Discriminate MSSM Higgs Sector from its Alternative

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Based on collaborations with:

- S. Kanemura, PLB 530 (2002) 188, hep-ph/0112165
- S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha, PLB 558 (2003) 157, hep-ph/0211308
- Q.-H. Cao, S. Kanemura, PRD (2004), hep-ph/0311083.

Introduction

- After the discovery of the Higgs bosons, we have to ask whether we have detected the Higgs bosons predicted by the MSSM (Minimal Supersymmetry Standard Model), not, say, the 2HDM (Two-Higgs-Doublet Model)?

  (Both models predict h^0, H^0, $H^\pm$ and A.)

  ⇒ Check their Couplings and Masses.

- Measuring the Higgs self-coupling (λ_{hhh})

- Testing the MSSM mass relation

$$\boxed{M_{H^+}^2 = M_A^2 + m_W^2}$$

via the associated production of A and H^+.

Introduction

LEP: 114GeV $< m_h^{\mathrm{SM}} <$ 196 GeV (95% CL)
Tevatron, LHC: Discovery of at least one Higgs boson

Once a Higgs boson (h) is found,
precision study at Linear Colliders (LC's)

TESLA TDR
ACFA Report
Snowmass Resource Book

- Nature of EWSB g_{hWW}, g_{hZZ}

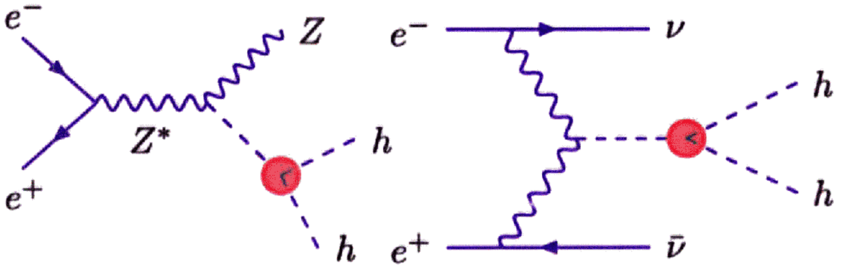
  $\sigma(e^+e^- \to Zh)$, $\sigma(e^+e^- \to \bar{\nu}\nu h)$ $\Rightarrow \mathcal{O}(1\%)$

- Origin of fermion masses: Yukawa couplings Y_f

  $B(h \to \bar{f}f') \Rightarrow \mathcal{O}(1\%)$.

- Higgs potential: Higgs self-coupling λ_{hhh}

  Double Higgs production



λ_{hhh} can be measured in $\mathcal{O}(10-20\%)$ accuracy at LC: $\sqrt{s} = 0.5 - 1.5$ TeV, $\mathcal{L} = 1ab^{-1}$

Radiative corrections

Precision Measurement at a LC

$$\Delta^{\mathrm{Exp}} g_{hVV}/g_{hVV} \sim 1\%$$

$$\Delta^{\mathrm{Exp}} \lambda_{hhh}/\lambda_{hhh} \sim 10 - 20\%$$

$\Longleftrightarrow$ Radiative Corrections

Leading top-loop contribution

- hVV **coupling**

$$g_{hZZ} \simeq \frac{2m_Z^2}{v}\left(1 - \frac{5N_c m_t^2}{96\pi^2 v^2} + \cdots\right),$$

loop effect ~ 1%

- hhh **coupling**

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

A m_t^4 term appears in the 1-loop correction.
loop effect ~ 10%

The corrections are comparable to the measurement accuracy
$\Rightarrow$ How about new physics effects?

The two Higgs doublet model

A simplest extension of the SM Higgs sector
for various physics motivations

(MSSM, extra CP phases, topcolor, etc)

- THDM with a softly-broken discrete symmetry:

$$(\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2)$$

$\Rightarrow$ Natural FCNC suppression

Yukawa interaction (Model II):

$$\mathcal{L}_{\text{II}} = -y_D \overline{Q}_L \Phi_1 b_R - y_U \bar{t}_R \Phi_2^\dagger Q_L + (h.c.).$$

Higgs potential:

$$\begin{aligned} V_{\text{THDM}} &= +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)} \\ &+ \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \\ &+ \lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right]. \end{aligned}$$

Φ_1 and $\Phi_2 \Rightarrow$ h, H, A^0, $H^\pm$ $\oplus$ 3 Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

8 parameters : $\Rightarrow \{m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \alpha,\ \beta,\ v,\ M_{\text{soft}}\ \}$

v (VEV) $\simeq$ 246 GeV, $\tan\beta\ (= \langle\Phi_2\rangle/\langle\Phi_1\rangle)$

α: mixing angle between h and H

$M_{\text{soft}}\ \ (= \frac{m_3}{\sqrt{\cos\beta \sin\beta}})$:
soft-breaking scale of the discrete symm.

- Masses of physical Higgs bosons:

$$\begin{aligned} m_h^2 &= v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2} \sin^2 2\beta\right) + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}), \\ m_H^2 &= M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda) \sin^2\beta \cos^2\beta + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}), \\ m_{H^\pm}^2 &= M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2, \\ m_A^2 &= M_{\text{soft}}^2 - \lambda_5 v^2. \end{aligned}$$

M_{soft}: soft breaking scale
of the discrete symmetry

- M_{soft} determines decoupling/non-decoupling property of heavy Higgs bosons ($\Phi = A, H^\pm$ or H)

$$m_\Phi^2 = M_{\text{soft}}^2 + \lambda_i v^2,$$

Decoupling: for $m_\Phi^2 \sim M_{\text{soft}}^2$ $(M_{\text{soft}}^2 \gg \lambda v^2)$

Loop-effects of $H, A, H^\pm$ decouple

(Decoupling Theorem)

Non-Decoupling: for $m_\Phi^2 \sim \lambda_i v^2$ $(M_{\text{soft}}^2 \lesssim \lambda v^2)$

$\mathcal{O}(m_\Phi^n)$ terms in the low energy observables

(similar to the top effects: $m_t^2 = y_t^2 v^2/2$)

The tree-level coupling constants in the THDM

$$g_{hZZ}^{\text{tree}} = +\frac{2m_Z^2}{v}\sin(\beta-\alpha)$$

$$\lambda_{hhh}^{\text{tree}} = -\frac{3}{2v\sin 2\beta}\left[\{\cos(3\alpha-\beta)+3\cos(\beta+\alpha)\}\, m_h^2 -4\cos^2(\alpha-\beta)\cos(\alpha+\beta)M_{\text{soft}}^2\right]$$

- $\sin(\beta-\alpha) \simeq 1$ (Decoupling regime)

$$g_{hZZ}^{\text{tree}} \simeq \frac{2m_Z^2}{v} = g_{hZZ}^{\text{tree}}(\text{SM}) \, ,$$

$$\lambda_{hhh}^{\text{tree}} \simeq \frac{3m_h^2}{v} = \lambda_{hhh}^{\text{tree}}(\text{SM})$$

Loop correction is essentially important!

- $\sin(\beta-\alpha) \not\simeq 1$

The tree-level deviation from the SM prediction appears.

Tree-Level Deviation $\oplus$ Loop Correction

Radiative corrections to g_{hZZ} and λ_{hhh} in the THDM

One-loop calculation in the on-shell scheme

The 1-loop contribution for $\sin(\beta-\alpha) \simeq 1$

$$g_{hZZ}^{\text{reno}} \simeq \frac{2m_Z^2}{v}\left[1-\frac{1}{16\pi^2}\left\{\frac{5}{6}\frac{N_c m_t^2}{v^2}+\frac{2}{3}\frac{m_\Phi^2}{v^2}\left(1-\frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^2\right\}\right]$$

$$\lambda_{hhh}^{\text{reno}} \simeq -\frac{3m_h^2}{v}\left[1+\frac{1}{16\pi^2}\left\{ -\frac{16}{3}\frac{N_c m_t^4}{v^2 m_h^2}+\frac{16}{3}\frac{m_\Phi^4}{m_h^2 v^2}\left(1-\frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^3\right\}\right]$$

$$(\Phi = H, A, H^+)$$

In $\lambda_{hhh}^{\text{reno}}$, $\mathcal{O}(m_\Phi^4)$ terms appear with a suppression factor

$$m_\Phi^4\left(1-\frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^3 \rightarrow \begin{cases} \dfrac{\lambda_i v^2}{m_\Phi^2}, \quad (m_\Phi^2 \sim M_{\text{soft}}^2), & \text{MSSM} \\ \quad \text{decoupling for } m_\Phi \rightarrow \infty & \\ m_\Phi^4, \quad (m_\Phi^2 \sim \lambda_i v^2), & \\ \quad \text{non decoupling effect} & \end{cases}$$

Dynamical SB, EW baryogen.

Scan Analysis

Free parameters in the THDM:

$\tan\beta$, m_H, $m_{H^\pm}$, m_A, M_{soft}

for fixed $m_h = 120$ GeV, and each $\delta \equiv 1 - \sin^2(\alpha - \beta)$.

Searching allowed region for the deviation in the hZZ and hhh vertices from the SM prediction.

Parameter constrained by

- LEP Precision Data:

  Constraint on the (S,T) parameters

- Perturbative unitarity — Lee,Quigg,Thacker

  $|a^0(W_L^+W_L^- \to W_L^+W_L^-)| < \xi, \quad (\xi = 1/4)$

  for 15 channels $W_L^+W_L^-$, Z_LZ_L, Z_Lh, hh, hH, ...

  Kanemura,Kubota,Takasugi

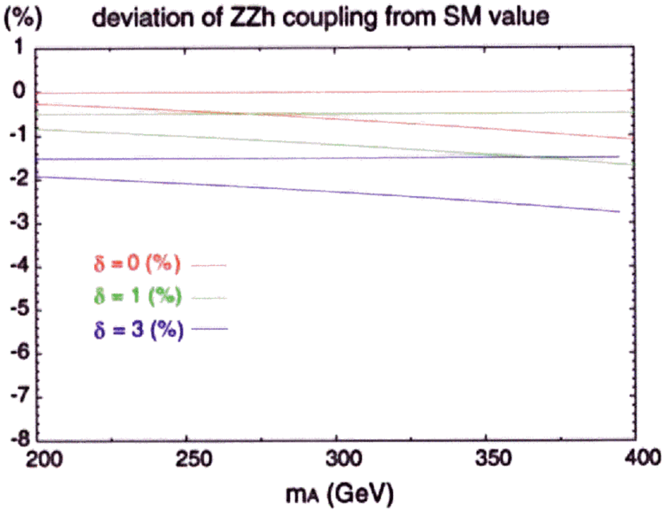
  Akeroyd,Arhrib,Naimi

- Vacuum stability

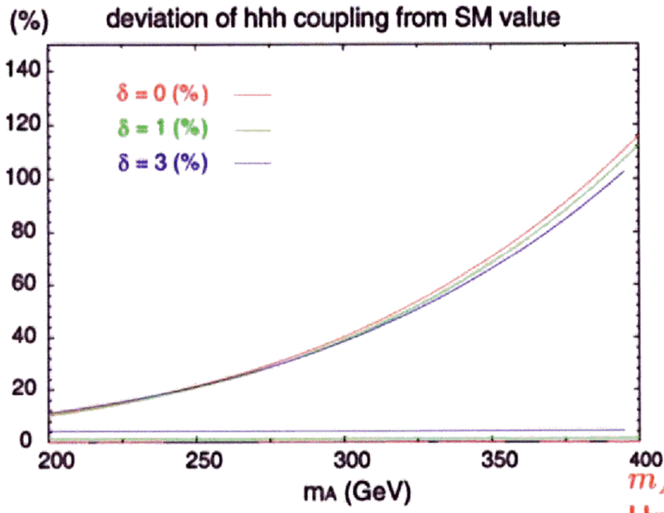
  $V_{\text{eff}}(\langle\Phi_1\rangle, \langle\Phi_2\rangle) \geq 0$ for $\langle\Phi_i\rangle \to \infty$.

  Deshpande, Ma; Sher

Non-decoupling Effects



hZZ coupling
Rediative corr.
$\sim 1\%$



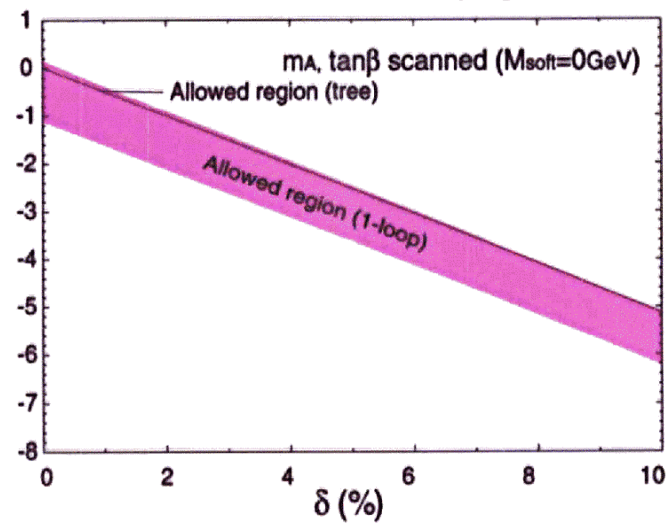
hhh coupling
Rediative corr.
$\sim$ 30-100%
due to
the m_A^4 term

$m_A \lesssim 400$ GeV
Unitarity Bound

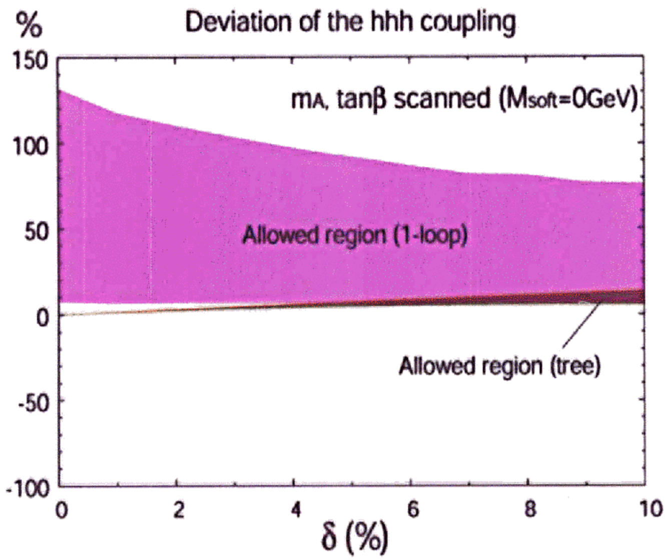
$\delta \equiv 1 - \sin^2(\alpha - \beta)$

$M_{\text{soft}} = 0$, $\tan\beta = 1$, $m_A = m_H = m_{H^\pm}$

Allowed Region ($M_{\text{soft}} = 0$ GeV)



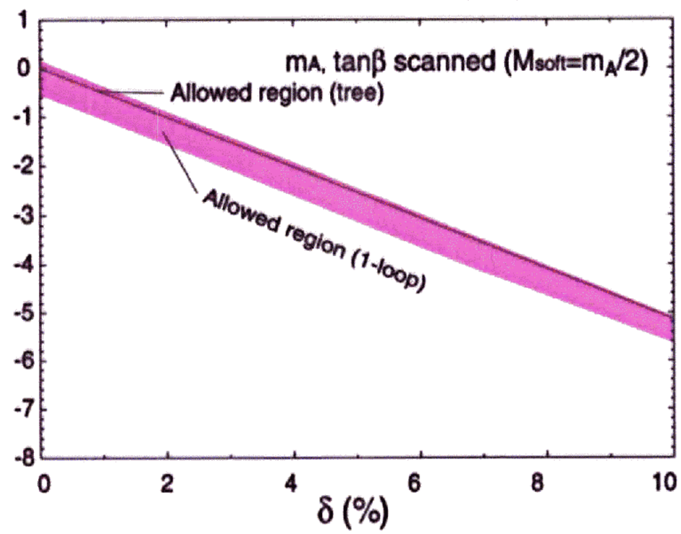
hZZ coupling
Deviation
from the SM
$\sim 1\%$



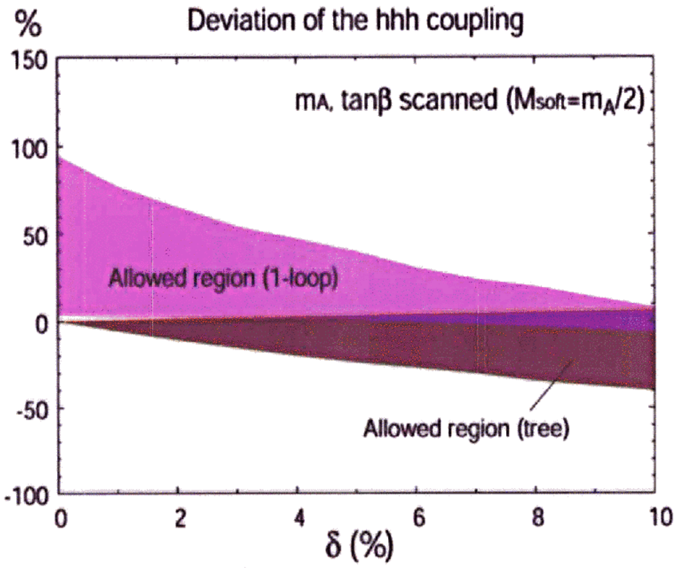
hhh coupling
Deviation
from the SM
$\sim 100\%$
due to
the m_A^4 term

$\delta \equiv 1 - \sin^2(\alpha - \beta)$

Allowed Region ($M_{\text{soft}} = m_A/2$)



hZZ coupling
Deviation
from the SM
$\lesssim 1\%$



hhh coupling
Deviation
from the SM
$\lesssim$ 30-90%
due to
the m_A^4 term

$\delta \equiv 1 - \sin^2(\alpha - \beta)$

Summary

One-loop effective couplings of hZZ and hhh in the SM and the THDM

Scan Analysis:

- hZZ: deviation from the SM

  One-loop contribution $(\sim 1\%)$

  $\oplus$ Tree-level difference when $\delta = 1 - \sin^2(\alpha - \beta) \neq 0$

- hhh: deviation from the SM

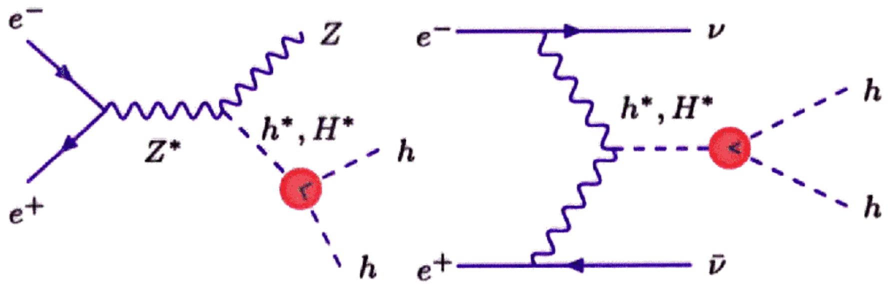
  One-loop $\mathcal{O}(m_A^4)$ contribution $\sim +30$ to $+100\%$

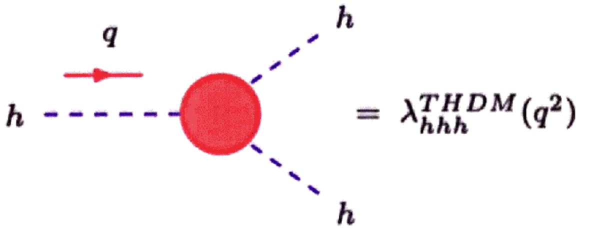
  $\oplus$ Tree-level difference when $\delta \neq 0$

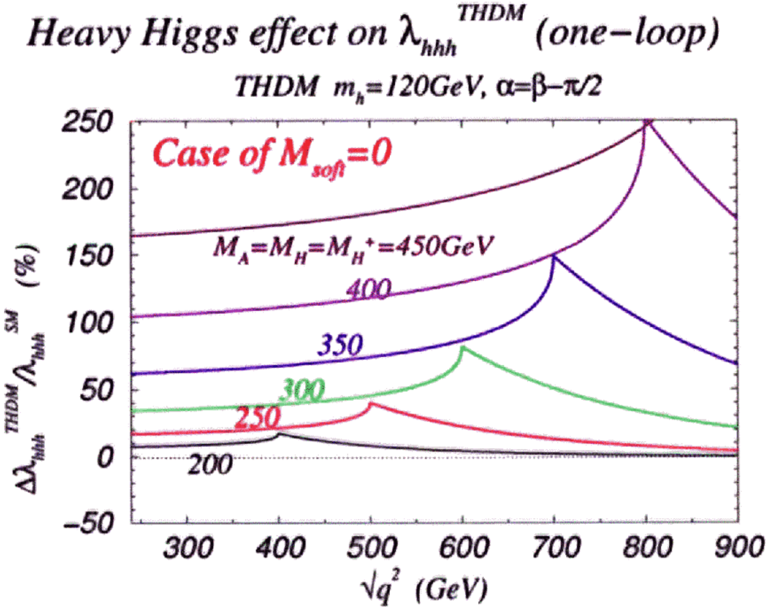
Even when the hZZ measurement is consistent with the SM by $\mathcal{O}(1)$ %, hhh can deviate from the SM by $+30$ to $+100$ % due to the non-decoupling loop effect of heavy Higgs bosons

Such deviation in the hhh coupling is testable at a Linear Collider

Momentum dependences







Self-coupling λ_{hhh} in the MSSM

Hollik, Panaranda
Dobado et al.

The MSSM Higgs sector: a decoupling THDM ($\lambda_i \sim \mathcal{O}(g^2)$)

Relations among heavy Higgs bosons:

$$\begin{aligned} M^2_{\text{soft}} &= m^2_A, \\ m^2_{H+} &= m^2_A + m^2_W, \\ m^2_H &\sim m^2_A, \quad (m_A \to \infty) \\ \sin^2(\alpha-\beta) &\sim 1, \quad (m_A \to \infty) \end{aligned}$$

$$\frac{\Delta\lambda^{MSSM}_{hhh}}{\lambda^{SM}_{hhh}} \propto m^4_{H+}\left(1-\frac{M^2_{soft}}{m^2_{H+}}\right)^3 \to \frac{m^6_W}{m^2_{H+}}. \qquad \text{(Decoupling)}$$

Loop corrections due to H, H^+, A
⇒ small for $\sin^2(\alpha-\beta) \simeq 1$ (less than 1%)

- Stop ($\tilde{t}$) loop contributions to λ_{hhh}

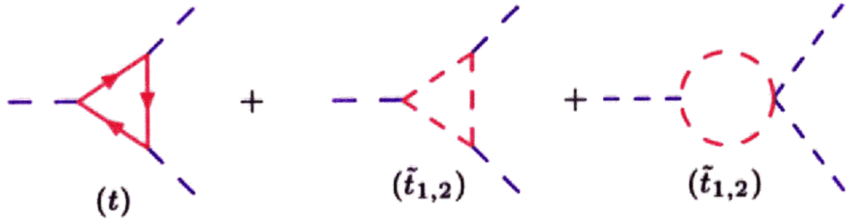
The stop mass matrix

$$M^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{Q}} + m^2_t + \mathcal{O}(m^2_Z) & m_t X_t \\ m_t X_t & M^2_{\tilde{U}} + m^2_t + \mathcal{O}(m^2_Z) \end{pmatrix},$$

where $X_t = A_t + \mu \cot\beta$.

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & -\sin\theta_{\tilde{t}} \\ \sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}.$$

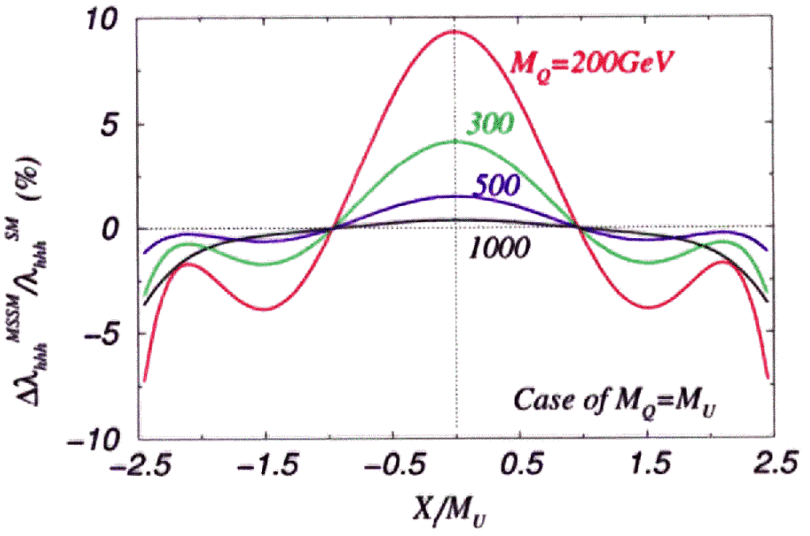
Feynman diagrams



+ (Counter Terms)

The leading contributions of stops to λ_{hhh}

$$\frac{\Delta\lambda^{MSSM}_{hhh}}{\lambda^{SM}_{hhh}} = \frac{N_{c_t} m^4_t}{3\pi^2 v^2 m^2_h}\frac{m^2_t}{M^2_Q}\left(+1-\frac{3}{2}\frac{X^2_t}{M^2_Q} +\frac{1}{2}\frac{X^4_t}{M^4_Q}-\frac{1}{20}\frac{X^6_t}{M^6_Q}\right). \quad (M^2_{\tilde{Q}} = M^2_{\tilde{U}})$$



Summary

- In THDM, heavy Higgs (H, A and H^+) effects

$$\frac{\Delta\lambda_{hhh}^{THDM}}{\lambda_{hhh}^{SM}} \sim + \frac{M_\Phi^4}{16\pi^2 v^2 m_h^2}\left(1 - \frac{M_{\rm soft}^2}{M_\Phi^2}\right)^3$$

The correction can be $\mathcal{O}(100\%)$
for a light h ($m_h \sim 120 - 160$GeV)

even if the data for
$\sigma(e^+e^- \to Xh)$, $Br(h \to X)$ and Γ_h
agree with the SM prediction.

⇓

Such large non-decoupling effects
is testable at LC.

- MSSM

Decoupling for $m_A^2 \to \infty, M_{\tilde{Q}}^2 \to \infty$.

The stop-loop correction can
reach to 5-8% for small $M_{\tilde{Q}}^2$

- A typical SUSY phenomenology study depends on at least two SUSY parameters,

  e.g. $\tan\beta$ and m_A,

  and

  various physics reach depends on other SUSY parameters as well,

  e.g. μ value and stop mixings.

  ⇒ Very often, the physics reach of a process is expressed in terms of bounds on

  $\boxed{\sigma \text{ (production)} \times \text{Br (decay branching ratio)}}$

  where both σ and Br depend on SUSY parameters.

- In general, detection efficiency also depends on SUSY parameters,

  e.g. a Higgsino and a gaugino type of chargino have different decay distributions.

⇒

Physics predictions depend strongly on the details of SUSY parameters.

Our task is to find a SUSY process

- whose tree level σ (production) only depends on ONE SUSY parameter that can be determined by kinematic variable (e.g. invariant mass).
- that is not sensitive to the detailed SUSY parameters via radiative corrections.
- that can bound the SUSY models by (product of) Br (decay branching ratio) without convoluting with σ (production).
- that can be used to distinguish MSSM from its alternatives, e.g. 2HDM.
- whose final state particle kinematics can be properly modeled without specifying any SUSY parameters.

  $\Rightarrow$ The detection efficiency can be accurately determined.

Here is that promising process

$$\boxed{p\bar{p}, pp \to W^{\pm} \to AH^{\pm}}$$

- The vertex $W^{\mu} - A - H^{+}$ is determined by **gauge interaction**, which gives

$$\frac{g}{2}(p_A - p_{H^+})^{\mu}\,.$$

$\Rightarrow$

No SUSY parameter.

- The production cross section $\sigma(AH^{+})$ in general depends on two masses:

M_A **and** M_{H^+}

e.g. in 2HDM.

But, in MSSM,

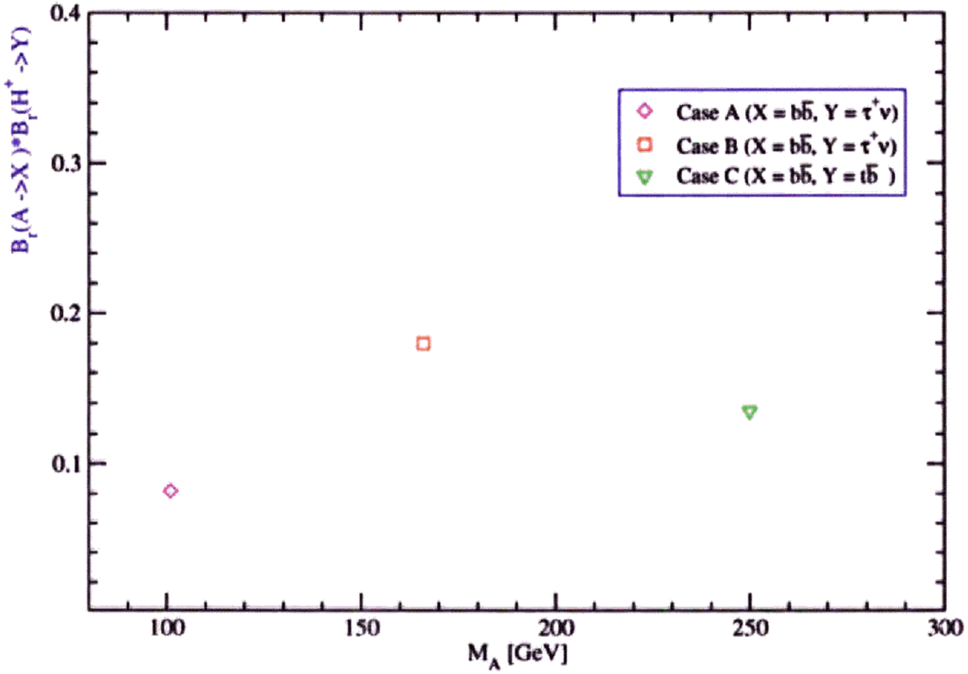
$$\boxed{M_{H^+}^2 = M_A^2 + m_W^2.}$$

$\Rightarrow$ $\sigma(AH^{+})$ only depends on g and M_A.

(M_A can be determined from its decay kinematics, e.g. the ivariant mass of $b\bar{b}$ in $A \to b\bar{b}$.)

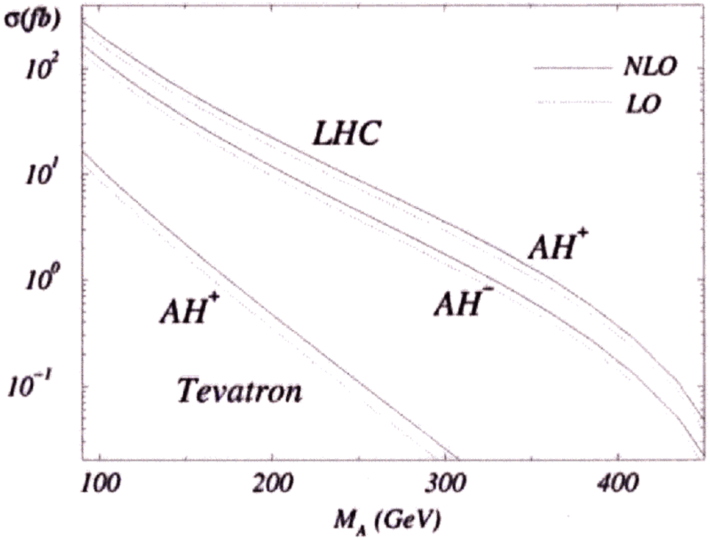
Constraint on MSSM

Constraints on the product of branching ratios $B(A \to b\bar{b}) \times B(H^+ \to \tau^+\nu_\tau)$ as a function of M_A for Case A and Case B, and $B(A \to b\bar{b}) \times B(H^+ \to t\bar{b})$ for Case C, at the LHC, where τ^+ decays into $\pi^+\bar{\nu}_\tau$ channel.



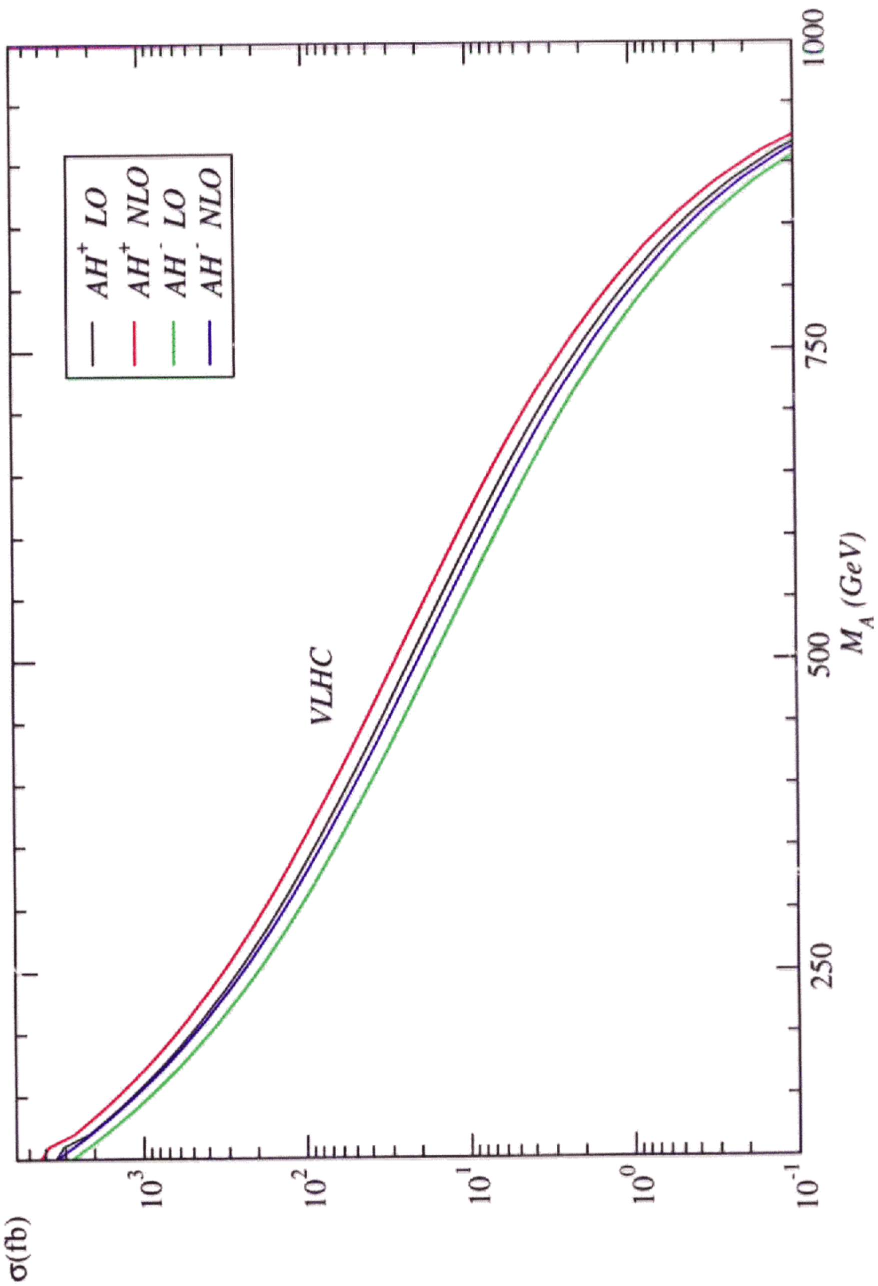
Production rates

The LO (dotted lines) and NLO QCD (solid lines) cross sections of the AH^+ and AH^- pairs as a function of M_A. The cross sections for AH^+ and AH^- coincide at the Tevatron for being a $p\bar{p}$ collider.



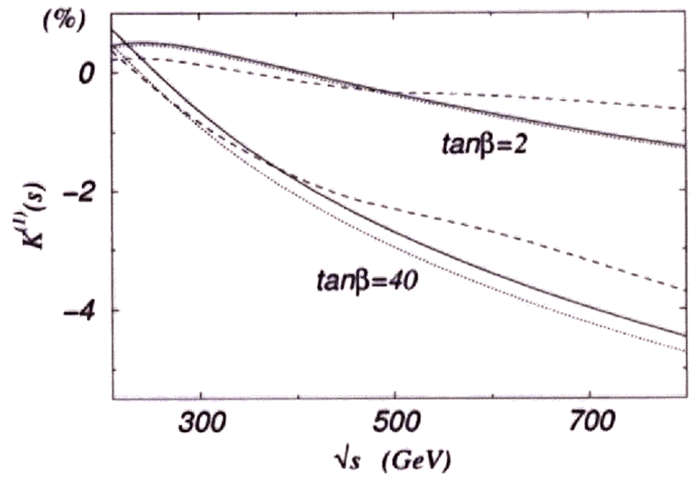
- The NLO QCD correction is about 20%.
- Uncertainty due to parton distribution is about 6% at Tevatron and 5% at LHC for $M_A = 120\,\text{GeV}$, when applying the prescription given in hep-ph/0101032 (by Pumplin,Stump,Tung).
- The higher order QCD correction is estimated to be about 10% at Tevatron and less than 1% at LHC, when varying the factorization scale around the c.m. energy of $q\bar{q}' \to AH^\pm$ by a factor of 2.

The LO and NLO QCD cross sections of the AH^+ and AH^- pairs as a function of M_A at VLHC



Electroweak K-factor

The K-factor of $q\bar{q}' \to H^+A$ for $M_A = 90$ GeV, as a function of the invariant mass $\sqrt{s}$ of $q\bar{q}'$. The solid curves come from the top and bottom quark contributions. The squark-loop contributions are shown by dotted curves for those without stop mixing and by dashed curves for those with maximal stop mixing, respectively.



- The K-factor at the parton level:

$$K^{(1)}(q^2) \equiv 2\,\mathrm{Re}\,F^{(1)}(q^2).$$

- The one-loop electroweak correction to the production rate of pp, $p\bar{p} \to AH^\pm$ is smaller than the PDF uncertainties.

Radiative correction to the MSSM mass relation

$$\boxed{M_{H^+}^2 = M_A^2 + m_W^2.}$$

- In the on-shell scheme, after fixing M_A and $\tan\beta$, M_{H^+} is determined by

$$\begin{aligned} M_{H^\pm}^2 &= M_A^2 + m_W^2 + \Pi_{AA}(M_A^2) \\ &\quad -\Pi_{H^+H^-}(M_A^2 + m_W^2) + \Pi_{WW}(m_W^2), \end{aligned}$$

  where $\Pi(q^2)$ are the self-energies.

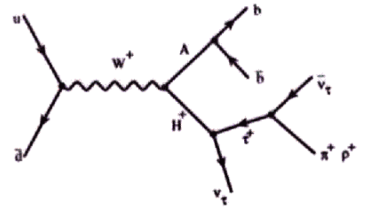
- There are 7 parameters in the Higgs sector of the MSSM. They are g', g, v_1, v_2, m_1, m_2, and m_3.

  Beyond the Born level, the wavefunction renormalization factors Z_{H_1} and Z_{H_2} are also needed.

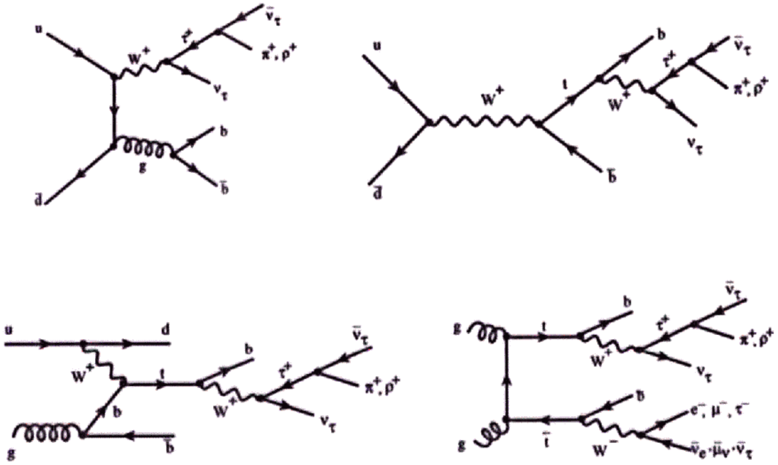
- The standard model parameters are fixed by defining α_{em}, m_W and m_Z, and the additional SUSY parameters in the Higgs sector are fixed by the following renormalization conditions:
  - the tadpole contributions ($T_{H_1} = 0$, $T_{H_2} = 0$),
  - the on-shell condition for the mass of A,
  - the on-shell condition for the wavefunction of A,
  - a renormalization condition on $\tan\beta$ (which requires $\delta v_1/v_1 = \delta v_2/v_2$), and
  - a vanishing $A - Z$ mixing for an on-shell A.

Detecting the Signal Event

- Signal



- Backgrounds



- Veto additional lepton and jet from the parton level background events that satisfy

  $p_T(lepton) > 10$ GeV, and $|\eta(lepton)| < 3$.
  $p_T(jet) > 10$ GeV, and $|\eta(jet)| < 3.5$.

- The model parameters, production rates and decay branch ratios

Sets	A	B	C
m_A/Γ_A	101 /3.7	165.7 /5.6	250 /7.9
m_h/Γ_h	96.8 / 3.3	112 /0.04	112 /0.01
m_H/Γ_H	113 /0.38	163 /5.5	247.8 /7.8
m_{H^+}/Γ_{H^+}	126 / 0.43	182 / 0.68	261.4 / 4.2
$\sigma(AH^+)$ [fb]	164	36	5.4
$\sigma(HH^+)$ [fb]	137.4	37.4	5.4
$Br(A \to b\bar{b})$	0.91	0.90	0.89
$Br(H \to b\bar{b})$	0.90	0.90	0.89
$Br(H^+ \to \tau^+\nu)$	0.98	0.90	0.00
$Br(H^+ \to t\bar{b})$	0.00	0.09	0.79
$Br(\tau^+ \to \pi^+\nu)$	0.11	0.11	0.11

where $\tan\beta = 40, \mu = M = 500$GeV.

- Imposing the following *Basic Cuts* :

$$P_T(b, \bar{b}, \pi^+) > 15 \text{ GeV},$$
$$|\eta(b, \bar{b}, \pi^+)| < 3.5,$$
$$\Delta R(b, \bar{b}, \pi^+) > 0.4.$$

Set A ($m_A = 101$GeV)

- Numbers of signal and background events at the LHC with 100 fb^{-1}. The b-tagging efficiency (50%, for tagging both b and $\bar{b}$ jets) is included, and the kinematic cuts listed in each column are applied sequentially.

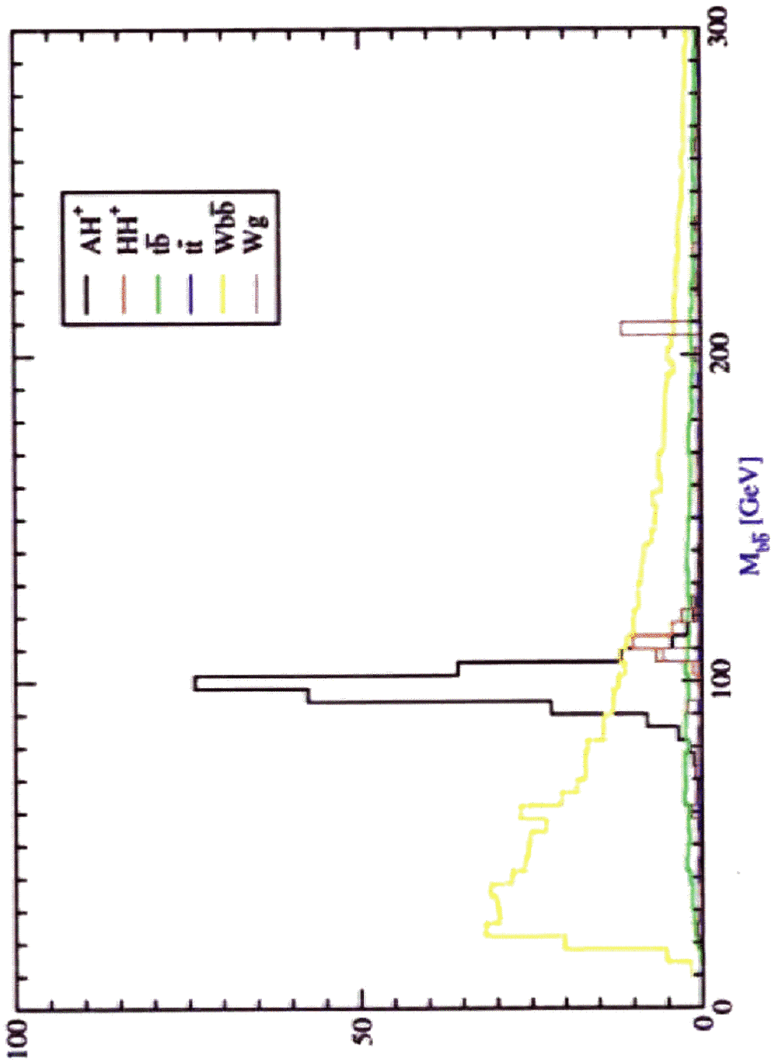
- Signal: AH^+

	Basic Cuts	$\not{E}_T > 50$	$P_T^\pi > 40$	$90 < M_{b\bar{b}} < 110$ [GeV]
AH^+	507	391	241	216
HH^+	48	38	24	0
$Wb\bar{b}$	11555	3111	864	67
$t\bar{b}$	1228	614	163	12
Wg	567	236	68	11
$t\bar{t}$	110	80	17	2
Signal (S)	507	391	241	216
Bckg (B)	13507	4078	1135	92
S/B	0.038	0.095	0.212	2.35
$S/\sqrt{B}$	4.36	6.12	7.14	22.5
$\sqrt{S+B}/S$	0.23	0.17	0.15	0.08

- Signal: HH^+

	Basic Cuts	$\not{E}_T > 50$	$P_T^\pi > 40$	$105 < M_{b\bar{b}} < 125$ [GeV]
HH^+	48	38	24	24
AH^+	507	391	241	26
$Wb\bar{b}$	11555	3111	864	58
$t\bar{b}$	1228	614	163	11
Wg	567	236	68	13
$t\bar{t}$	110	80	17	2
Signal (S)	48	38	24	24
Bckg (B)	13966	4431	1352	101
S/B	0.003	0.008	0.018	0.22
$S/\sqrt{B}$	0.41	0.57	0.65	2.26
$\sqrt{S+B}/S$	2.47	1.76	1.55	0.49

- The invariant mass of $b\bar{b}$, $M(b\bar{b})$:

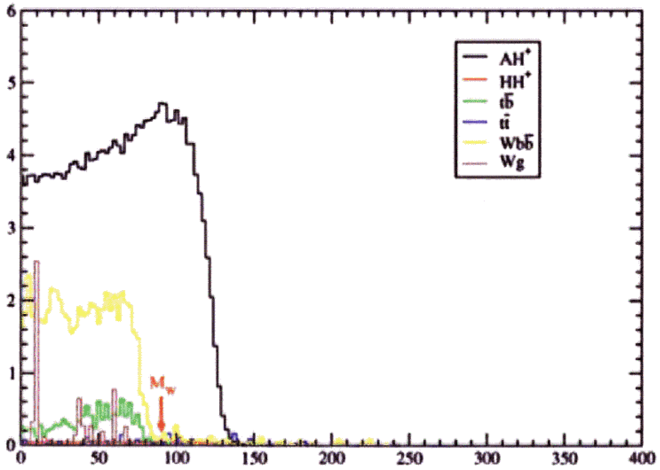


- The transverse mass of π^+ and $\not{E}_T$, i.e. of H^+ in the signal event, after imposing the additional cuts:

$$AH^+ :\ |M(b\bar{b}) - 100| < 10\ \text{GeV}$$

or

$$HH^+ :\ |M(b\bar{b}) - 115| < 10\ \text{GeV}$$



- $\Delta\phi$ is the azimuthal angle between π^+ and $\not{E}_T$, the transvse mass

$$M_T = \sqrt{2\, p_T(\pi)\ \not{E}_T (1 - \cos\Delta\phi)}$$

Summary

- Assuming the double b-tagging efficiency to be 50%, there will be about 190 signal events,
  $$pp \to A(\to b\bar{b})\, H^{+}(\to \tau^{+}(\to \pi^{+}\bar{\nu})\,\nu)$$
  detected at the LHC (with a $100\,\mathrm{fb}^{-1}$ integrated luminosity).
- The total number of background events is about half of the signal event.
- Including the negative charge of π^{-} inreases the signal and the background rate by about 50%.
- One can also include the decay mode
  $\tau^{\pm} \to \rho^{\pm}\nu$
  whose Br is about 22%. Hence, the event rate will roughly be tripled.

⇒ The observed signal event rate can be at the order of 500 to 1000 per LHC year.

⇒

The $AH^{\pm}$ signal is
a promising one, indeed.

Conclusion

- If a signal is not found, studying the $AH^{\pm}$ associated production process can provide an upper bound on the product of the decay branching ratios of A and $H^{\pm}$ as a function of the only one SUSY parameter – M_A.
- In case that a signal is found, the analysis is slightly more complicated.
  - For $M_A \gtrsim 120$ GeV and $\tan\beta \gtrsim 10$, $M_H \sim M_A$ (less than about 10 GeV).

    For $M_A \gtrsim 190$ GeV and $\tan\beta \gtrsim 10$, $\sin^2(\alpha-\beta) \simeq 1$ and $\sigma(q\bar{q}' \to HH^{\pm}) \sim \sigma(q\bar{q}' \to AH^{\pm})$.

    [Generally, the coupling of $W^{\pm}HH^{\mp}$ depends on g and $\sin(\alpha-\beta)$.]
  - Studying different decay channels can help to separate these two production modes. For instance, a heavy H can decay into a ZZ pair at the Born level, but A cannot.
- In conclusion, if no signal is found experimentally, a *conservative* bound on the product of the decay branching ratios of A and $H^{\pm}$ can be derived for a CP-conserving model. This is because in a CP-conserving model, the AH^{+} and HH^{+} production modes do not interfere even if the masses of A and H are about the same. (A is a CP-odd scalar, while H is CP-even.)