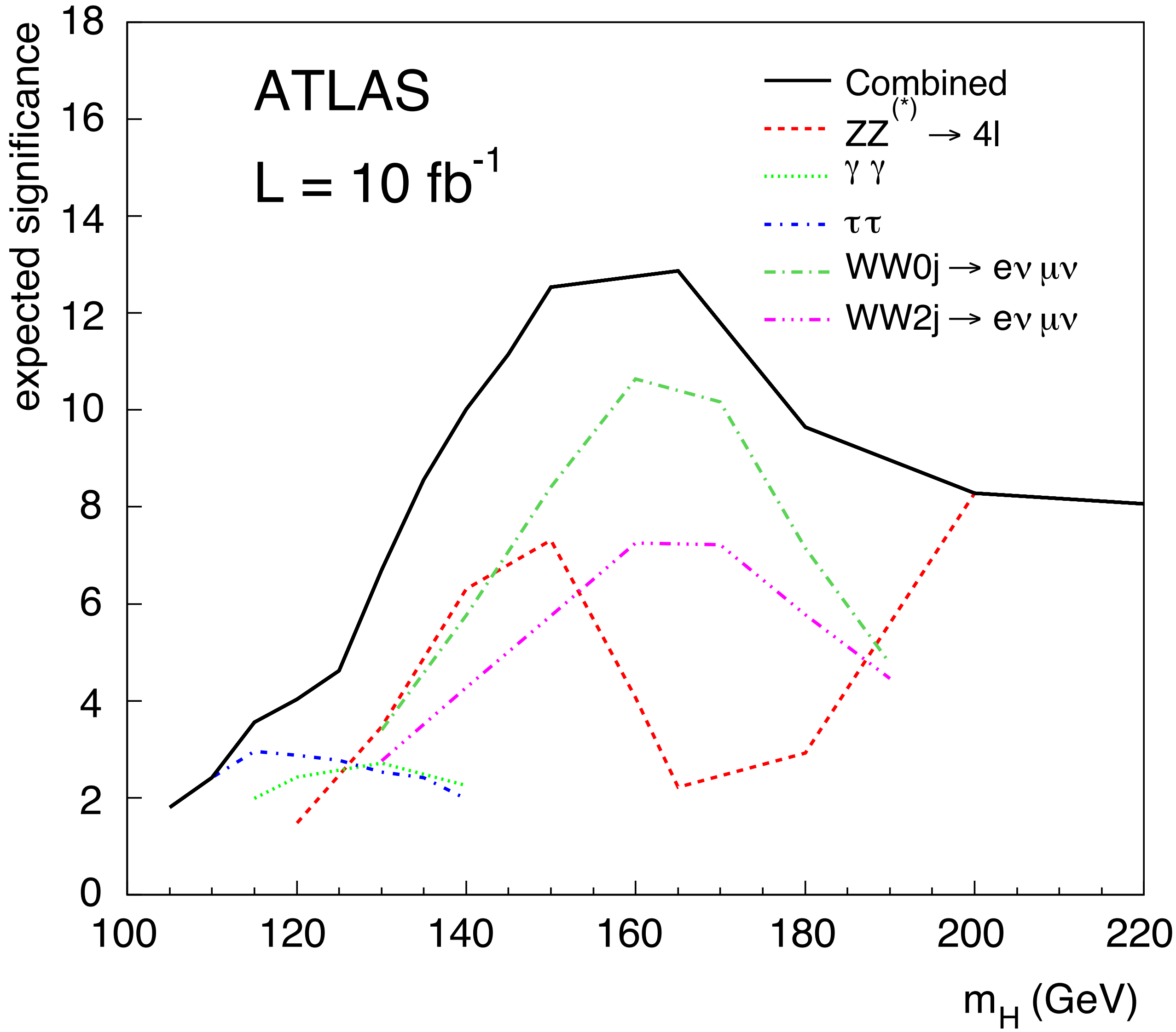
## LHC searches for $h^0$

Decoupling limit
(large $M_{A^0}$):

- $h^0$ search basically the same as SM Higgs search

- Mass $\lesssim$ 135 GeV: lower-mass search channels most important

- Challenging channels




SM Higgs significance, ATLAS CSC book, arXiv:0901.0512

## Couplings of $H^0$ and $A^0$

$$H^0W^+W^- \; : \; igM_W g_{\mu\nu} \cos(\beta - \alpha)$$

$$H^0ZZ \; : \; i\frac{gM_Z}{\cos\theta_W} g_{\mu\nu} \cos(\beta - \alpha)$$

$$H^0\bar{t}t \; : \; i\frac{gm_t}{2M_W}\left[-\cot\beta \sin(\beta - \alpha) + \cos(\beta - \alpha)\right]$$

$$H^0\bar{b}b \; : \; i\frac{gm_b}{2M_W}\left[\tan\beta \sin(\beta - \alpha) + \cos(\beta - \alpha)\right]$$

$$A^0\bar{t}t \; : \; \frac{gm_t}{2M_W}\cot\beta\gamma^5 \qquad A^0\bar{b}b \; : \; \frac{gm_b}{2M_W}\tan\beta\gamma^5$$

Couplings to leptons have same form as $\bar{b}b$.

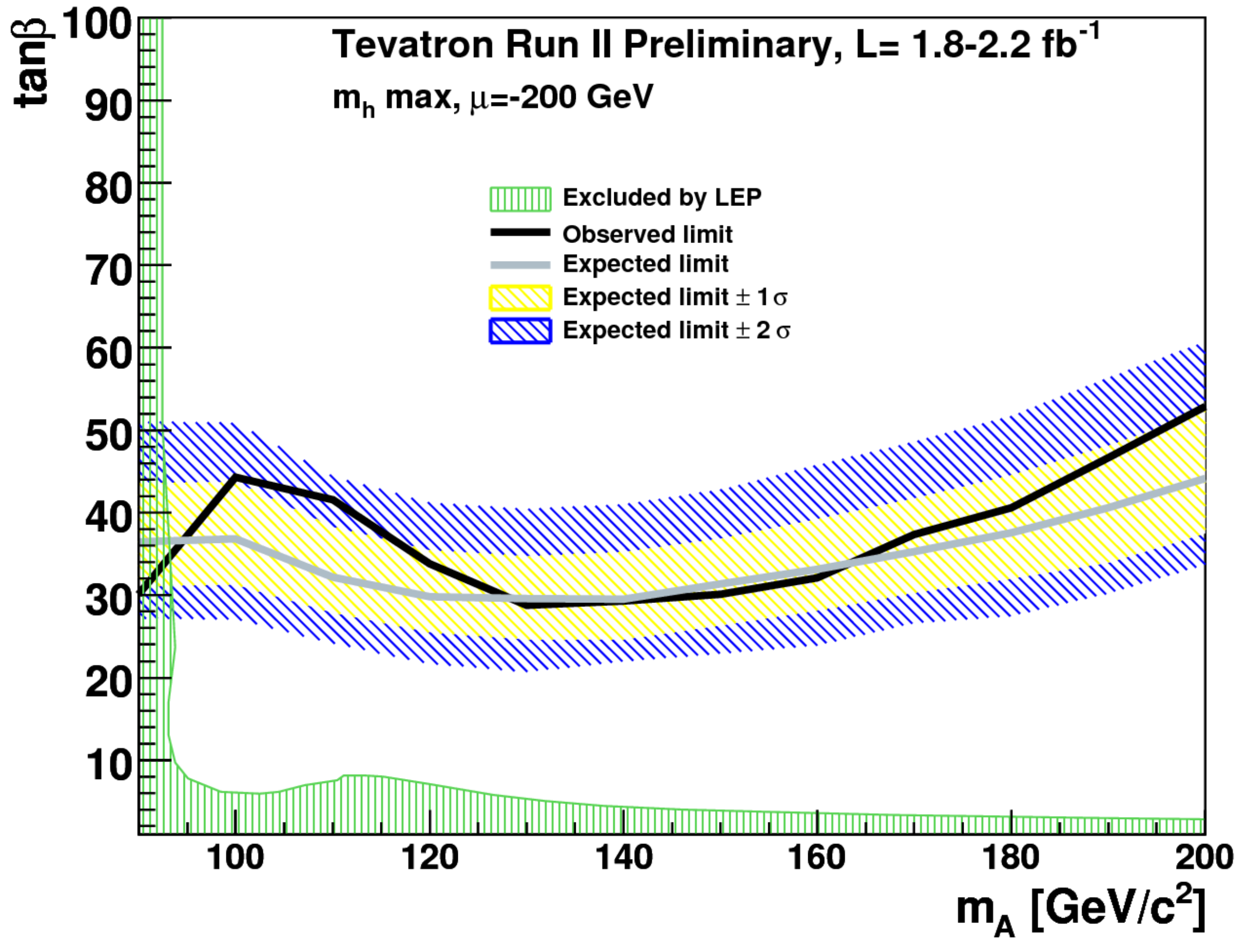
Remember the decoupling limit $\cos(\beta - \alpha) \to 0$:

- $\bar{b}b$ and $\tau\tau$ couplings go like $\tan\beta$: can be strongly enhanced.
- $\bar{t}t$ couplings go like $\cot\beta$: can be strongly suppressed.

Can't enhance $\bar{t}t$ coupling much: perturbativity limit.

## Tevatron searches for $H^0$ and $A^0$

Use $bbH^0$, $bbA^0$ couplings: enhanced at large $\tan\beta$
- $bb \to H^0, A^0$, decays to $\tau\tau$ (most sensitive) or $bb$

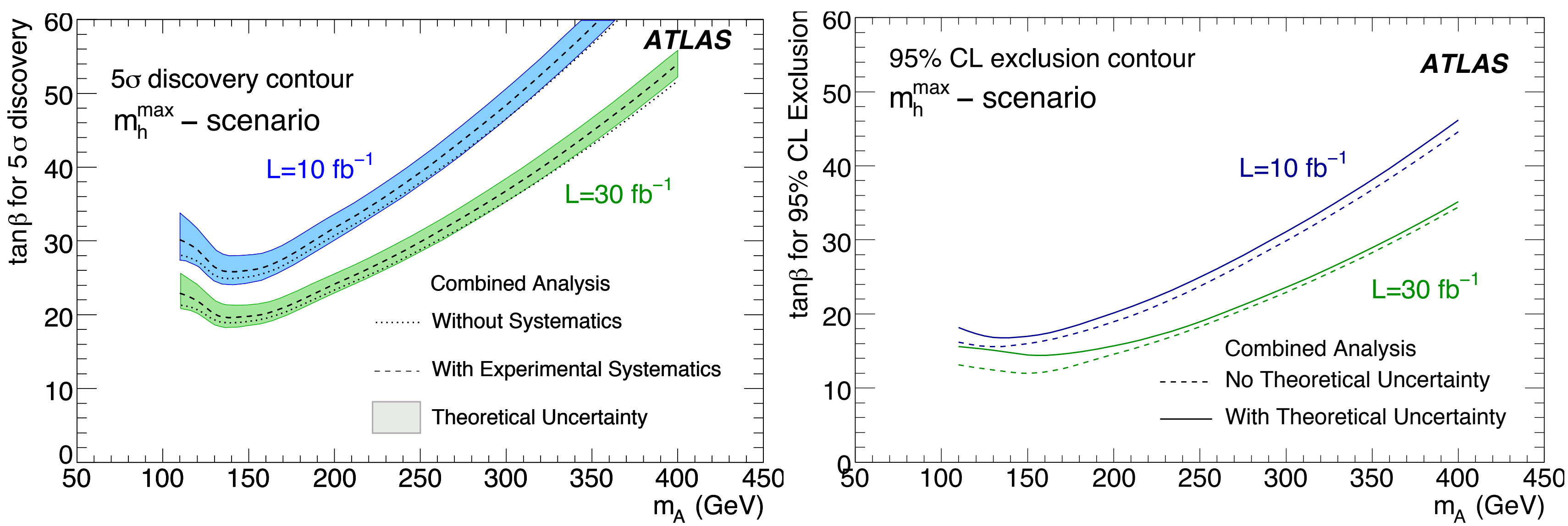



$\tau\tau$ channel, CDF + DZero, arXiv:1003.3363

# LHC searches for $H^0$ and $A^0$

Same idea, higher mass reach because of higher beam energy and luminosity

$bb \to H^0, A^0 \to \mu\mu$ channel: rare decay but great mass resolution!




$\mu\mu$ channel, ATLAS CSC book, arXiv:0901.0512

## Couplings of $H^{\pm}$

$$H^+\tau^-\bar{\nu} \ : \ i\frac{g}{\sqrt{2}M_W}\left[m_\tau \tan\beta P_R\right]$$

Important for decays

$$H^+\bar{t}\,b \ : \ i\frac{g}{\sqrt{2}M_W}V_{tb}\left[m_t \cot\beta P_L + m_b \tan\beta P_R\right]$$

Important for production and decays

$H^+\bar{c}s$ coupling has same form

Couplings to another Higgs and a gauge boson are usual SU(2) form.

$\gamma H^+H^-$, $ZH^+H^-$ — Search for pair production at LEP

$W^+H^-A^0$, $W^+H^-H^0$ — Associated production at LHC

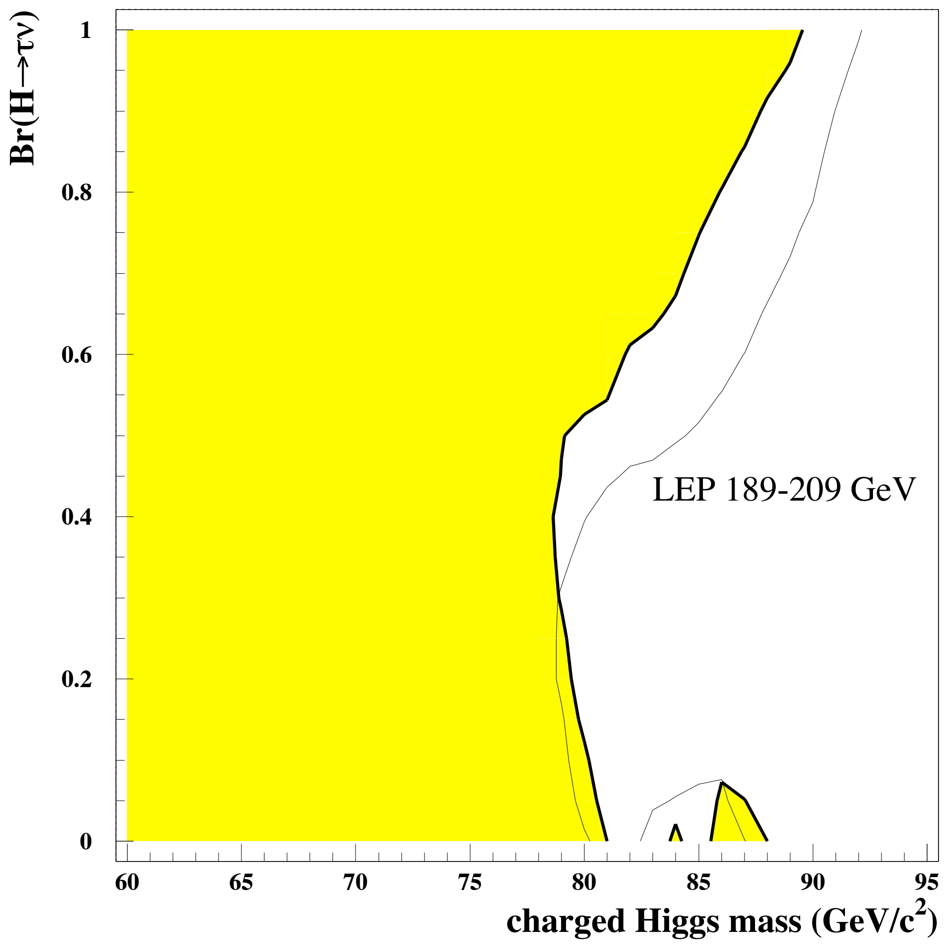
# LEP searches for $H^{\pm}$

$e^+e^- \to \gamma^*, Z^* \to H^+H^-$

$H^{\pm}$ decays to $\tau\nu$ or $cs$
- Assume no other decays

Major background from $W^+W^-$
especially for $H^+ \to cs$

Limit $M_{H^+} > 78.6$–89.6 GeV




LEP combined, hep-ex/0107031

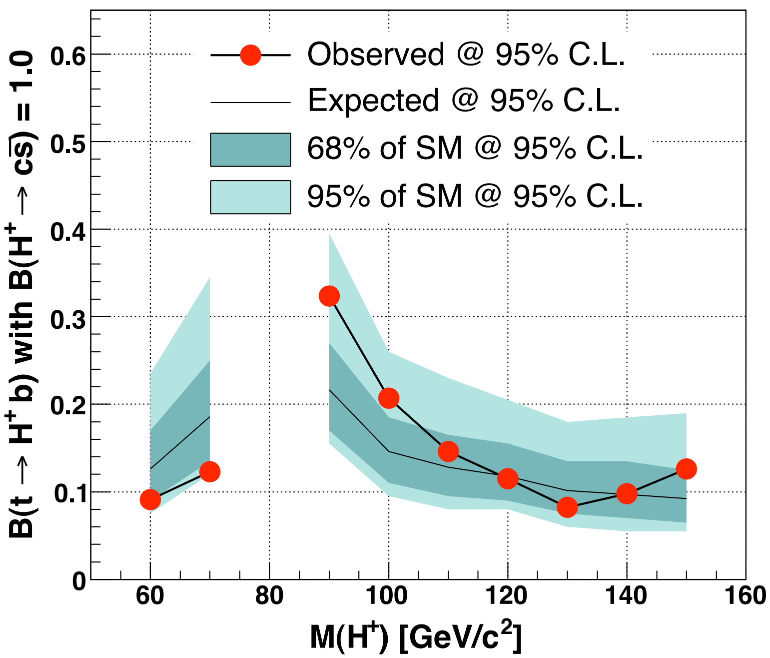
## Tevatron searches for $H^{\pm}$

Look for $t \to H^+ b$.

Coupling $\frac{igV_{tb}}{\sqrt{2}M_W}[m_t \cot\beta P_L + m_b \tan\beta P_R]$

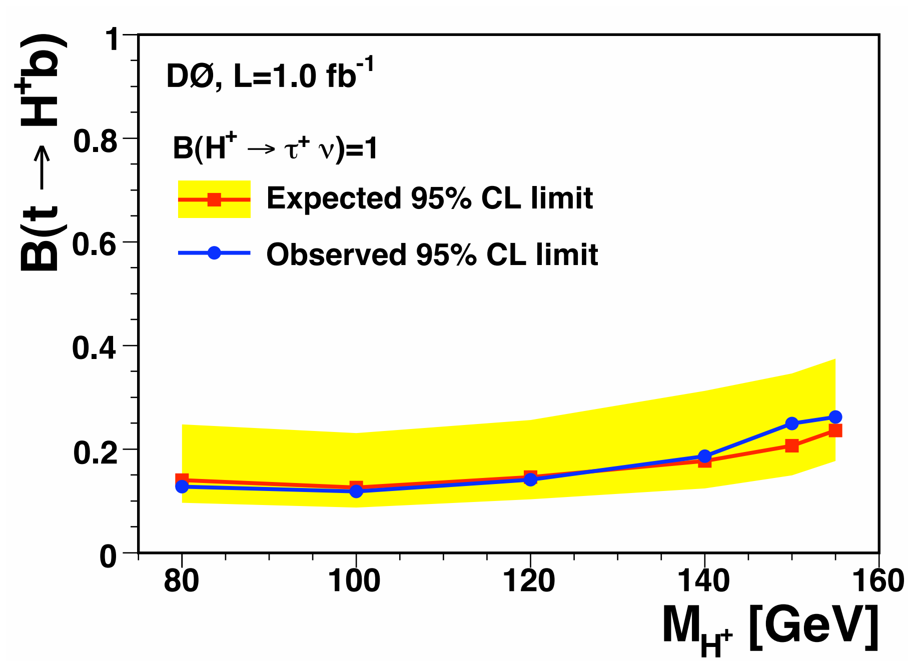
- Sensitive at high and low $\tan\beta$.
- Decays to $\tau\nu$ or $cs$.

BR($H^+ \to c\bar{s}$) = 1:
Look for $M_{jj} \neq M_W$.




CDF, PRL103, 101803 (2009)

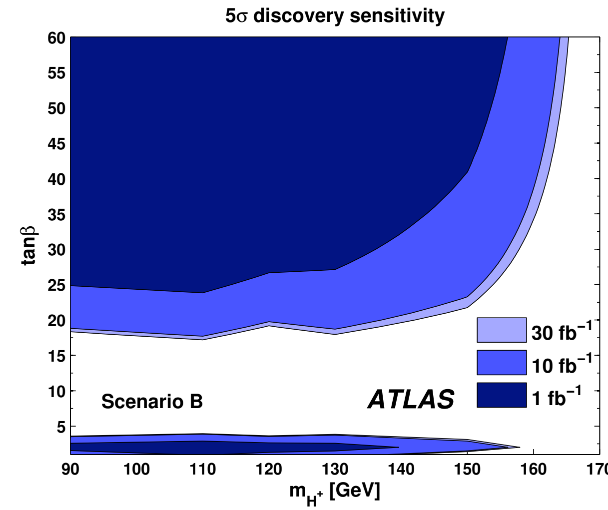
BR($H^+ \to \tau\nu$) > 0:
Look at final-state fractions.




DZero, arXiv:0908.1811

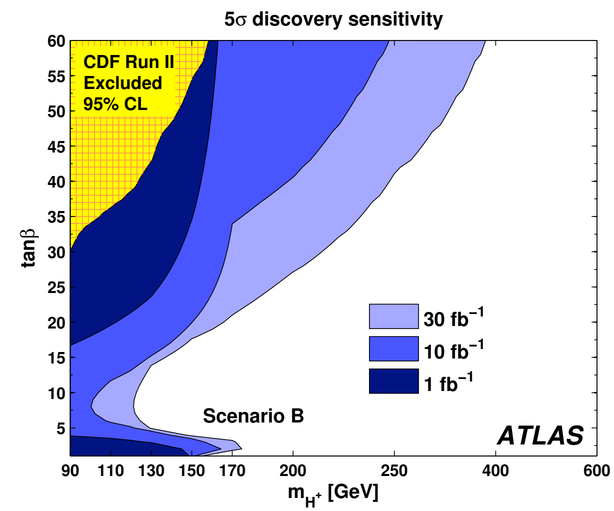
# LHC searches for $H^\pm$

Light charged Higgs:
top decay $t \to H^+ b$ with $H^+ \to \tau\nu$.

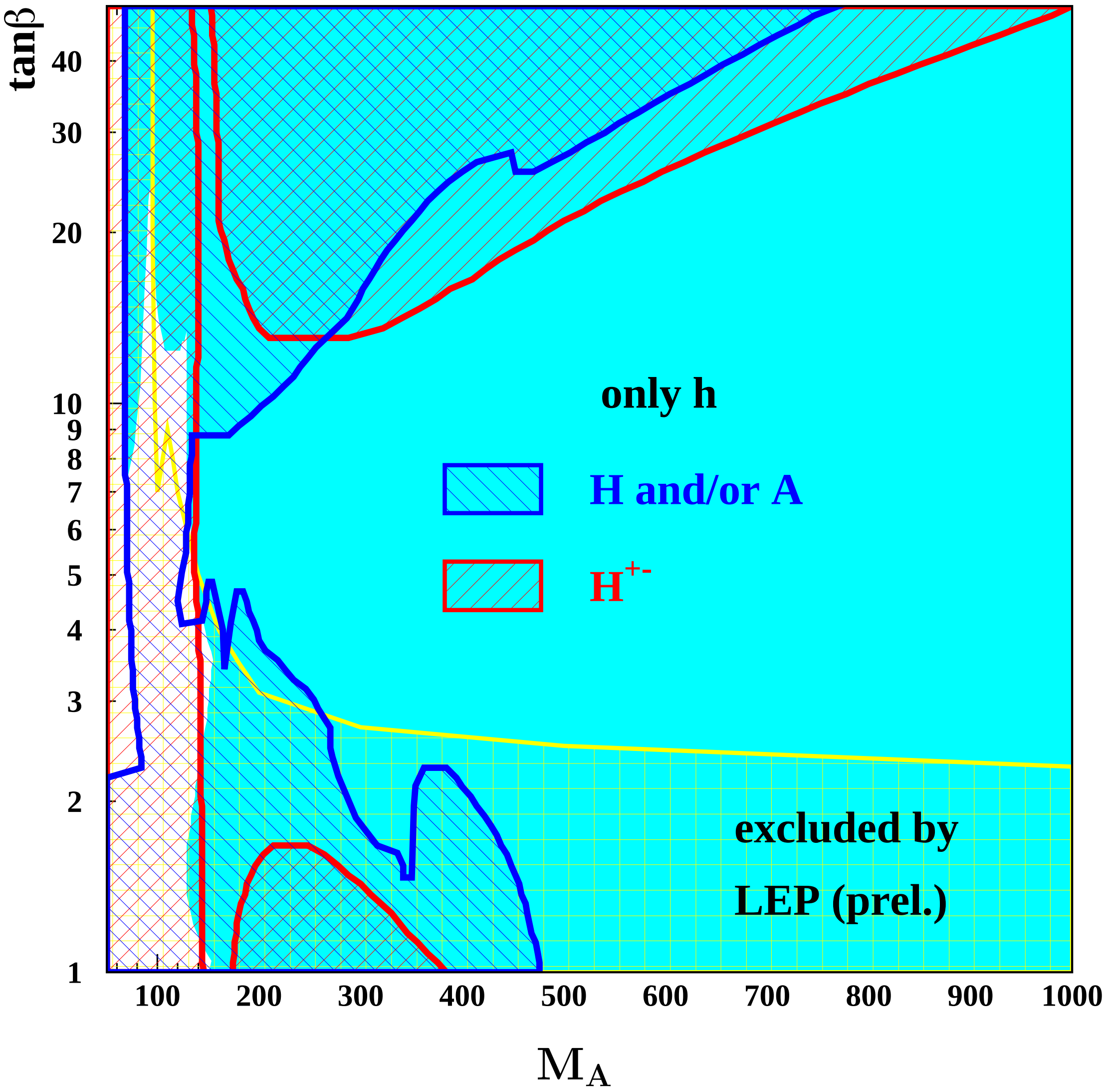



ATLAS CSC book, arXiv:0901.0512

Heavy charged Higgs:
associated production $pp \to t\, H^-$.
most of sensitivity with $H^+ \to \tau\nu$;
$H^+ \to t\bar{b}$ contributes but large background.



# Search for all the MSSM Higgs bosons at LHC




ATLAS, 300 fb$^{-1}$, $m_h^{\rm max}$ scenario. From Haller, hep-ex/0512042

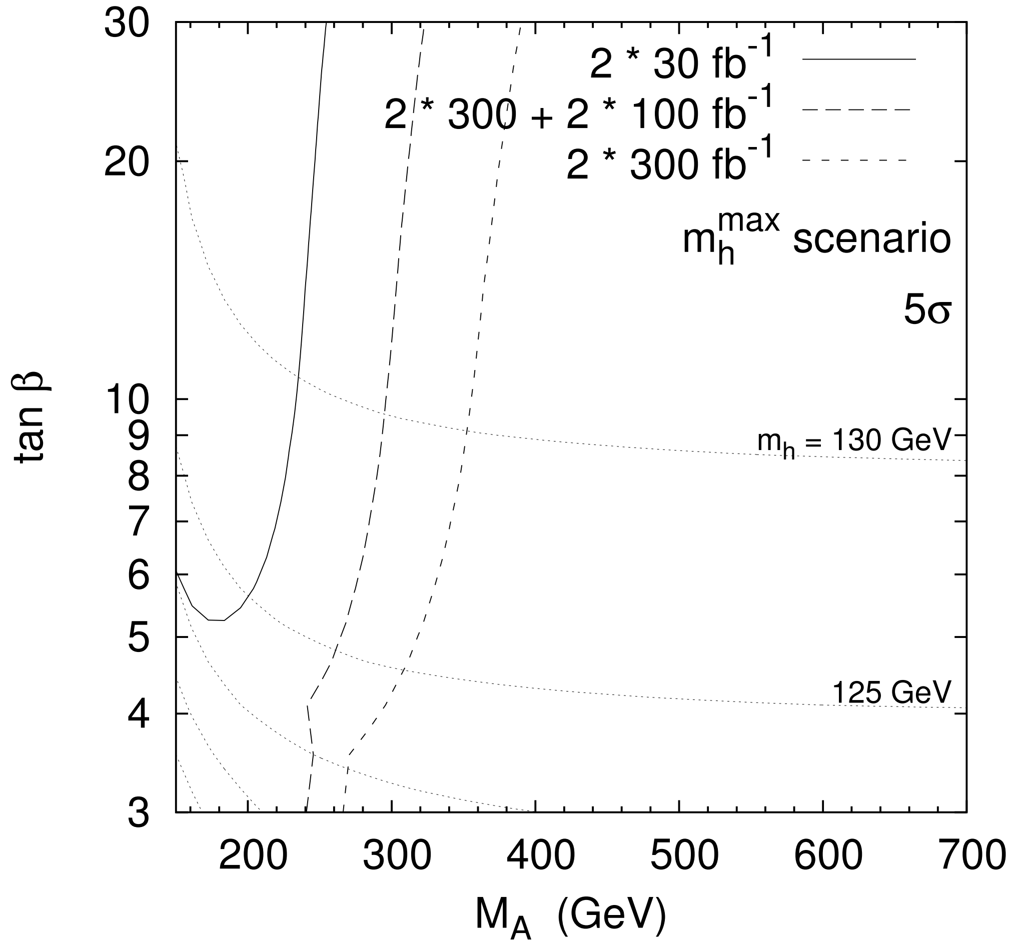
What if only $h^0$ is accessible?

Try to distinguish it from the SM Higgs using coupling measurements.

$$\begin{aligned}
h^0 W^+ W^- &: \; i g M_W g_{\mu\nu} \sin(\beta - \alpha) \\
h^0 ZZ &: \; i \frac{g M_Z}{\cos\theta_W} g_{\mu\nu} \sin(\beta - \alpha) \\
h^0 \bar{t} t &: \; i \frac{g m_t}{2 M_W} \left[\sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)\right] \\
h^0 \bar{b} b &: \; i \frac{g m_b}{2 M_W} \left[\sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha)\right]
\end{aligned}$$

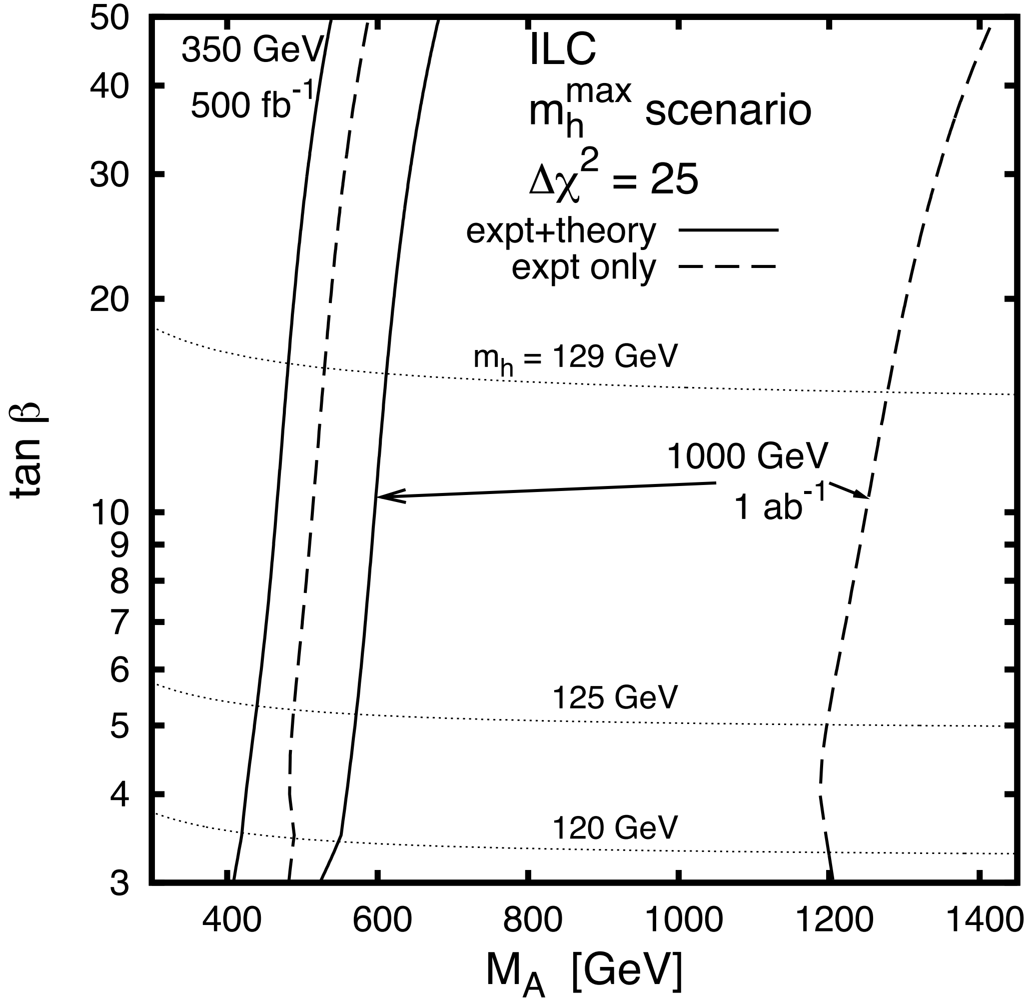
Other couplings:
- $ggh^0$: sensitive to $h^0\bar{t}t$ coupling, top squarks in the loop.
- $h^0\gamma\gamma$: sensitive to $h^0W^+W^-$, $h^0\bar{t}t$, couplings, charginos and top squarks in the loop.

Coupling fit at the LHC:
Look for discrepancies from SM predictions




Dührssen et al, PRD70, 113009 (2004)

Major motivation for ILC: probe $h^0$ couplings with much higher precision.




Logan & Droll, PRD76, 015001 (2007)

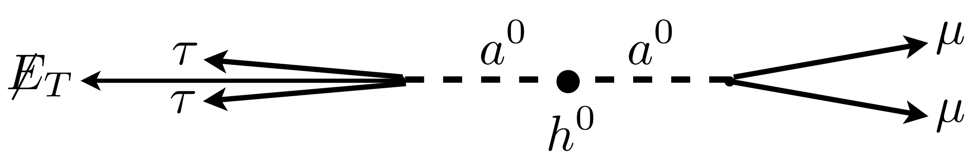
# Going beyond the MSSM

Simplest extension of MSSM is to add an extra Higgs particle.

- NMSSM, nMSSM, MNSSM, etc.

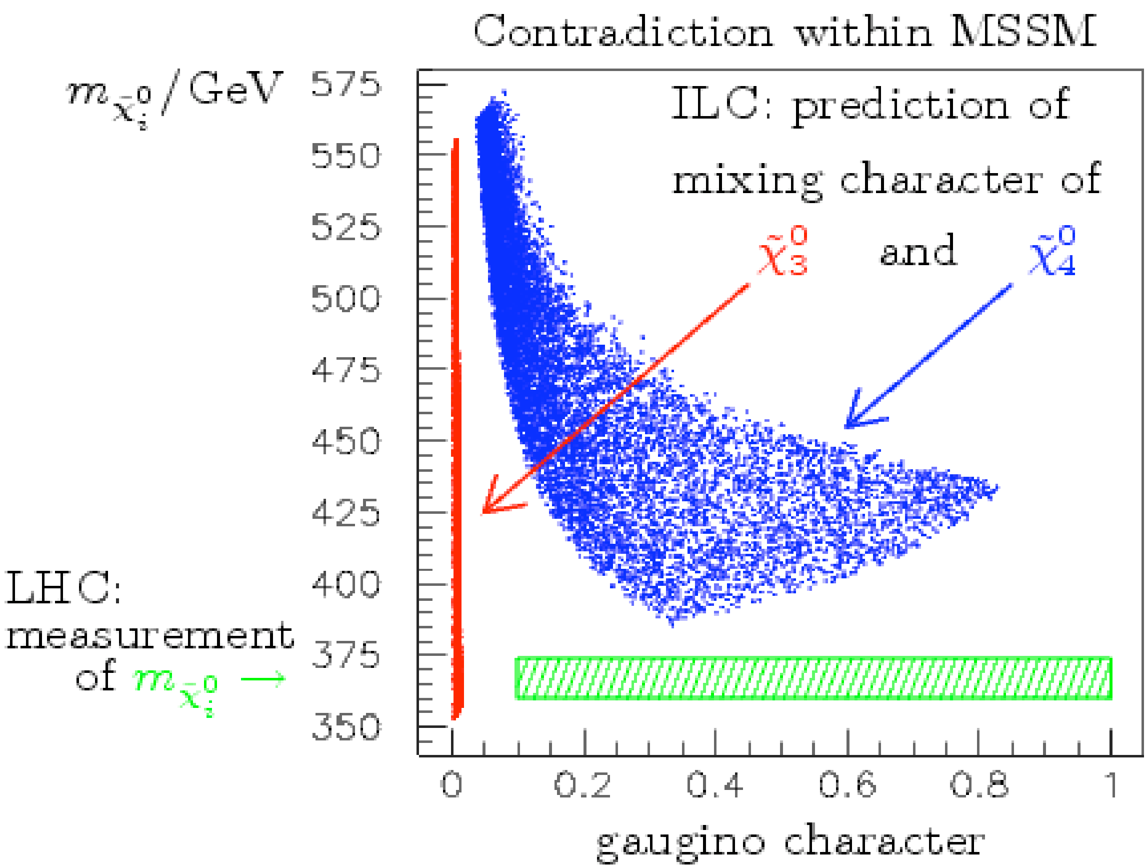
New chiral supermultiplet $S$

- Gives an "extra Higgs"
- Couples only to other Higgses (before mixing): hard to detect, can be quite light
- Exotic decays $h^0 \to ss$
- Decays $s \to \bar{b}b$, $\tau\tau$, $\gamma\gamma$ made possible by mixing




Lisanti & Wacker, PRD79, 115006 (2009)

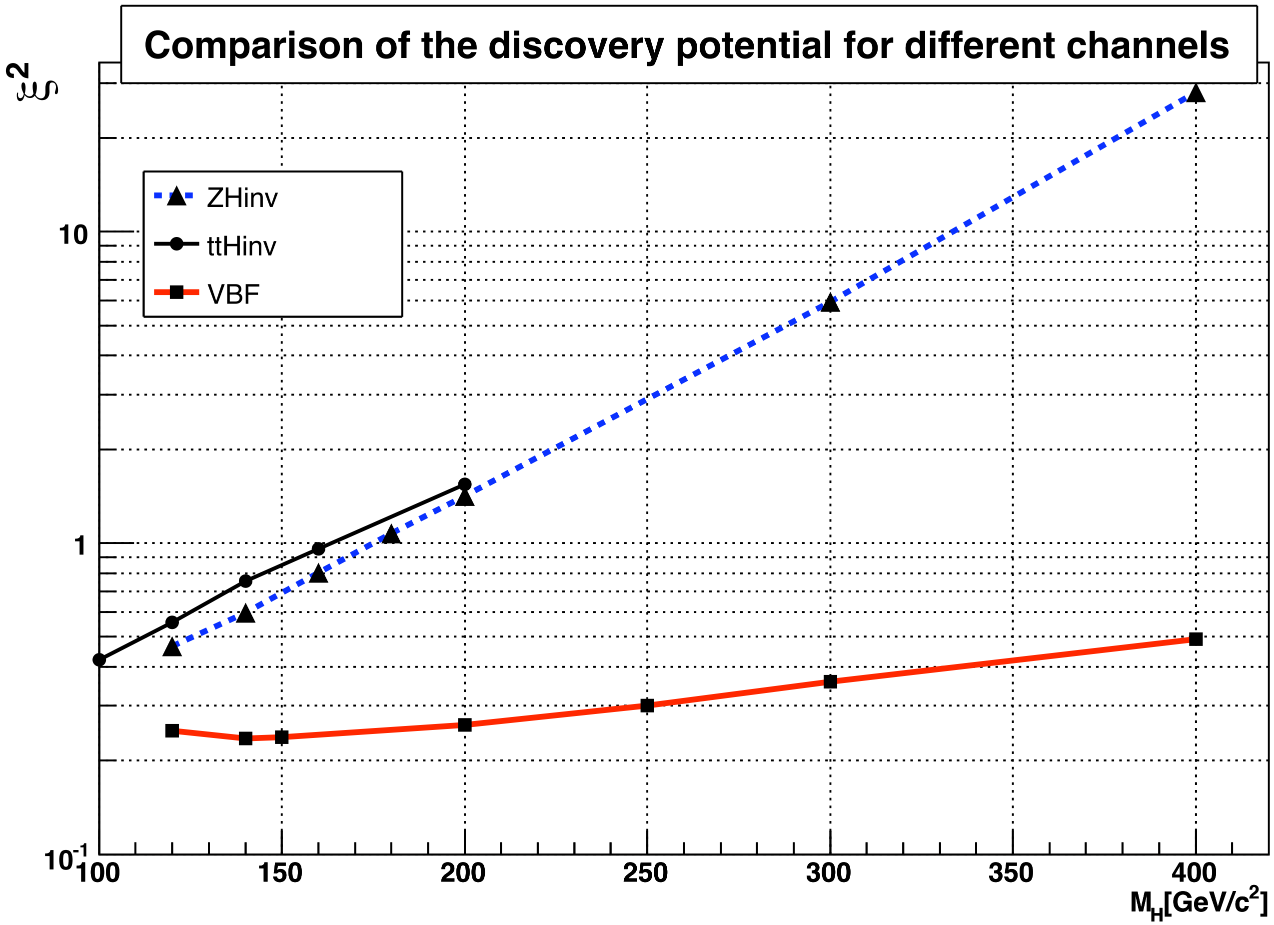
New chiral supermultiplet $S$ also gives an extra neutralino $\tilde{s}$
- Makes the neutralino sector more complicated: may need LHC and ILC synergy to unravel.




Moortgat-Pick et al, hep-ph/0508313

New chiral supermultiplet $S$ also gives an extra neutralino $\tilde{s}$
- Dark matter particle, can be quite light
- Invisible Higgs decay $h^0 \to \tilde{s}\tilde{s}$ if light enough

Plot: ATLAS with 30 fb$^{-1}$. Scaling factor $\xi^2 \sigma_{\rm SM} \equiv \sigma \times {\rm BR}(H \to {\rm invis})$




$ZH_{\rm inv}$ – uses $Z \to \ell^+\ell^-$

VBF looks very good, but not clear how well events can be triggered.

$t\bar{t}H_{\rm inv}$ – may be room for improvement? ATLAS study in progress.

[ATL-PHYS-PUB-2006-009]

## Summary

MSSM Higgs sector has a rich phenomenology

One Higgs boson $h^0$
- Can be very similar to SM Higgs
- Mass is limited by MSSM relations, $\lesssim$ 135 GeV

Set of new Higgs bosons $H^0$, $A^0$, and $H^\pm$
- Can be light or heavy
- Search strategy depends on mass, $\tan\beta$

Beyond the MSSM:
- Usually one more new Higgs
- Can have dramatic effect on Higgs phenomenology