SEARCHING FOR THE HIGGS BOSON

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1850

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- Collider searches for the Higgs
- Is it the SM Higgs boson?
- SUSY & other BSM Higgs sectors

Some recommended references

The Anatomy of electro-weak symmetry breaking. I/II: [SM & MSSM]
Abdelhak Djouadi, hep-ph/0503172 and 0503173.

Electroweak symmetry breaking: The bottom-up approach,
Wolfgang Kilian, Springer Tracts Mod.Phys.198:1-113,2003.

QCD effects in Higgs physics, [Higgs formulae]
Michael Spira, Fortsch.Phys.46:203-284,1998, hep-ph/9705337.

A Supersymmetry primer, Stephen P. Martin, hep-ph/9709356.

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$\boxed{\text{II}}$ strong dynamics – strongly coupled

Technicolor, Extended Technicolor, Walking Technicolor, Stumbling Drunk Technicolor, ...

Topcolor-assisted technicolor (TC2)

BSM Higgs pheno without BSM

BSM deviations to $\lambda, \tilde{\lambda}$ *in SM*

With 1 doublet, only 2 possible D6 operators:

$$\mathcal{O}_1 = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) \qquad \& \qquad \mathcal{O}_2 = -\frac{1}{3}(\Phi^\dagger\Phi)^3$$

for the effective Lagrangian contribution $\mathcal{L}_{6D,\Phi} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2}\mathcal{O}_i \ , \quad f_i > 0$

$\Lambda \sim$ few TeV, otherwise we'd likely the new physics directly at LHC.

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Alternative effective theory for Higgs potential:

$$V_{\text{eff}} = \sum_{n=0} \frac{\lambda_n}{\Lambda^{2n}}\left(|\Phi|^2 - \frac{v^2}{2}\right)^{2+n}$$

so $\mathcal{O}_2$ corresponds to the $n = 1$ term in this expansion

- $\mathcal{O}_2$ modifies v: $\frac{v^2}{2} \approx \frac{v_0^2}{2}\left(1 - \frac{f_2}{4\lambda}\frac{v_0^2}{\Lambda^2}\right)$ where v is what G_F measures
- $\mathcal{O}_1$ modifies kinetic term: $\mathcal{L}_{\text{kin}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}f_1\frac{v^2}{\Lambda^2}\partial_\mu\phi\partial^\mu\phi$

so rescale ϕ to canonically normalize H: $\phi = NH,\, N = 1/\left(1 + f_1\frac{v^2}{\Lambda^2}\right)$

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so rescale ϕ to canonically normalize H: $\phi = NH$, $N = 1/\left(1 + f_1\frac{v^2}{\Lambda^2}\right)$

- Higgs mass altered: $M_H = 2\lambda v^2\left(1 - f_1\frac{v^2}{\Lambda^2} + \frac{f_2}{2\lambda}\frac{v^2}{\Lambda^2}\right)$
- VVH couplings altered:

$$\frac{1}{2}g^2 v\left(1 - \frac{f_1}{2}\frac{v^2}{\Lambda^2}\right)HW_\mu^+W^{-\mu} \qquad \frac{1}{4}g^2\left(1 - f_1\frac{v^2}{\Lambda^2}\right)HHW_\mu^+W^{-\mu}$$

$$\frac{1}{2}\frac{g^2}{c_W}v\left(1 - \frac{f_1}{2}\frac{v^2}{\Lambda^2}\right)HZ_\mu Z^\mu \qquad \frac{1}{4}\frac{g^2}{c_W}\left(1 - f_1\frac{v^2}{\Lambda^2}\right)HHZ_\mu Z^\mu$$

- 3,4-pt. self-couplings modified:

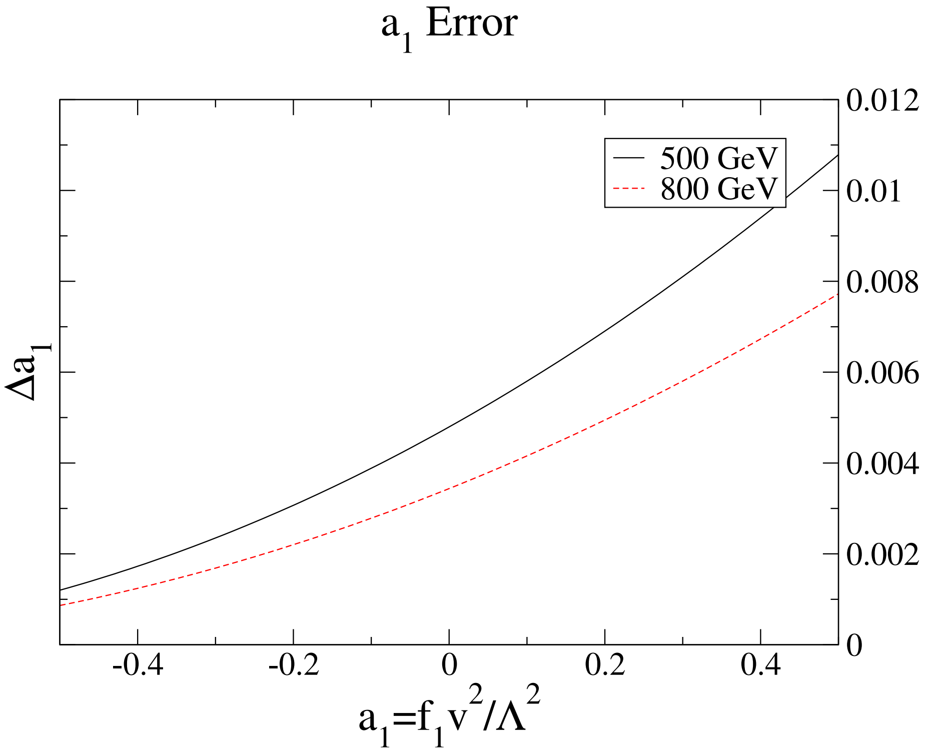
$$\lambda_{3H} = -i\frac{3m_H^2}{v}\left[\left(1 - \frac{f_1}{2}\frac{v^2}{\Lambda^2} + \frac{2f_2}{3}\frac{v^2}{M_H^2}\frac{v^2}{\Lambda^2}\right) + \frac{2f_1}{3M_H^2}\frac{v^2}{\Lambda^2}\sum_{i<j}^{3}p_i\cdot p_j\right]$$

$$\lambda_{4H} = -i\frac{3m_H^2}{v^2}\left[\left(1 - f_1\frac{v^2}{\Lambda^2} + 4f_2\frac{v^2}{M_H^2}\frac{v^2}{\Lambda^2}\right) + \frac{2f_1}{3M_H^2}\frac{v^2}{\Lambda^2}\sum_{i<j}^{4}p_i\cdot p_j\right]$$

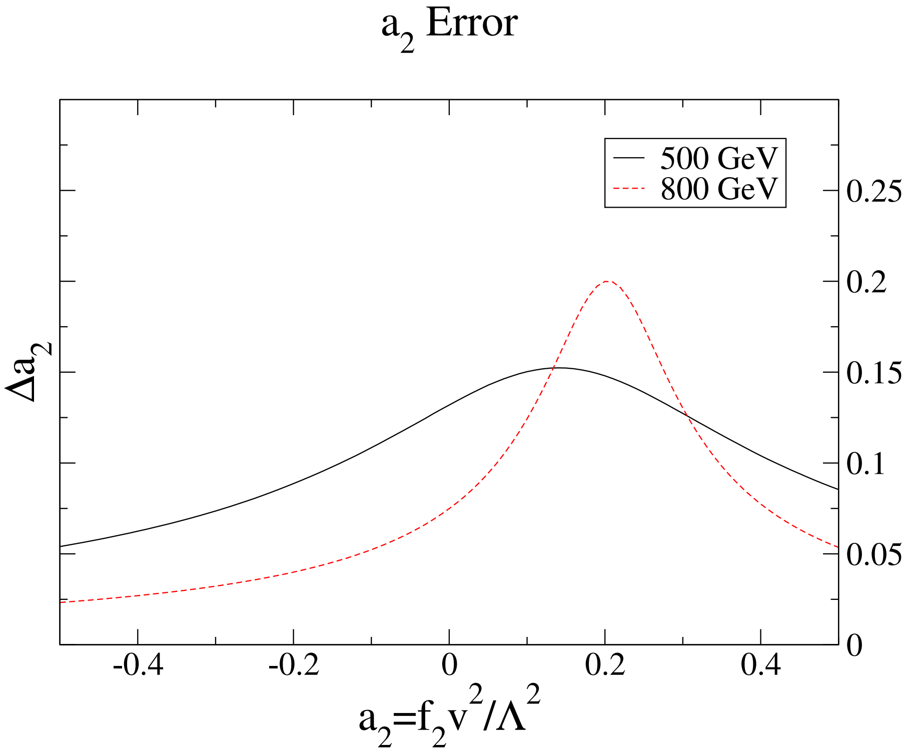
$\longrightarrow$ note momentum dependence from $\mathcal{O}_1$ operator

- phenomenological analyses exist only for ILC (and CLIC)

From $e^+e^- \to ZH$:



From $e^+e^- \to ZHH, \nu\bar{\nu}HH$:



For $f_1 = 1$, $\triangle a_1$ corresponds to $\Lambda \sim 4$ TeV

For $f_2 = 1$, $\triangle a_2$ corresponds to $\Lambda \sim 0.8$ TeV

Dimension-6 (D6) operators with Higgs, fermion and gauge fields

$$\begin{aligned}
O_{d\phi} &= (\phi^\dagger\phi)(\bar{q}d\phi) \\
O^{(1)}_{\phi q} &= i(\phi^\dagger D_\mu\phi)(\bar{q}\gamma^\mu q) \\
O^{(3)}_{\phi q} &= i(\phi^\dagger D_\mu\sigma^i\phi)(\bar{q}\gamma^\mu\sigma^i q) \\
O_{\phi d} &= i(\phi^\dagger D_\mu\phi)(\bar{d}\gamma^\mu d) \\
O_{\phi\phi} &= i(\phi^\dagger\epsilon D_\mu\phi)(\bar{u}\gamma^\mu d) \\
O_{Dd} &= (\bar{q}D_\mu d)D^\mu\phi \\
O_{\bar{D}d} &= (D_\mu\bar{q}d)D^\mu\phi \\
O_{dW} &= (\bar{q}\sigma^{\mu\nu}\sigma^i d)\phi W^i_{\mu\nu} \\
O_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\phi B_{\mu\nu}
\end{aligned}$$

- some constrained by $Zb\bar{b}$,$\gamma b\bar{b}$ coups
- others would give interesting rare decays: $H \longrightarrow b\bar{b}Z$, $b\bar{b}\gamma$, ...

▶ phenomenology not really studied

D6 operators with Higgs and gauge fields

$$
\begin{aligned}
O_{WW} &= (\phi^\dagger\phi)\left[W^+_{\mu\nu}W^{-\mu\nu} + \tfrac{1}{2}W^3_{\mu\nu}W^{3\mu\nu}\right] \\
O_{BB} &= (\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu} \\
O_{BW} &= B^{\mu\nu}\left[(\phi^\dagger\sigma^3\phi)W^3_{\mu\nu} + \sqrt{2}\left[(\phi^\dagger T^+\phi)W^+_{\mu\nu} + (\phi^\dagger T^-\phi)W^-_{\mu\nu}\right]\right] \\
O_W &= (D^\mu\phi)^\dagger\left[\sigma^3(D^\nu\phi)W^3_{\mu\nu} + \sqrt{2}\left[T^+(D^\nu\phi)W^+_{\mu\nu} + T^-(D^\nu\phi)W^-_{\mu\nu}\right]\right] \\
O_B &= (D^\mu\phi)^\dagger(D^\nu\phi)B_{\mu\nu} \\
O_{\Phi,1} &= (D_\mu\phi)^\dagger\phi\phi^\dagger(D^\mu\phi)
\end{aligned}
$$

$\longrightarrow$ give anomalous momentum-dependent $HHVV$ vertices

But highly constrained by S, ρ, g_{VVV}

(Note: no updates past ’98)

2HDMs AND THE MSSM

Overview of 2HDMs

Here, assume CP conservation is exact (both vevs real).

Five physical states: h, H, A, $H^{\pm}$ (2 CP-even; 1 CP-odd; charged)

Four types exist, depending on how Φ_1 and Φ_2 couple to fermions:

I only Φ_2 couples to fermions

II Φ_1 couples to down-type, Φ_2 to up-type fermions

III Φ_1 couples to down quarks, Φ_2 to up quarks and down leptons

IV Φ_1 couples to quark, Φ_2 to leptons

Vevs parameterized by $\tan\beta = \frac{v_2}{v_1}$; to solve unitarity, $v_1^2 + v_2^2 \equiv v^2$ (from G_F)

Recall:
$$\begin{cases} h &= \sqrt{2}\left[-(\mathrm{Re}\phi_1^0 - v_1)\sin\alpha + (\mathrm{Re}\phi_2^0 - v_2)\cos\alpha\right] \\ H &= \sqrt{2}\left[\ \ (\mathrm{Re}\phi_1^0 - v_1)\cos\alpha + (\mathrm{Re}\phi_2^0 - v_2)\sin\alpha\right] \end{cases}$$

Phenomenologically, Higgs sector defined by α, $\tan\beta$, potential param's.

· in many models, masses defined by M_A & M_Z

Overview of 2HDMs

General coupling structure of 2HDMs:

Type I model:

Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
h	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$\frac{1}{2}\cos(\beta-\alpha)$
H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}\sin(\beta-\alpha)$
A	$\mathrm{i}\,\gamma_5\cot\beta$	$-\mathrm{i}\,\gamma_5\cot\beta$	0	0

$$g_{H^-U\bar{D}} = \frac{g}{2\sqrt{2}M_W}\left[m_U\cot\beta(1+\gamma_5) - m_D\cot\beta(1-\gamma_5)\right]$$

Type II model:

(MSSM)

Φ	$\frac{g_{\Phi u\bar{u}}}{g_f}$	$\frac{g_{\Phi d\bar{d}}}{g_f}$	$\frac{g_{\Phi VV}}{g_V}$	$\frac{g_{\Phi ZA}}{g_V}$
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$\frac{1}{2}\cos(\beta-\alpha)$
H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}\sin(\beta-\alpha)$
A	$\mathrm{i}\,\gamma_5\cot\beta$	$\mathrm{i}\,\gamma_5\tan\beta$	0	0

$$g_{H^-U\bar{D}} = \frac{g}{2\sqrt{2}M_W}\left[m_U\cot\beta(1+\gamma_5) + m_D\tan\beta(1-\gamma_5)\right]$$

Types III & IV induce FCNC's – highly constrained $\therefore$ not usually studied

⟶ let's study the MSSM 2HDM, since SUSY is so well-motivated

Review: Higgs masses in the MSSM

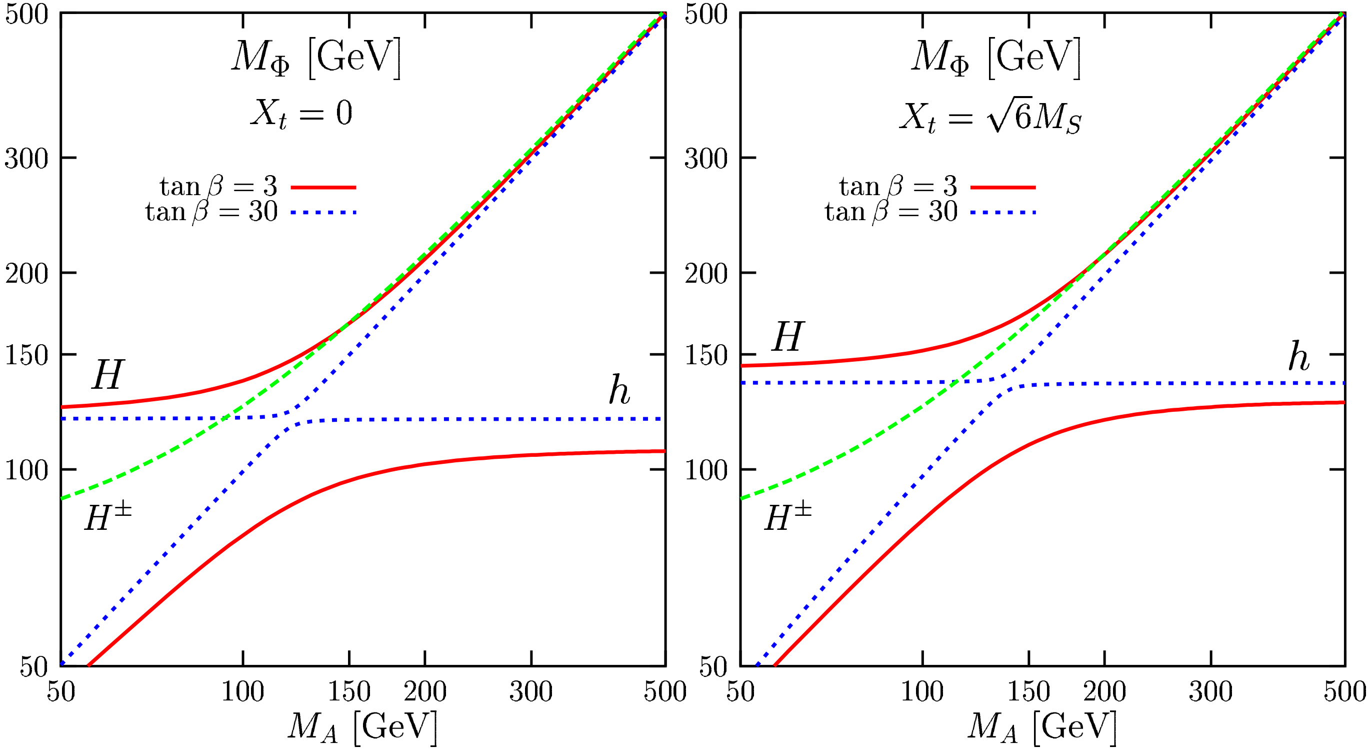
Pseudoscalar: M_A is an input! Others are $\tan\beta$, M_S (SUSY scale), A_t

$$\begin{aligned} M^2_{H,h} \;=\; & \tfrac{1}{2}\left(M_A^2 + M_Z^2 \pm \sqrt{(M_A^2+M_Z^2)^2 + 4M_A^2M_Z^2\sin^2(2\beta)}\right) \\ & + \tfrac{3}{8\pi^2}\sin^2\beta\, Y_t^2 m_t^2\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] \quad \text{for } M_h \text{ only} \end{aligned}$$

Charged Higgs:

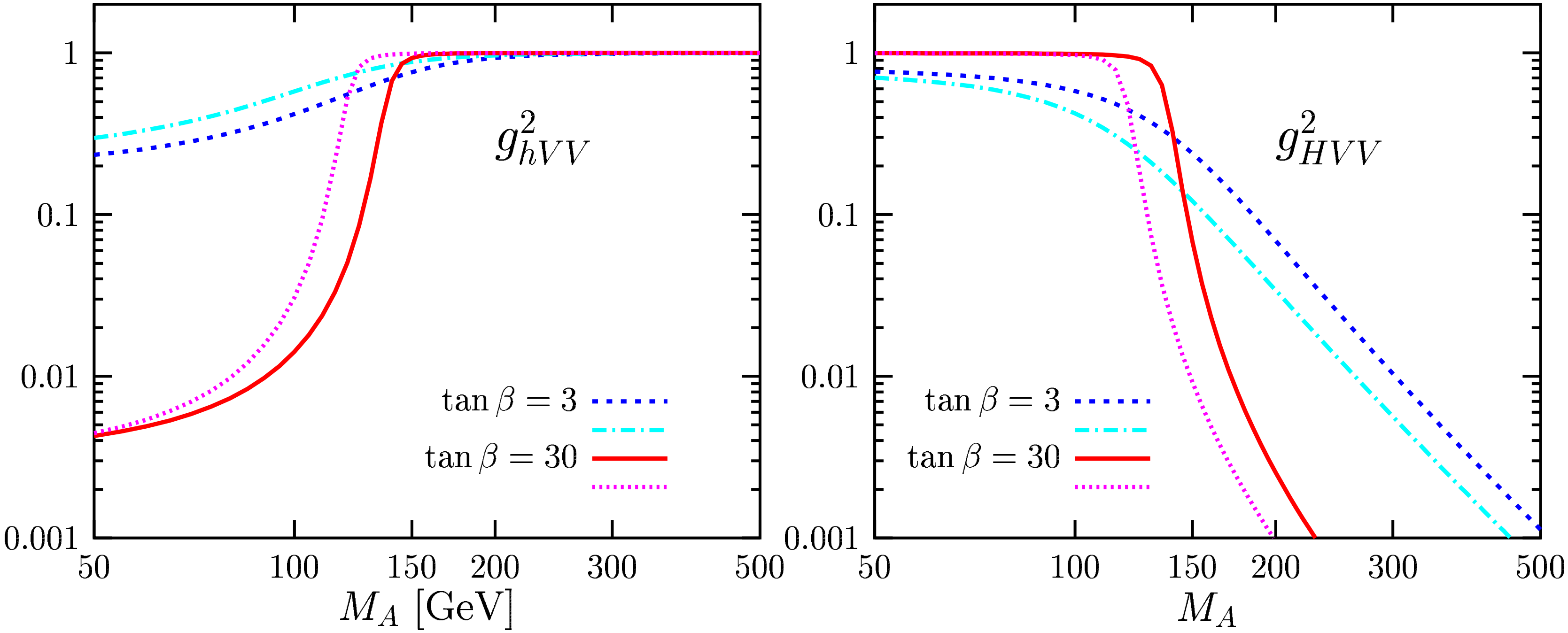
$$M^2_{H^\pm} = M_A^2 + M_W^2$$

Note: $M_{H^\pm,H}$ track M_A for large values.



- “transition region” for moderate M_A
- “decoupling” for large M_A

Couplings also have decoupling and transition regions



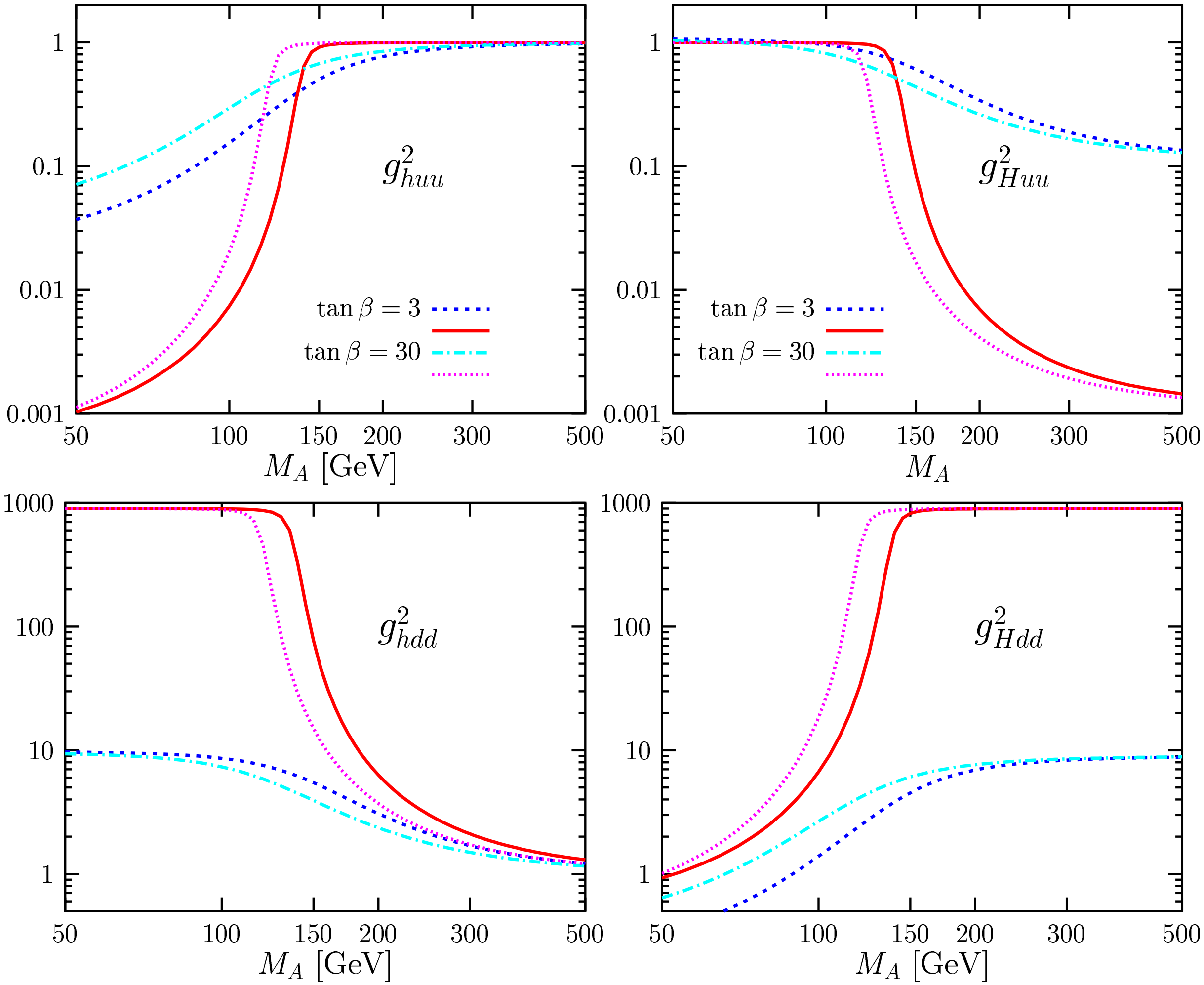
Important sum rule:

$$g^2_{hVV} + g^2_{HVV} = g^2_{HVV,SM}$$

► required to preserve $VV \to VV$ unitarity cancellation!

Couplings also have decoupling and transition regions

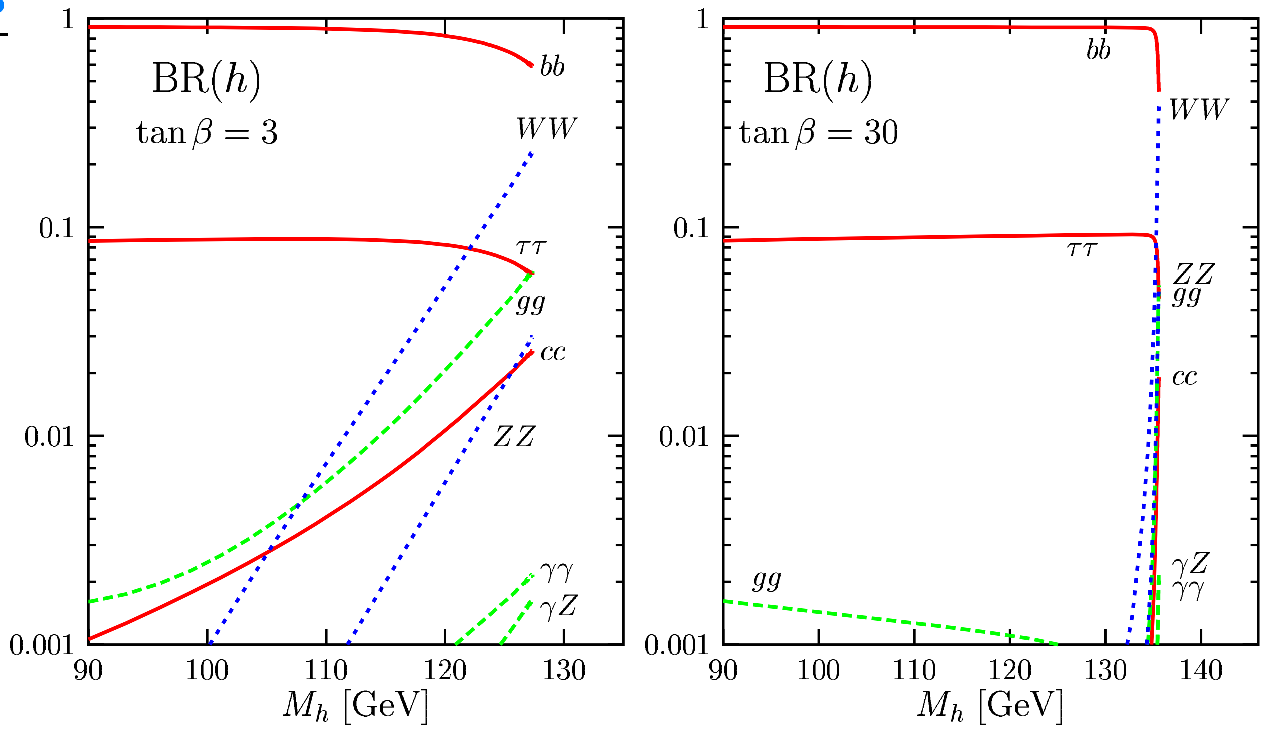
$$
\begin{aligned}
g_{hu\bar{u}} &= \frac{\cos\alpha}{\sin\beta}\,Y_u &&= \left[\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)\right]Y_u\\
g_{hd\bar{d}} &= -\frac{\sin\alpha}{\cos\beta}\,Y_d &&= \left[\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)\right]Y_d\\
g_{Hu\bar{u}} &= \frac{\sin\alpha}{\sin\beta}\,Y_u &&= \left[\cos(\beta-\alpha)-\cot\beta\sin(\beta-\alpha)\right]Y_u\\
g_{Hd\bar{d}} &= \frac{\cos\alpha}{\cos\beta}\,Y_d &&= \left[\cos(\beta-\alpha)+\tan\beta\sin(\beta-\alpha)\right]Y_d
\end{aligned}
$$



CP-even branching ratios

h has $f_d\bar{f}_d$ enhancement

at large $\tan\beta$ and low M_A



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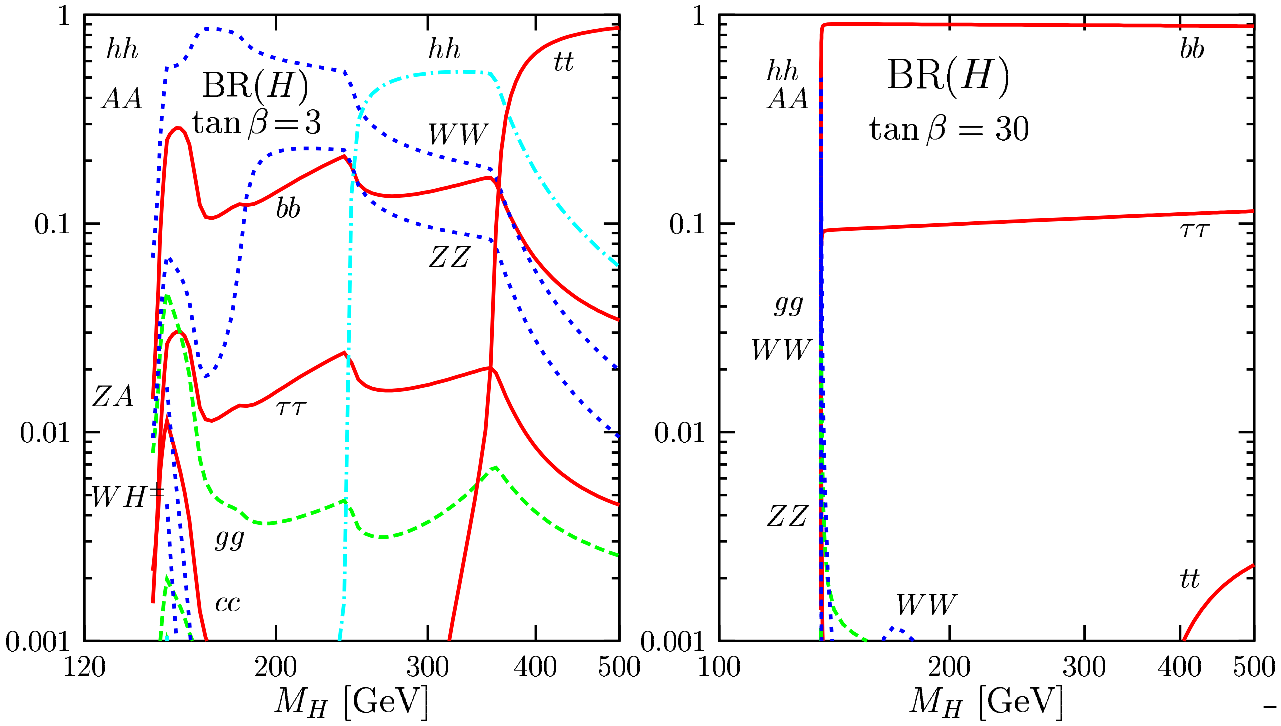
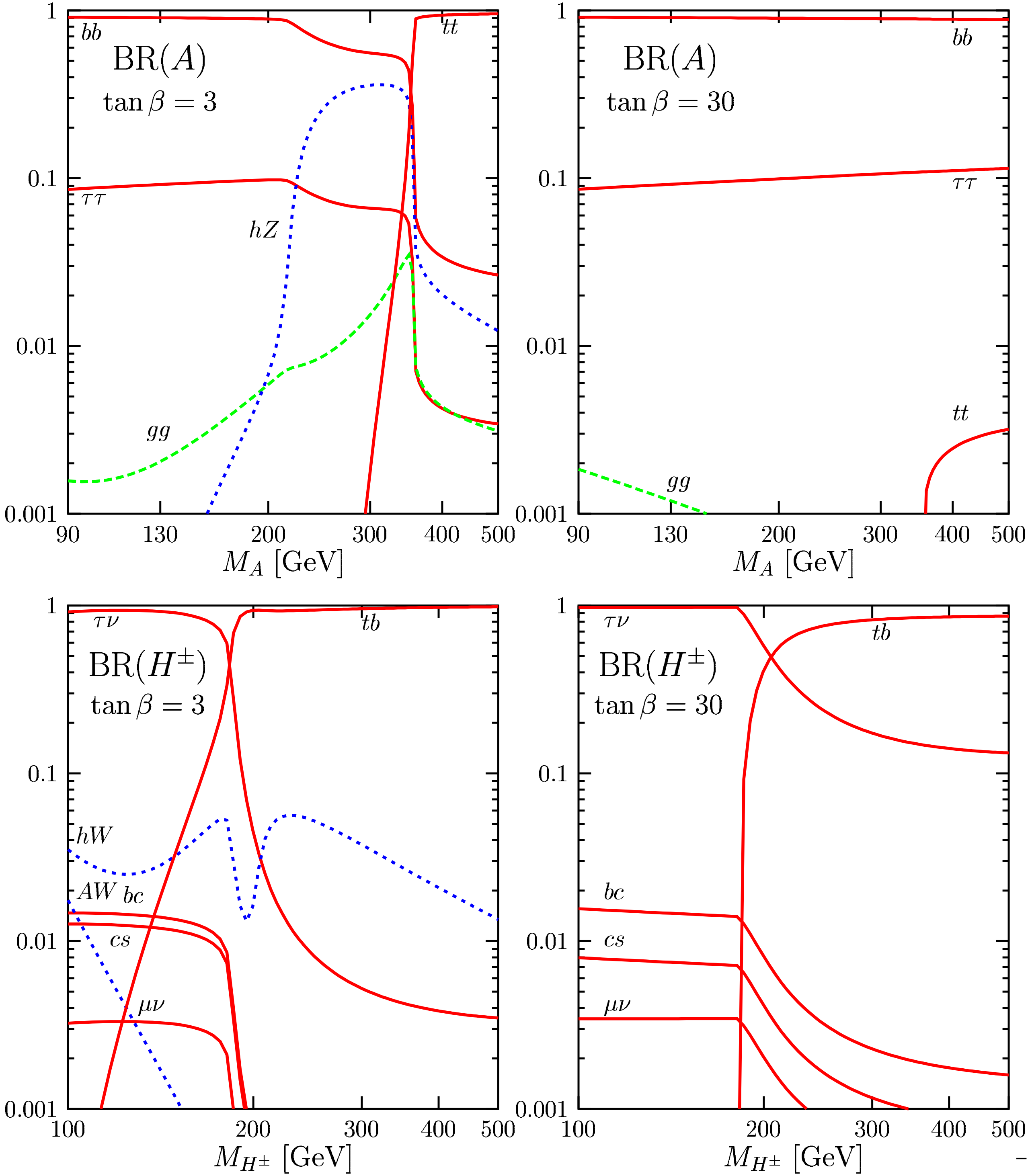


A,$H^{\pm}$ branching ratios

A has $f_d \bar{f}_d$ enhancement

at large $\tan\beta$ for all M_A

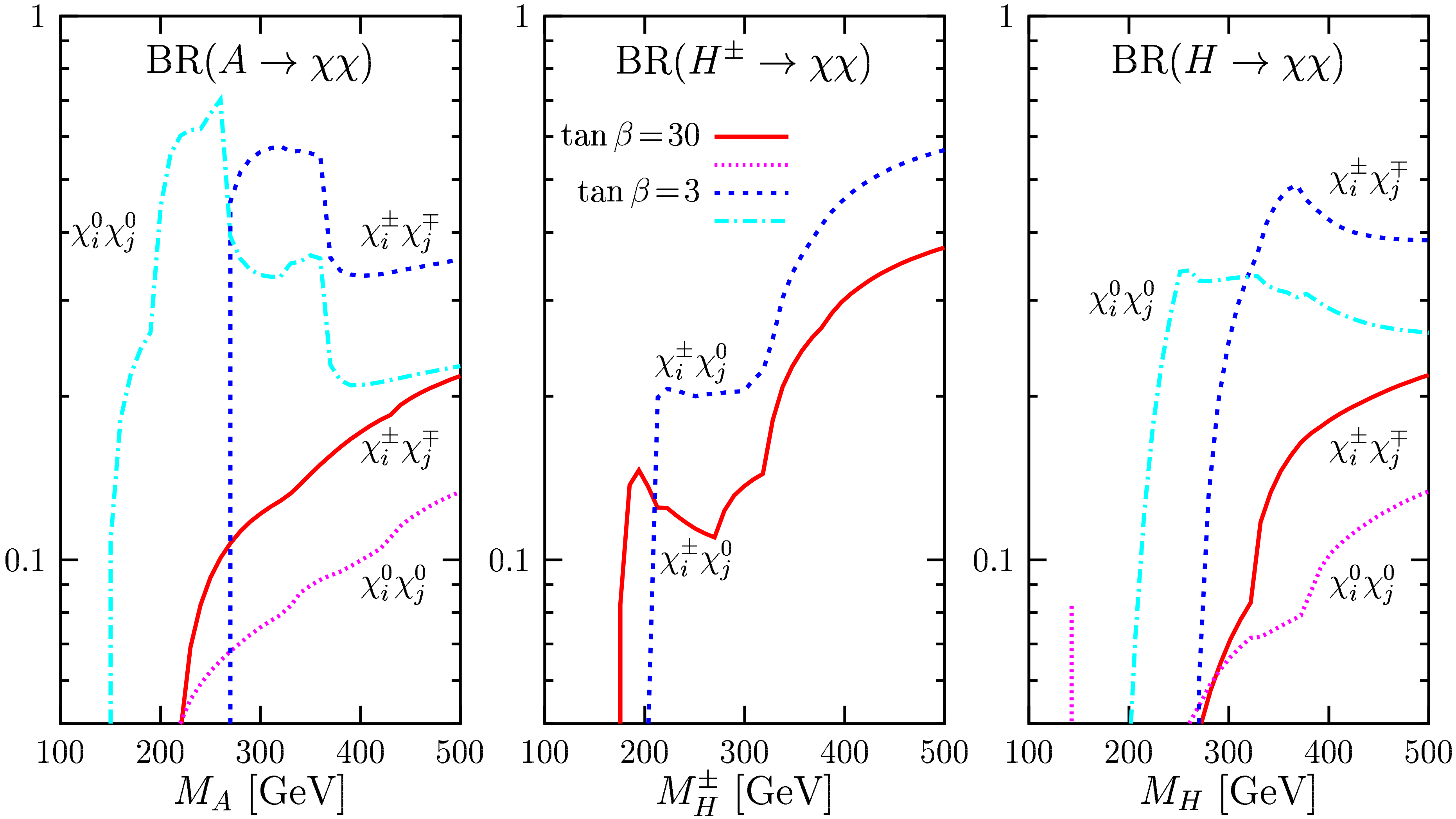


$H^{\pm}$ decay to:

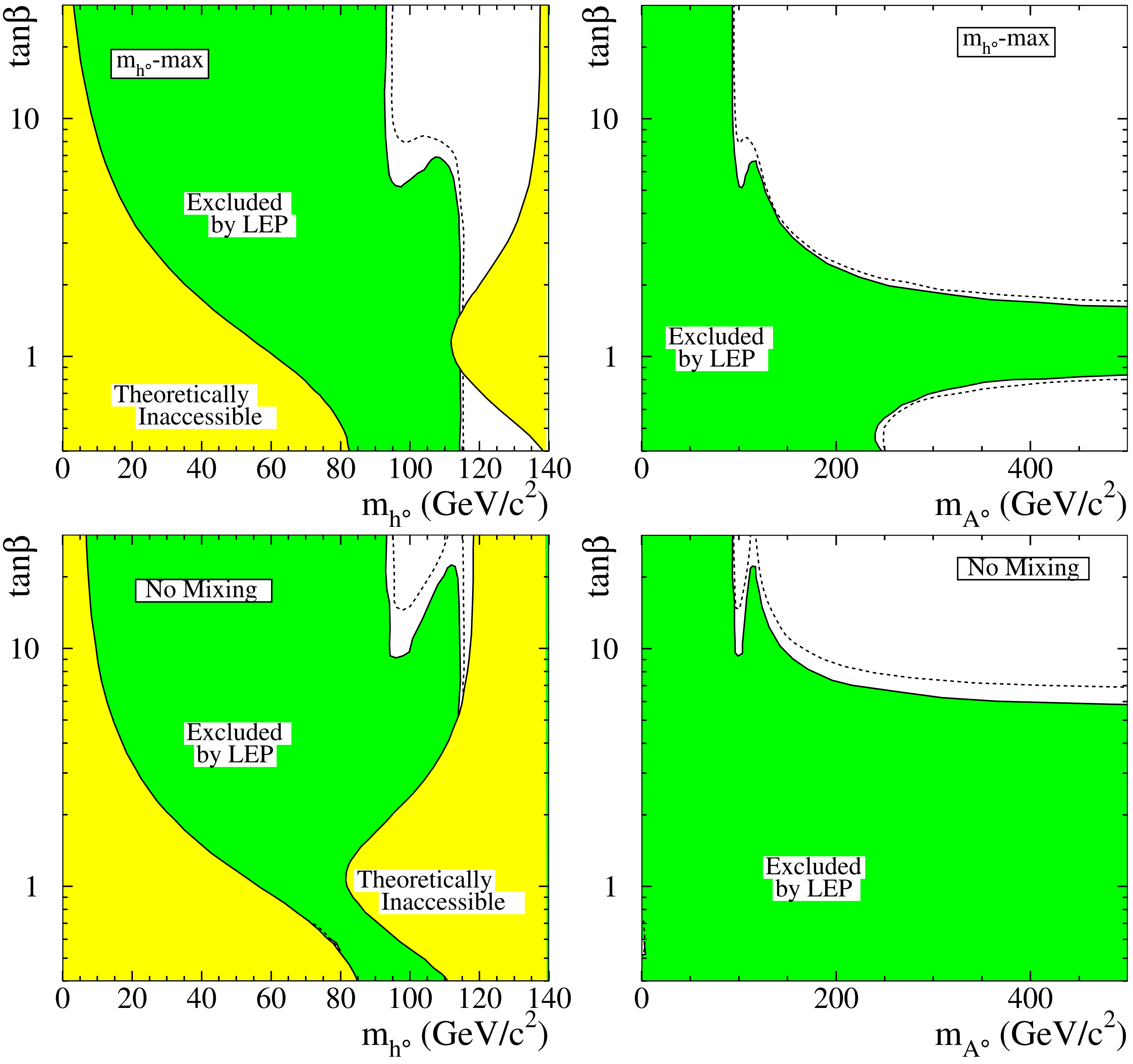
- $hW^{\pm}$ only at small $\tan\beta$
- $\tau\nu$ at low mass
- tb at high mass

BR’s to SUSY particles

Higgses can decay to SUSY pairs if light:

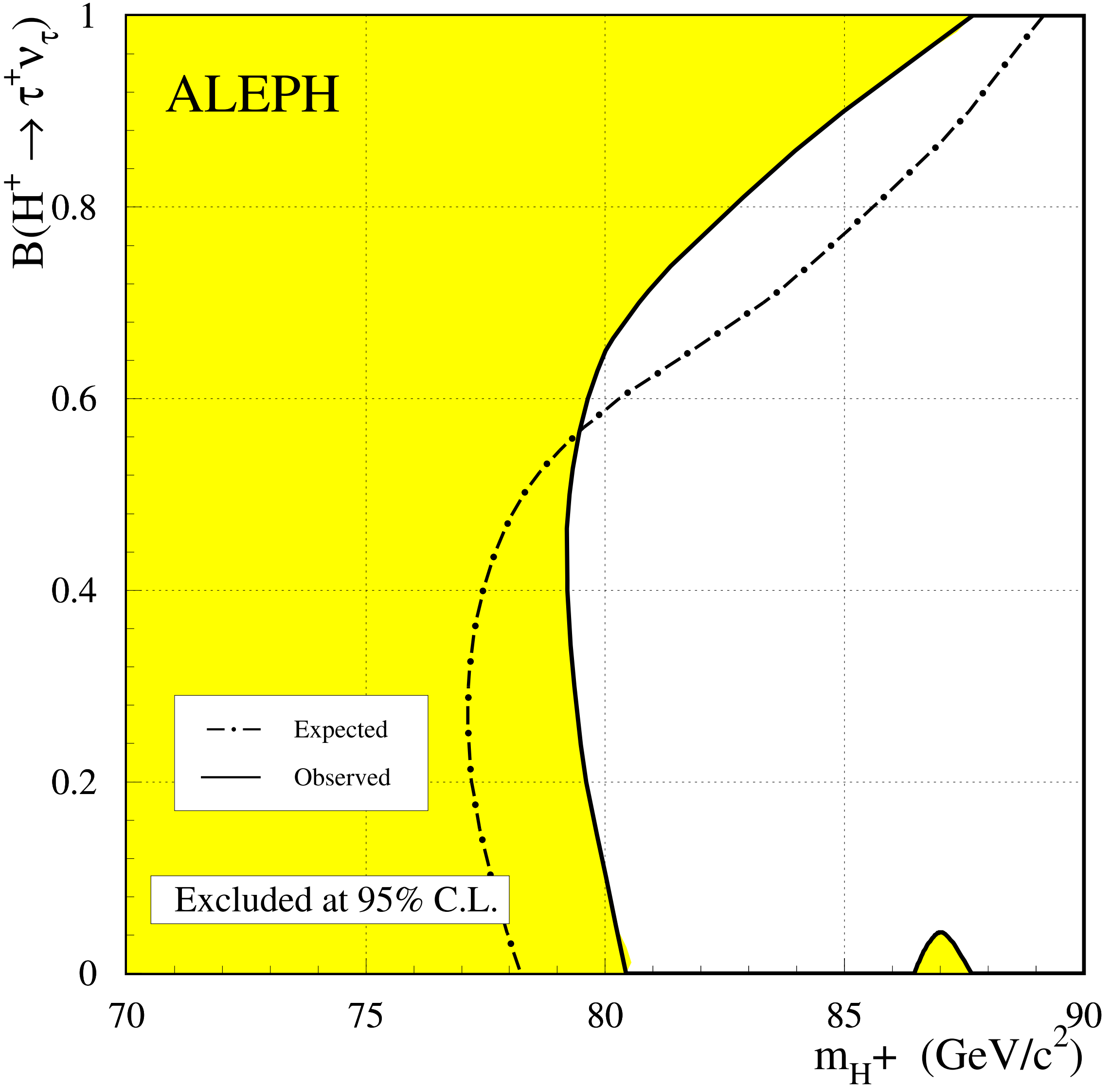


What did LEP already rule out?



What did LEP already rule out?

LEP's charged Higgs search was much less model-dependent:



Some notes on LHC MSSM Higgs production

Lest ye suffer from Plot Overload...

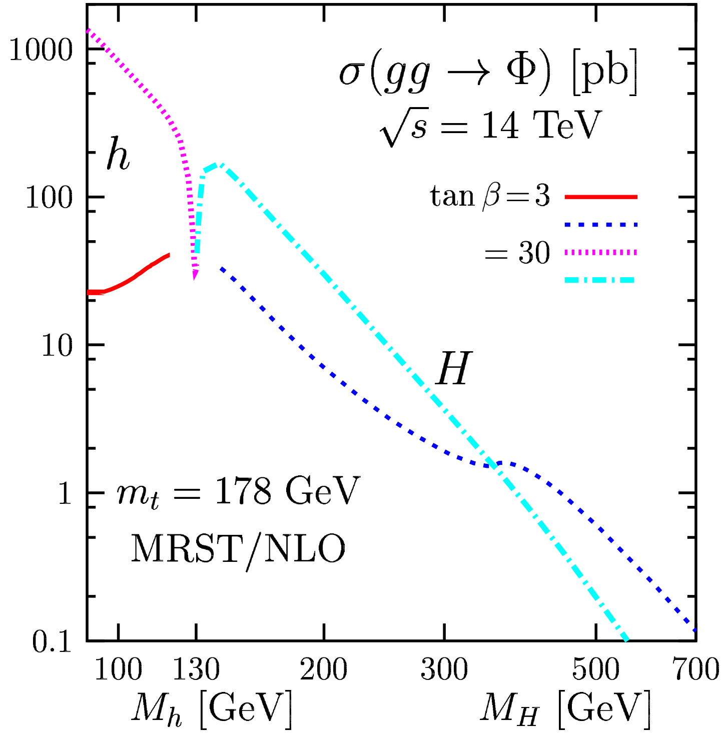
1. WBF and VH cross sections can only go *down*

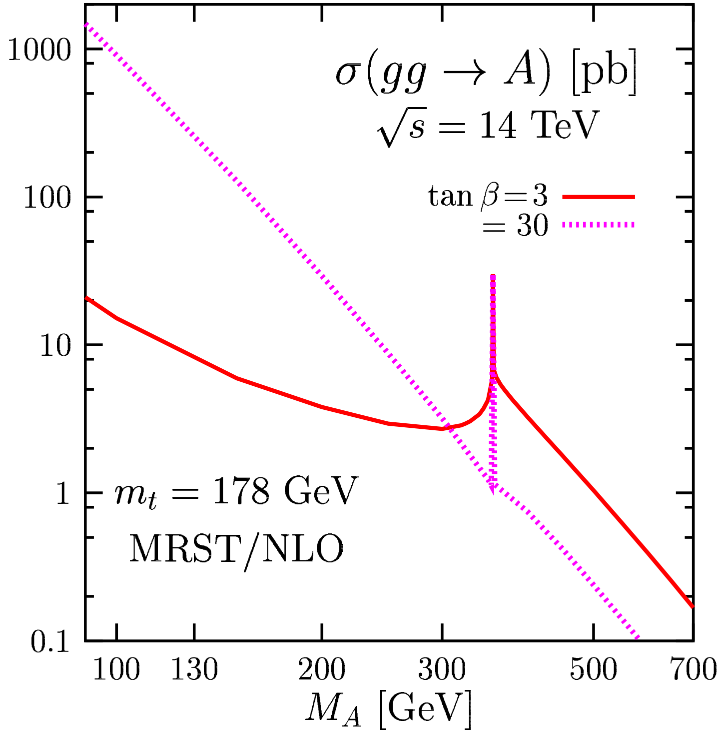
   $\longrightarrow \sin^2(\beta-\alpha), \cos^2(\beta-\alpha)$ suppression for h,H

2. $t\bar{t}\phi$ rates about same as SM for equivalent mass

3. $b\bar{b}\phi$ rates become very important for large $\tan\beta$

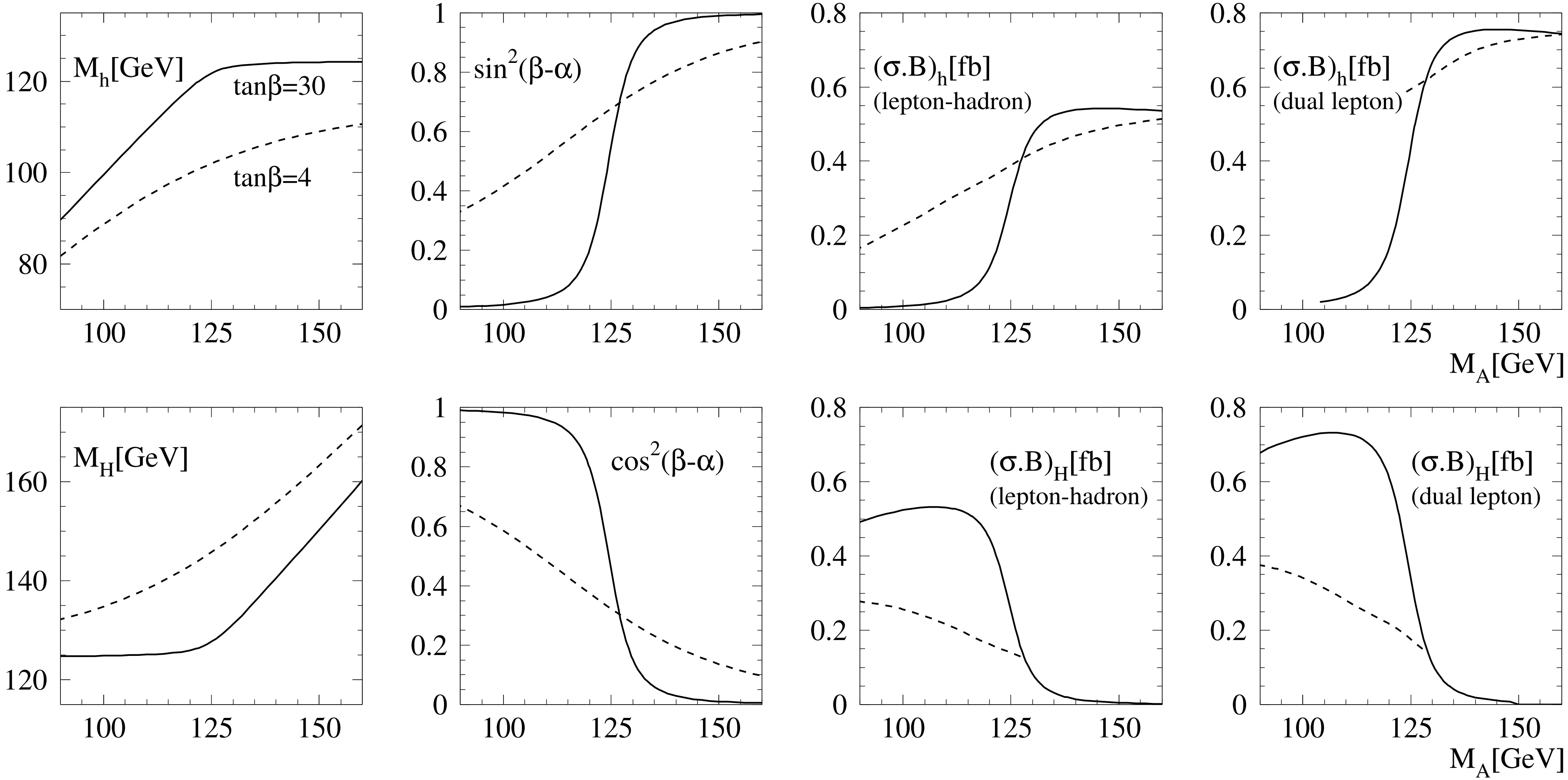
4. $pp \to \phi$ rates can alter dramatically; b loop extremely important





Back to h, H mass and coupling behavior in the MSSM

Right-hand $\boldsymbol{\sigma}$·B plots for WBF $H \to \tau^+\tau^-$ at LHC



- for large M_A, M_H tracks M_A and M_h plateaus – in “good” region
- for small M_A, M_h tracks M_A and M_H plateaus – in “good” region
- the Higgs which tracks M_A decouples from W, Z

WBF Higgs production at LHC looks extremely important.

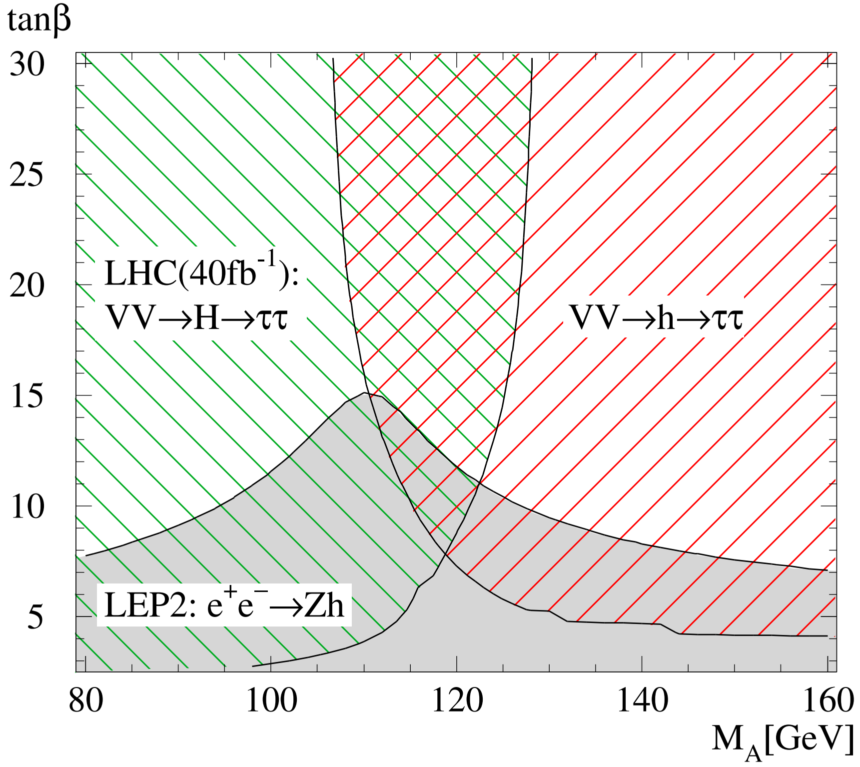
MSSM Higgs No-Lose Theorem

- No matter where in MSSM parameter space,

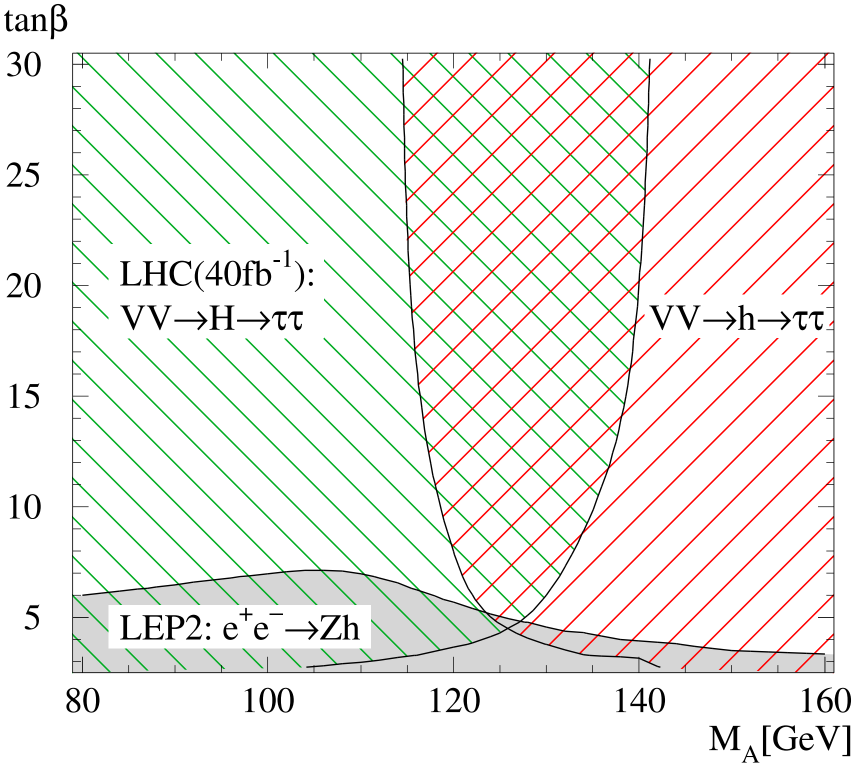
at least one of h or H can be observed in WBF production.

Relies on plateau behavior in $M_{h,H}$ and $g^2_{hVV} + g^2_{HVV} = g^2_{HVV,SM}$.

no mixing



maximal mixing



$\longrightarrow$ ATLAS confirmed - needs even less lumi ($\sim$30 fb^{-1})

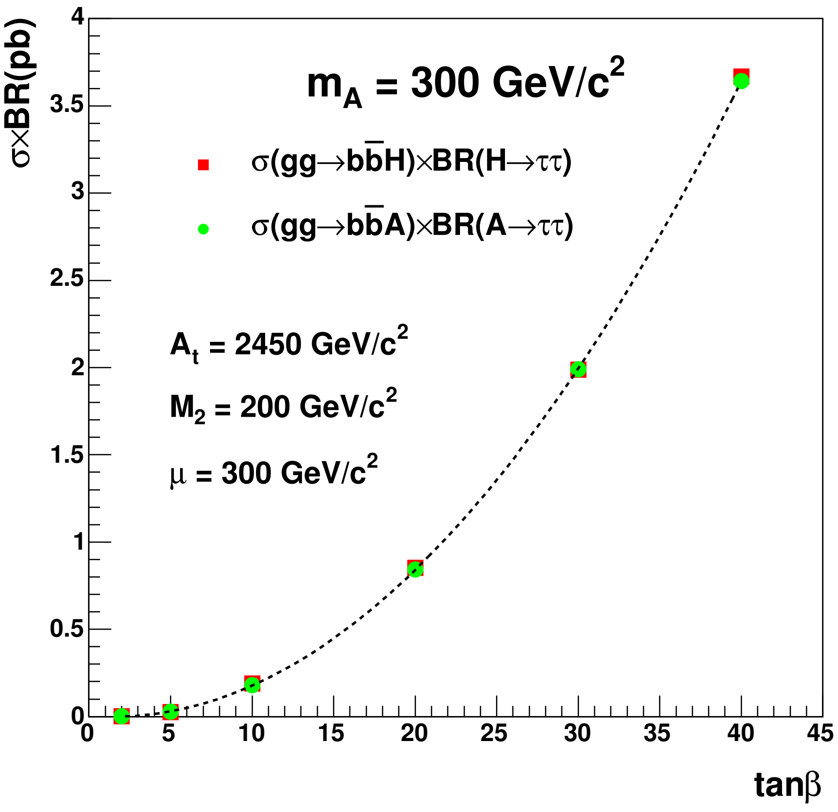
· ATLAS plots are a bit more confusing, though

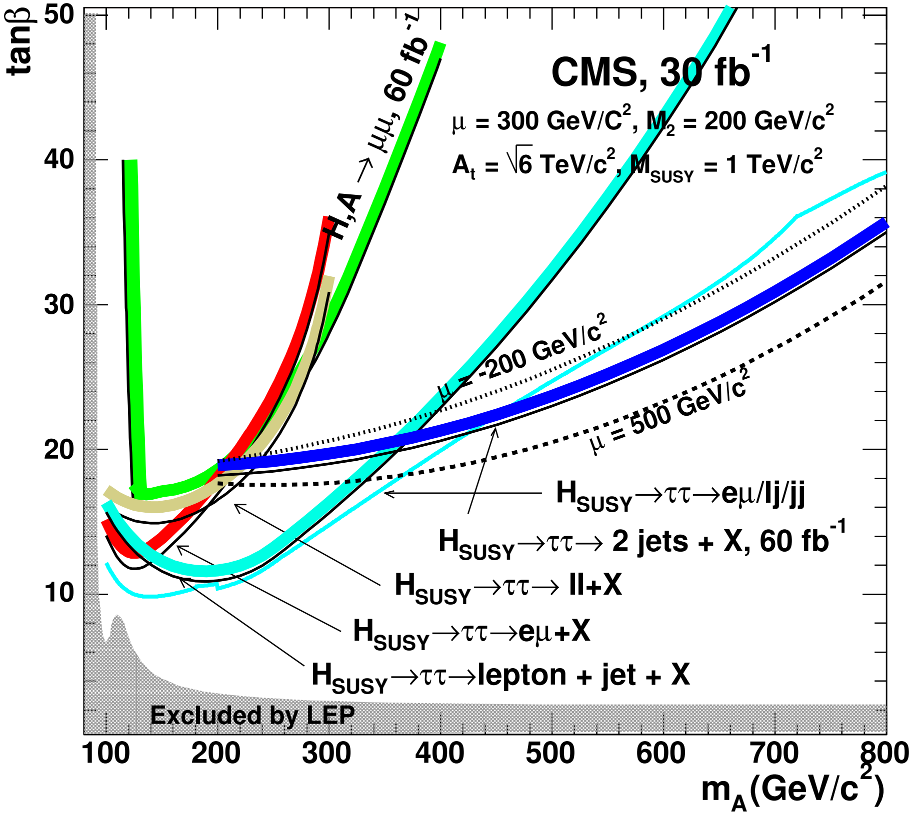
Observing MSSM H,A states when “decoupled”

Recall that H has $\tan\beta$ enhancement to down-type quarks in decoupling region, and A always has this enhancement.

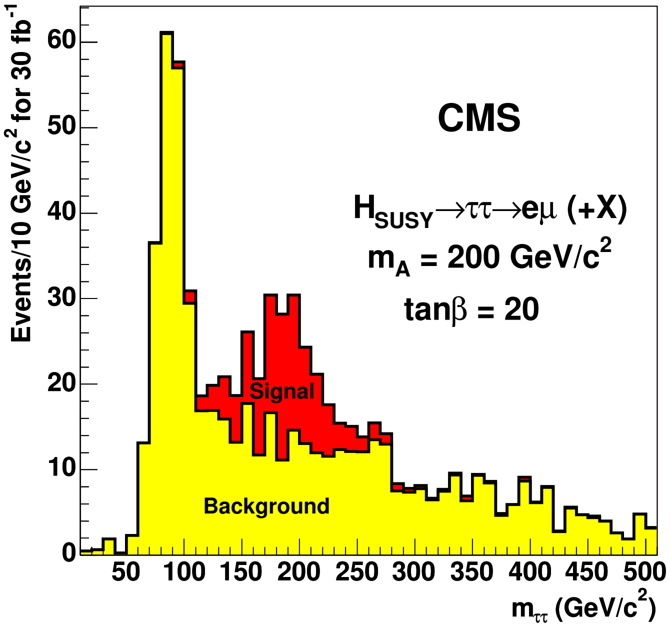
What decays to observe?

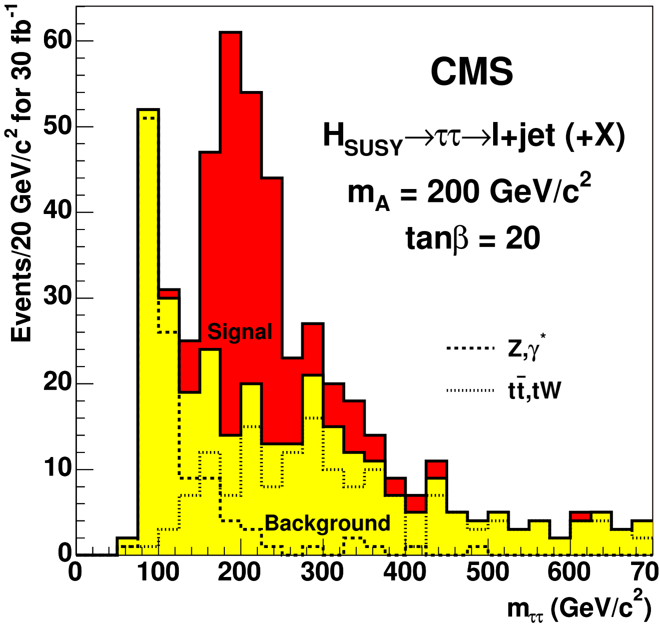
- forget about $H/A \to b\bar{b}$ - QCD overwhelms this
- BRs are dominantly to $\tau^+\tau^-$ and $\mu^+\mu^-$ as a rare mode
- $\tau^+\tau^-$ can work because H,A have large recoil in associated production

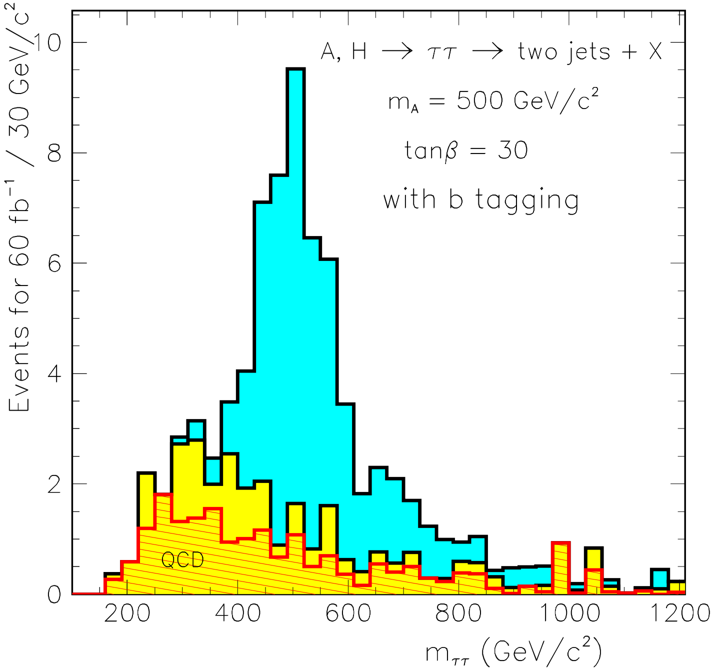


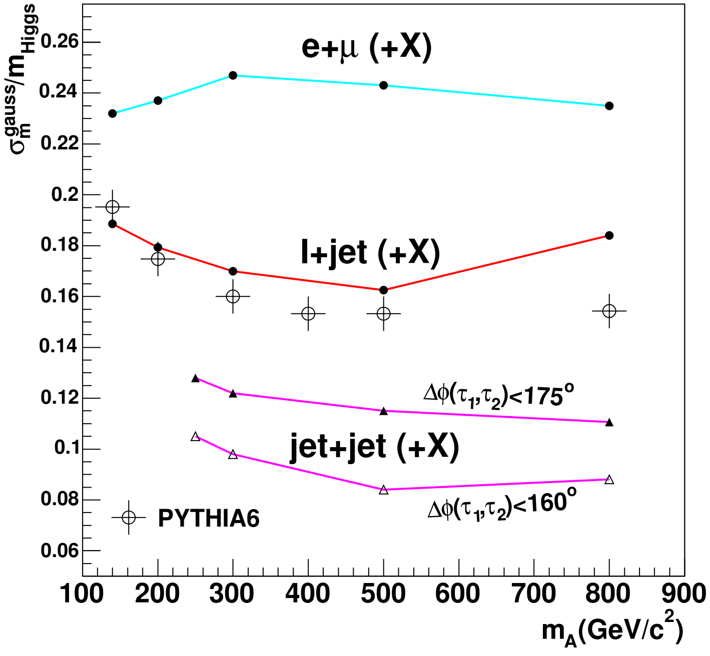


$H/A \rightarrow \tau^+\tau^-$ mass resolution is even pretty good



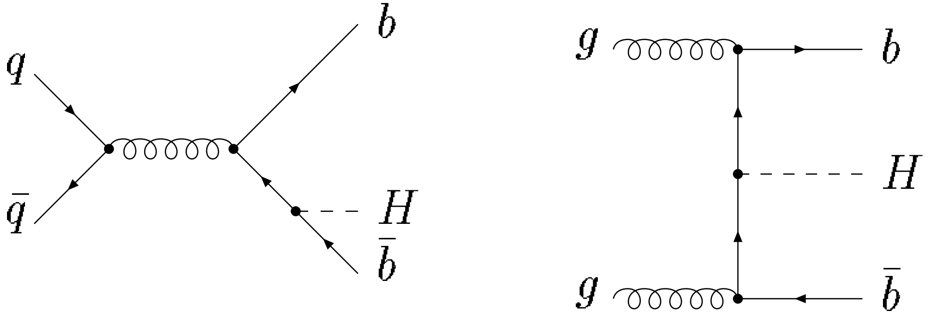


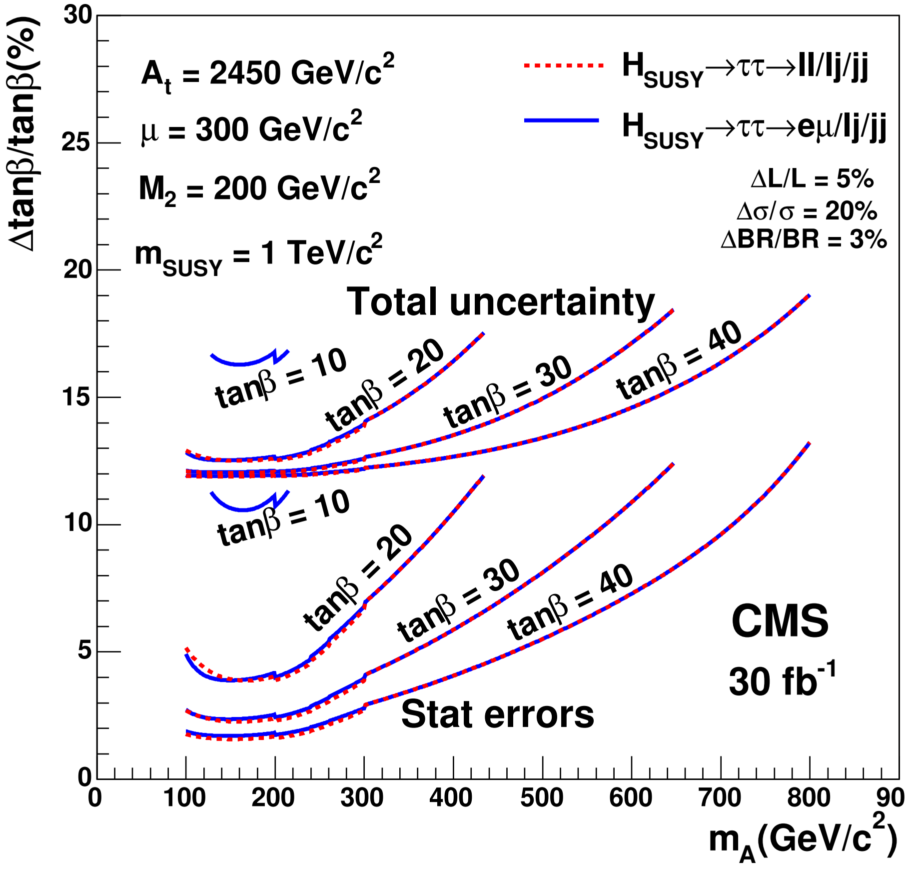


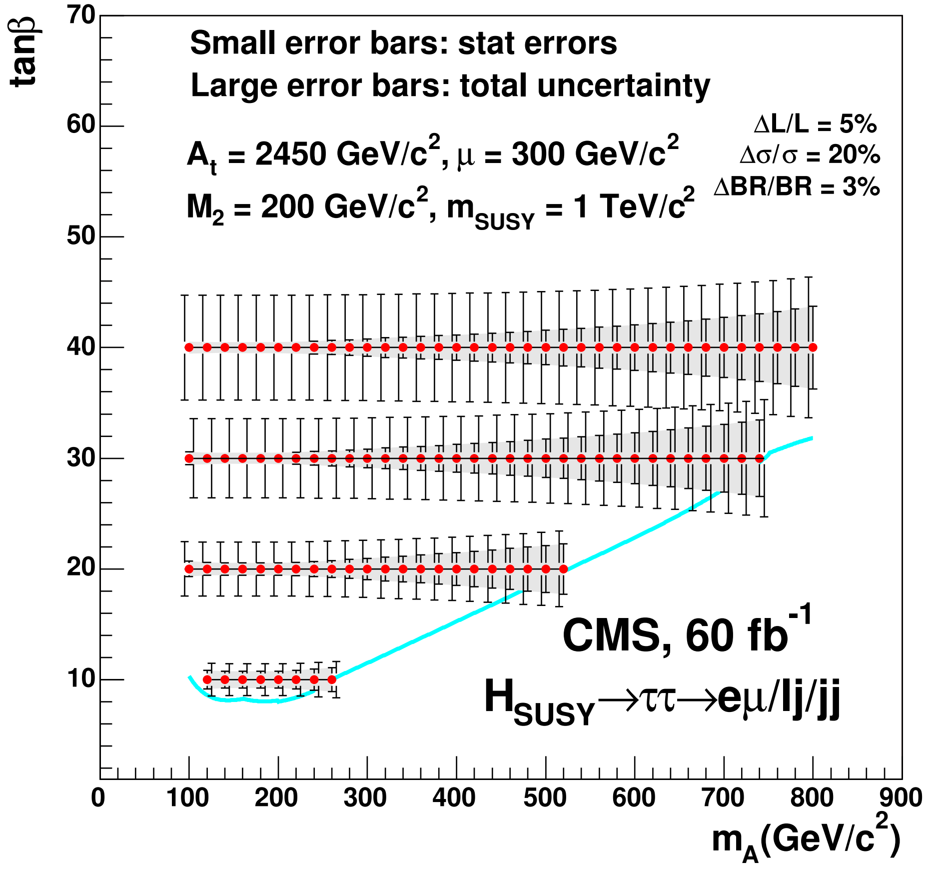


How to measure $\tan\beta$

Essentially, measure the rate of $H/Ab\bar{b}$ production. (coupling $\propto \tan\beta$)







Pretty good measurement for hadron collider environment.

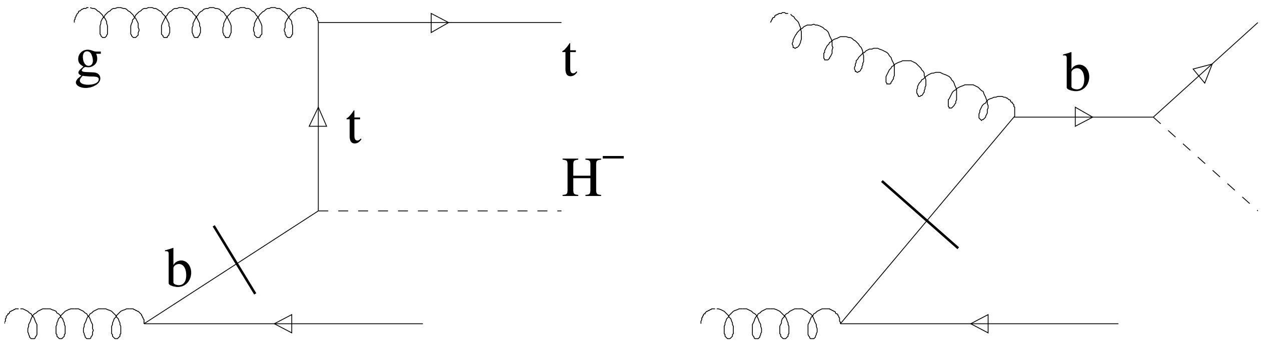
Systematic uncertainties dominate everywhere.

MSSM charged Higgs searches

Despite *everything else* we may see at Tevatron or LHC, the only way to prove the existence of two Higgs doublets is to directly observe the charged Higgs states.

❶ At Tevatron, this is most likely in top quark decays, $t \longrightarrow H^{\pm}b$.

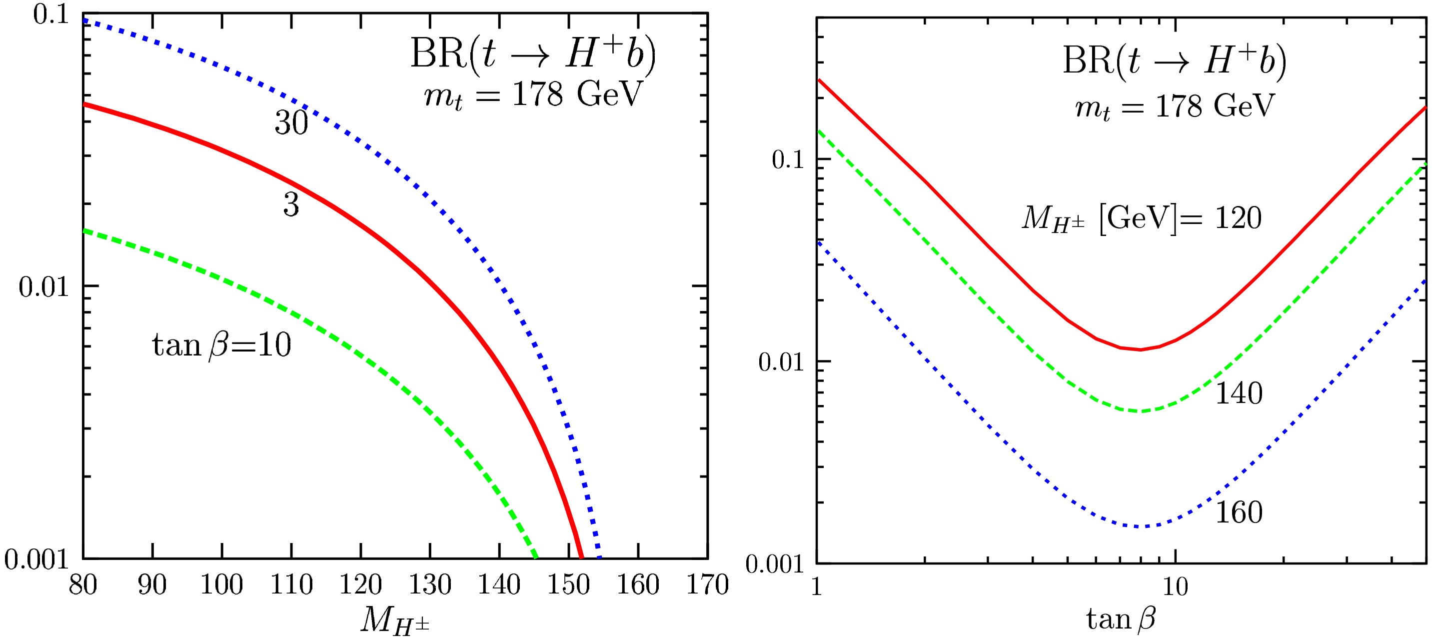
❷ At LHC, this is most likely in bottom-gluon fusion:



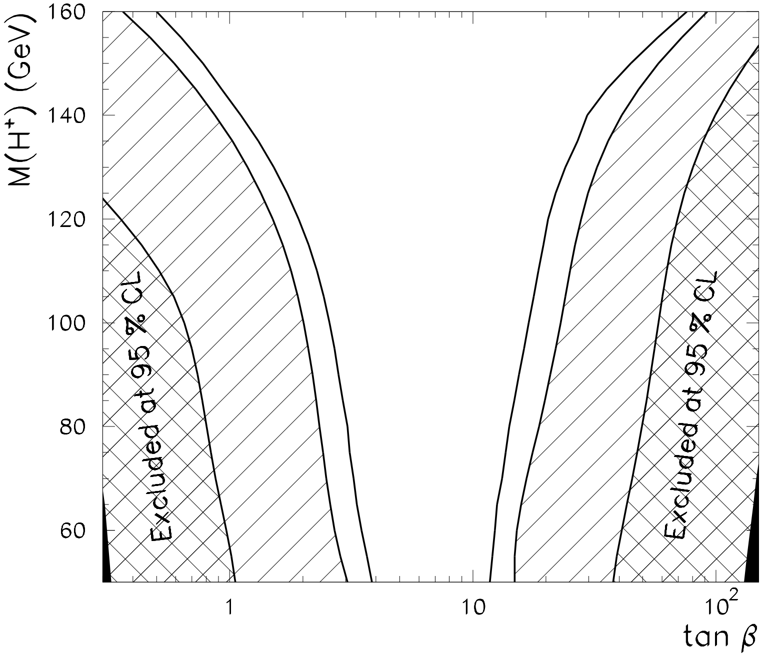
❸ At ILC, it depends strongly on $M_{H^{\pm}}$

$H^{\pm}$ at Tevatron

Recall coupling: $g_{H^- t\bar{b}} \;=\; \frac{g}{2\sqrt{2}M_W}\left[m_t \cot\beta(1+\gamma_5) + m_b \tan\beta(1-\gamma_5)\right]$



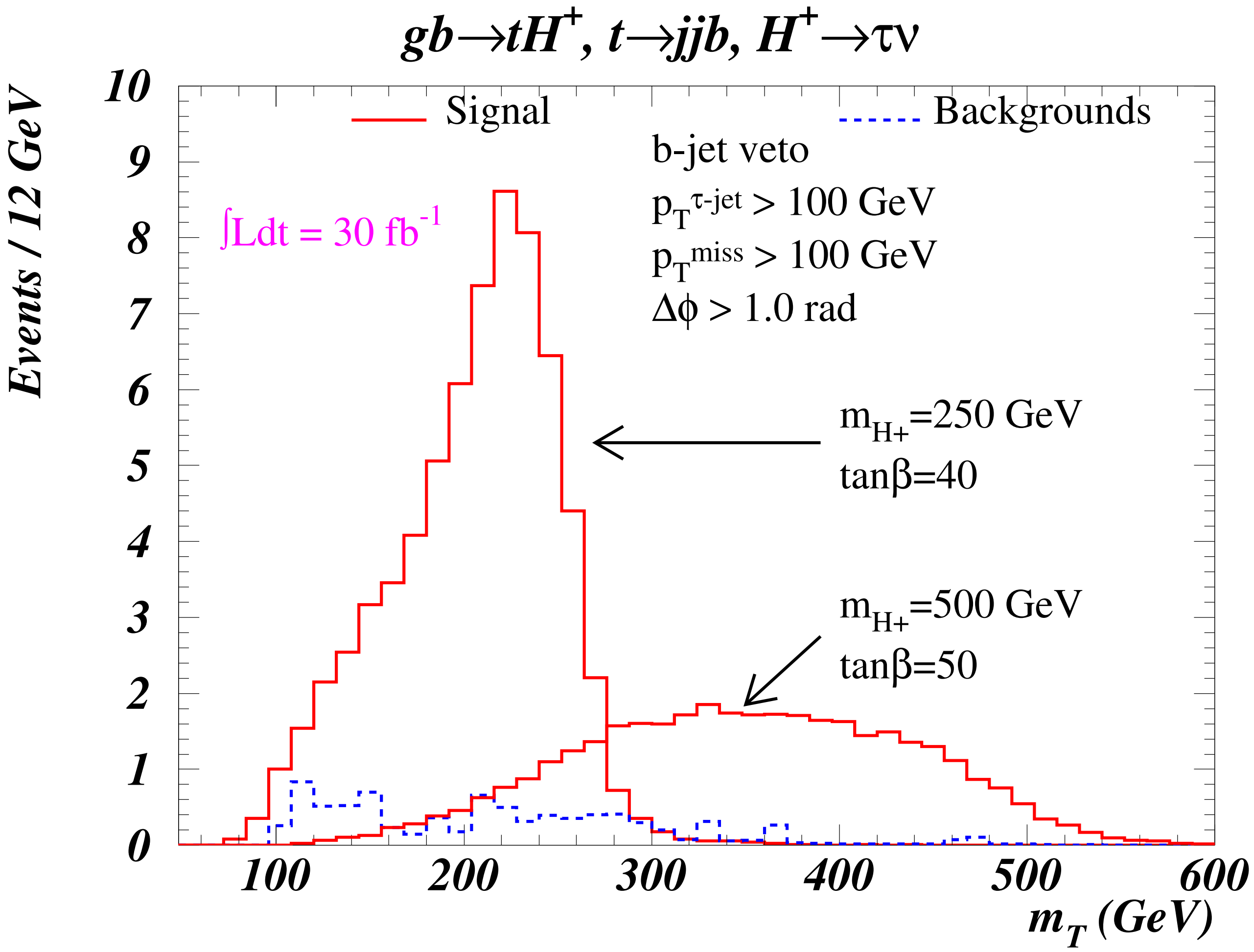
Run I and projected
Run II limits:



$H^{\pm}$ at LHC cover basically $M_{H^{\pm}} > m_t$

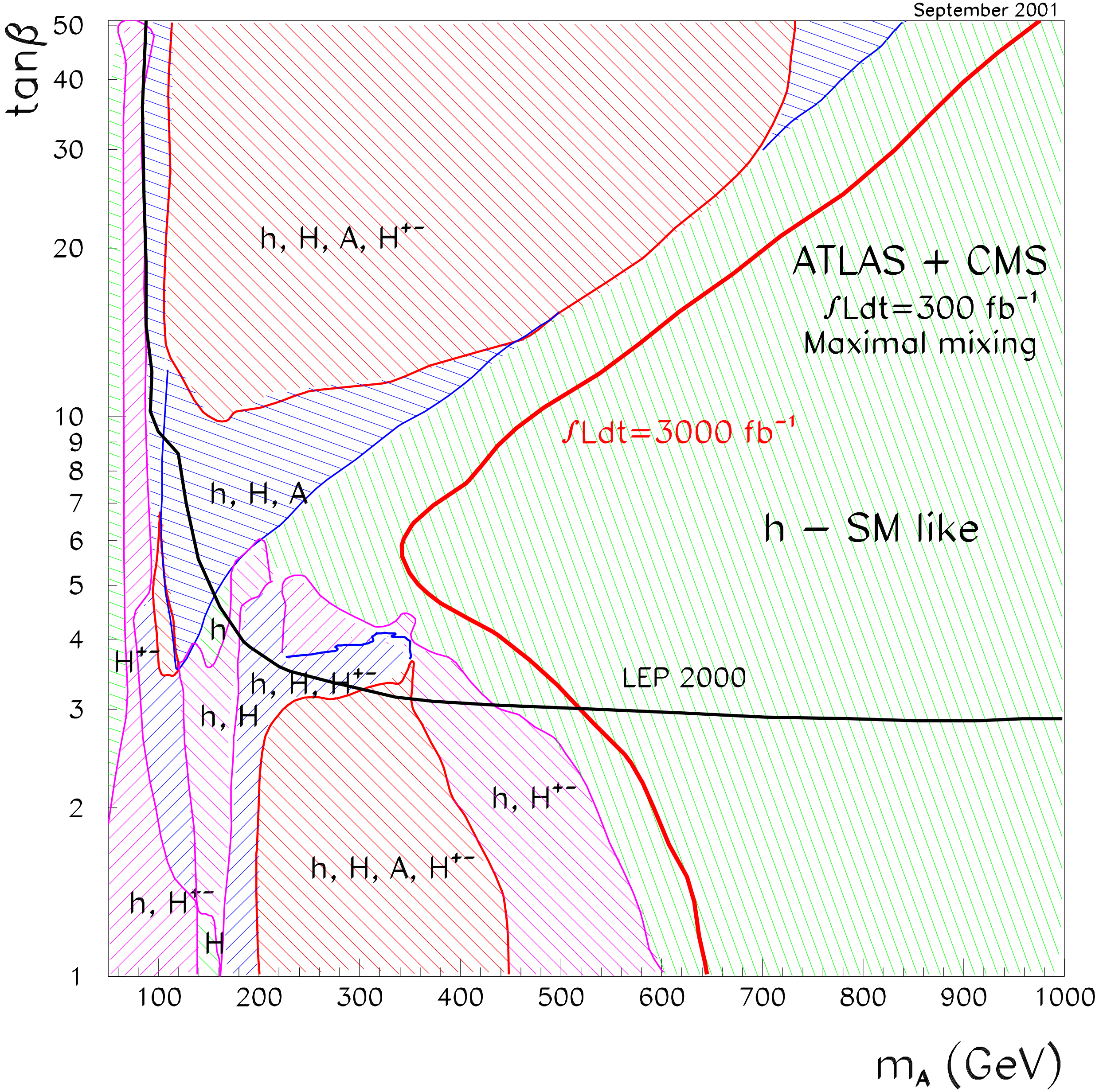
- decays to tb? fugeddaboutit! (QCD is *so* nasty)
- that leaves decays to $\tau\nu$

Note: $\tau\nu$ is a killer because $\tau_L \longrightarrow \ell$ decays are soft (low-$\not{p}_T$ leptons)



⟶ can work at LHC, but is weak at large $M_{H^{\pm}}$ and moderate $\tan\beta$

(S)LHC MSSM Higgs coverage summary



- large M_A and moderate $\tan\beta$ are *really* difficult (but needs updates)

MSSM Higgs potential and self-couplings

For the general MSSM Higgs potential, we have in $\lambda_{\phi_i \phi_j \phi_k}$ notation:

$$\begin{aligned}
\lambda_{hhh} &= 3\cos 2\alpha \sin(\beta+\alpha) + \frac{3\epsilon}{M_Z^2}\frac{\cos^3\alpha}{\sin\beta} \\
\lambda_{Hhh} &= 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha) + \frac{3\epsilon}{M_Z^2}\frac{\sin\alpha\cos^2\alpha}{\sin\beta} \\
\lambda_{HHh} &= -2\sin 2\alpha \cos(\beta+\alpha) - \cos 2\alpha \sin(\beta+\alpha) + \frac{3\epsilon}{M_Z^2}\frac{\sin^2\alpha\cos\alpha}{\sin\beta} \\
\lambda_{HHH} &= 3\cos 2\alpha \cos(\beta+\alpha) + \frac{3\epsilon}{M_Z^2}\frac{\sin^3\alpha}{\sin\beta} \\
\lambda_{hAA} &= \cos 2\beta \sin(\beta+\alpha) + \frac{\epsilon}{M_Z^2}\frac{\cos\alpha\cos^2\beta}{\sin\beta} \\
\lambda_{HAA} &= -\cos 2\beta \cos(\beta+\alpha) + \frac{\epsilon}{M_Z^2}\frac{\sin\alpha\cos^2\beta}{\sin\beta}
\end{aligned}$$

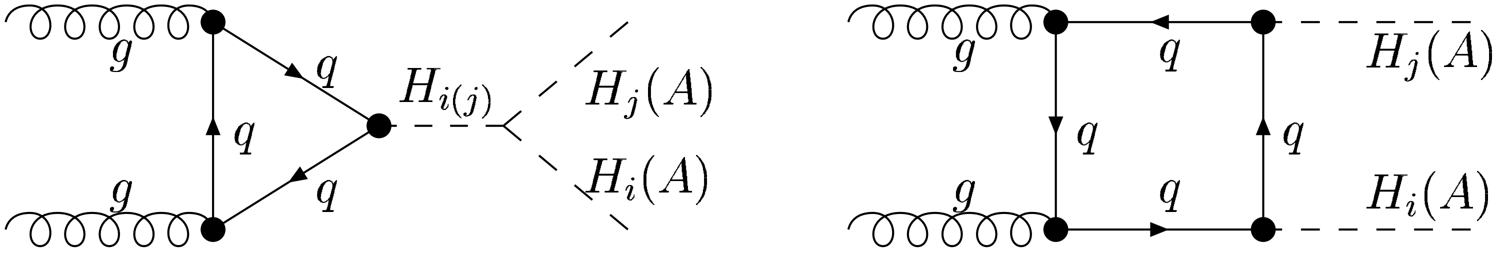
where $\epsilon = \frac{3G_F}{\sqrt{2}\pi^2}\frac{m_t^4}{\sin^2\beta}\log\left[1+\frac{M_S^2}{m_t^2}\right]$, all couplings normalized to $\frac{M_Z^2}{v}$

· realize that these couplings are partly gauge parameters

· $\lambda_{hhh} \longrightarrow \lambda_{SM}$ in decoupling limit

▶ must observe hh, hH, HH, hA, HA, AA production to measure potential!

MSSM $pp \to \phi_i\phi_j$ (LHC) at large $\tan\beta$

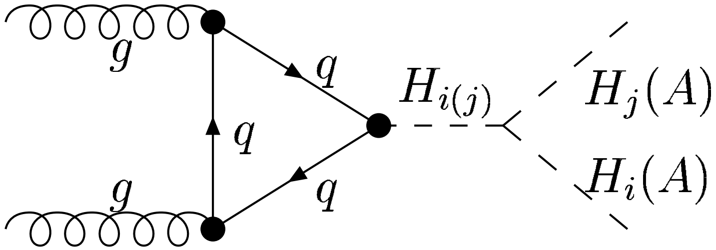


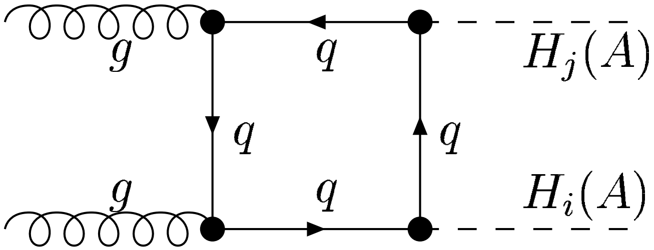
$g_{Hbb,Abb} \propto \tan\beta$, but not $\lambda \therefore$ box wins out by $\tan\beta^2$

(in addition, typically swamped by $H/Ab\bar{b}$ background)

$\longrightarrow$ measurement useless ...

MSSM $pp \to \phi_i \phi_j$ (LHC) at large $\tan\beta$



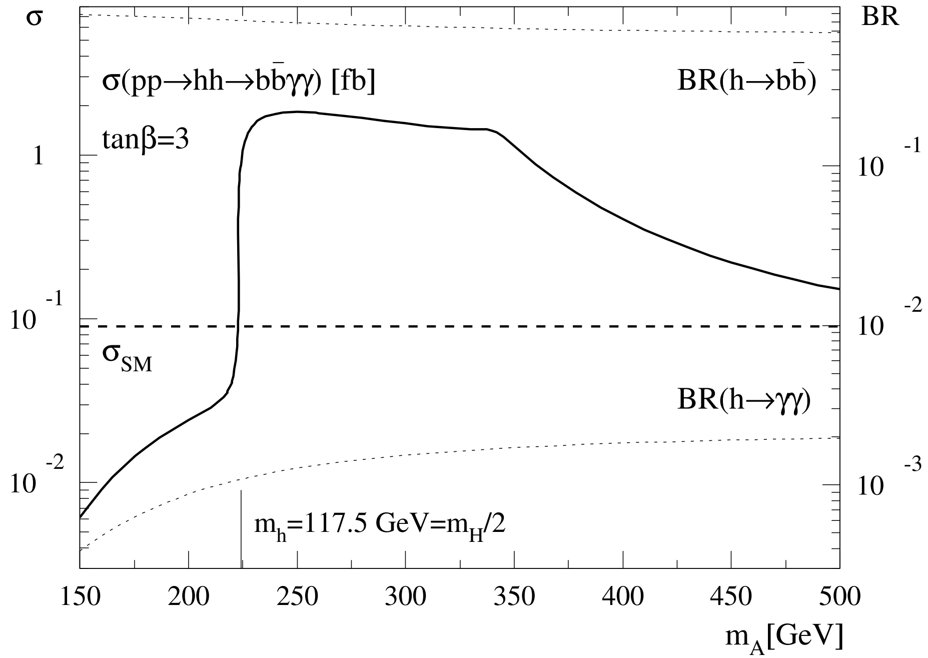


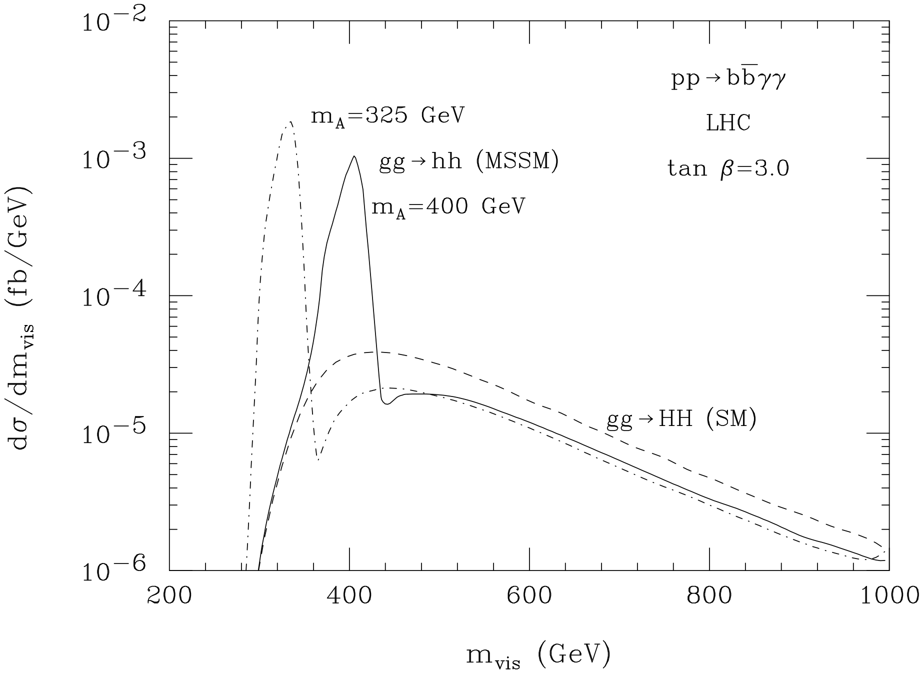
$g_{Hbb,Abb} \propto \tan\beta$, but not $\lambda \therefore$ box wins out by $\tan\beta^2$

(in addition, typically swamped by $H/Ab\bar{b}$ background)

$\longrightarrow$ measurement useless ...

...with an interesting exception: resonant $H \to hh$ production

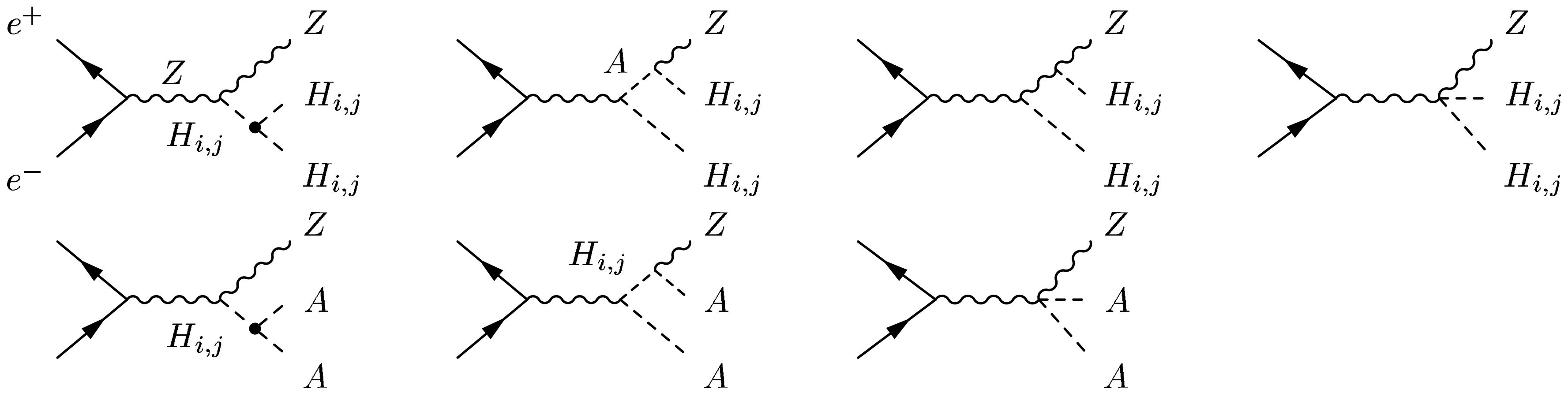




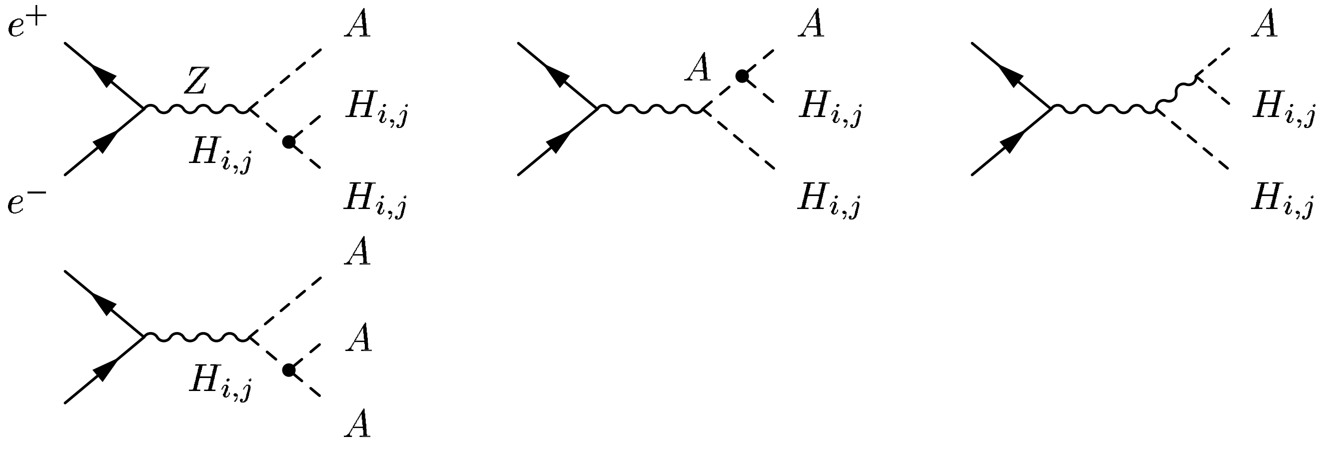
MSSM $e^+e^- \to \phi_i\phi_j$ at an ILC

Don't have annoying interference with dominant box diagrams...

double Higgs-strahlung: $e^+e^- \to ZH_iH_j,\ ZAA\ [H_{i,j} = h, H]$



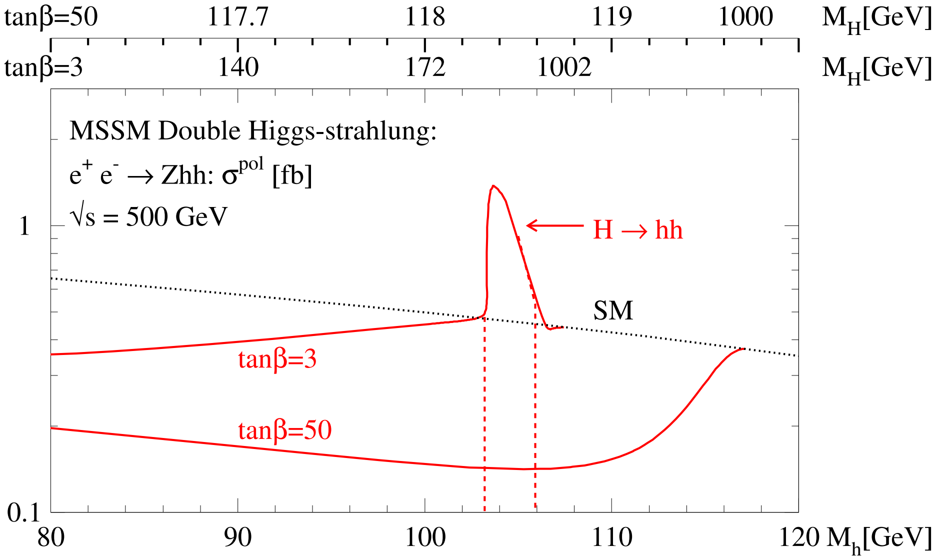
triple Higgs production: $e^+e^- \to AH_iH_j,\ AAA$

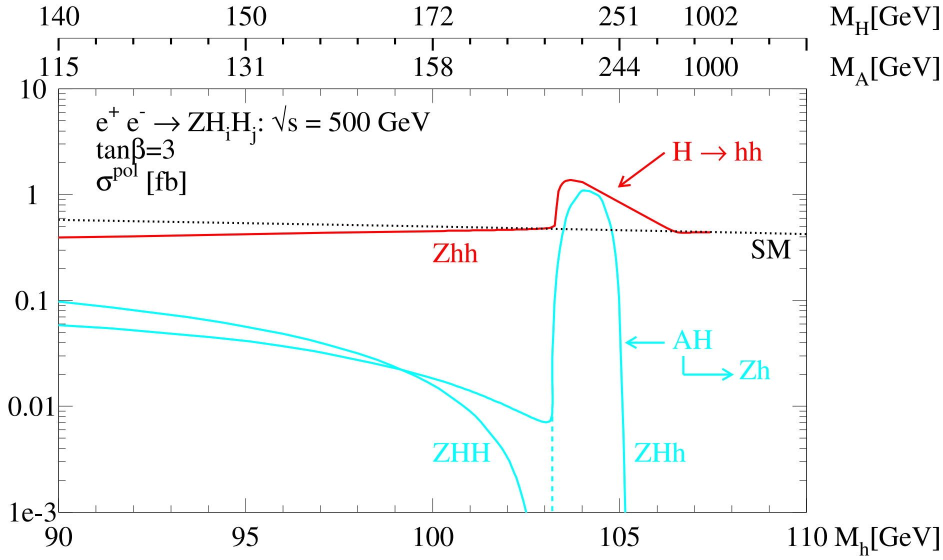


plus WBF diagrams...

MSSM $e^+e^- \to \phi_i\phi_j$ at an ILC

What do the cross sections look like compared to the SM?

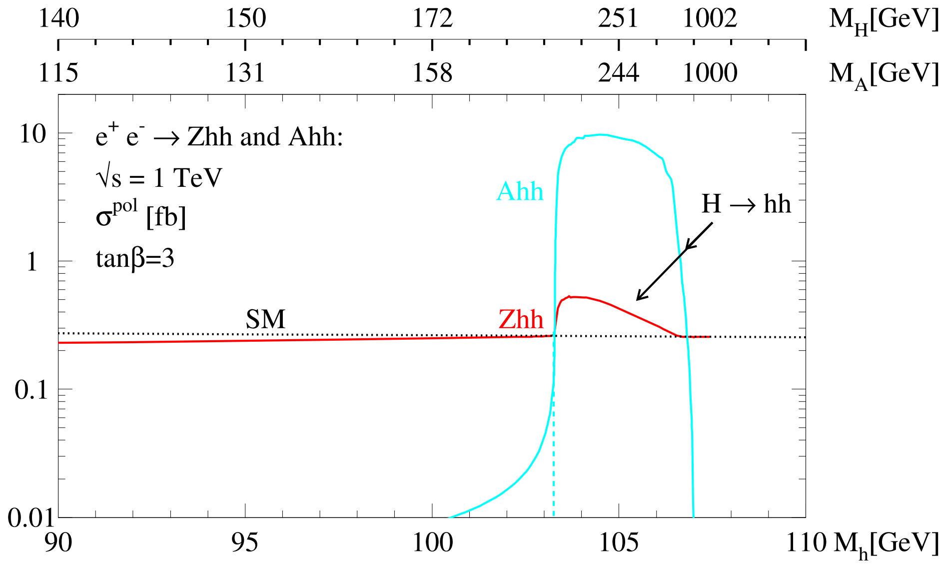




Mostly smaller than SM,

except where resonant

→ makes analyses very tough



SUMMARY PART 3

- In the absence of direct observation of new physics,
  make an anomalous couplings analysis using higher-dim. operators.
  $\longrightarrow$ probes to many TeV in general
- Variety of Higgs sectors BSM is vast.
  Working in the MSSM is “conventional” as SUSY is attractive.
- General 2HDMs have 5 states:
  2 CP-even neutrals, 1 CP-odd neutral, and a charged pair.
- MSSM Higgs sector defined mostly by M_A, $\tan\beta$, M_S and A_t.
- Become familiar with the general characteristics of
  h,H,A couplings as a function of M_A and $\tan\beta$.
- MSSM Higgs pheno is *mostly* variations on SM pheno.
- Charged Higgses are *tough* to find, but crucial.
- MSSM Higgs self-coups impossible to measure except resonantly.