Testing Supersymmetry in $AH^{\pm}$ Associated Production

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Based on collaborations with:

- S. Kanemura, PLB 530 (2002) 188, hep-ph/0112165
- 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.)

  $\Rightarrow$ 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^+.

Hunting for Higgs Bosons

- As promised, Tevatron and LHC can reveal SUSY via detecting Higgs bosons.

- But, how do we know we have detected the Higgs bosons predicted by the MSSM, not, say, the 2HDM ?

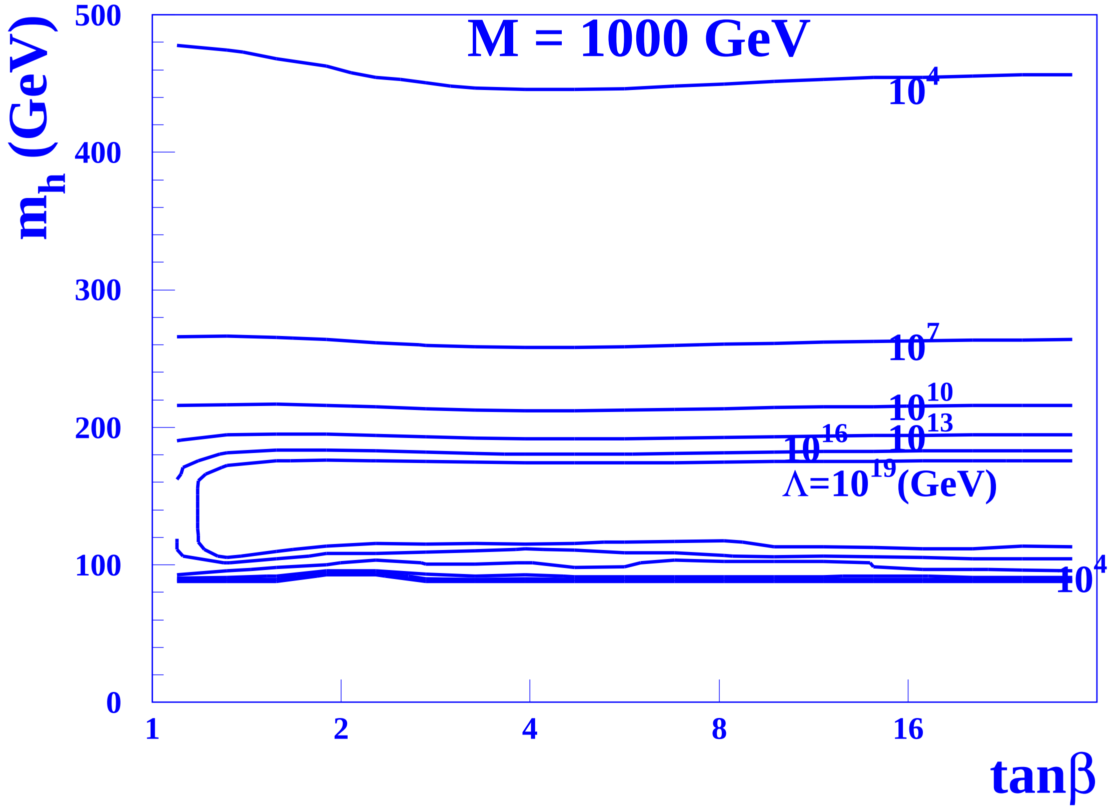
  (Both models predict h^0, H^0, $H^\pm$ and A.)

  $\Rightarrow$ Check their Couplings and Masses.

- The tree level couplings of Higgs bosons to fermions are the same in both models.

- A light h^0 does not exclude 2HDM or Zee model (with two Higgs doublets and one charged singlet to explain the tiny neutrino masses inferred by neutrino oscillation date).

The allowed mass range of
the lightest CP-even Higgs boson h^0



Kanemura, et al., hep-ph/0011357.

- Here, the soft-breaking mass $M = 1000\,\text{GeV}$, and Λ is the cut-off scale of the Zee model.

- The above result also holds for $1000\,\text{GeV} > M > 400\,\text{GeV}$, when $\Lambda \geq 10^7$ GeV.

- For a type-II 2HDM, $M < 400\,\text{GeV}$ implies a light $H^{\pm}$, and is constrained by $b \to s\gamma$ data.

- 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.

  $\Rightarrow$ Very often, the physics reach of a process is expressed in terms of bounds on

σ (production) $\times$ 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.

$\Rightarrow$

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.

The two Higgs doublet model (THDM)

- THDM with a softly-broken discrete symmetry:

$(\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2)$: Natural flaovr conservation

- Yukawa interaction (Model I, II):

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

- Higgs potential ($\supset$ MSSM Higgs sector)

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

Φ_1 and $\Phi_2 \Rightarrow h,\quad H,\quad A^0,\ H^\pm \oplus$ 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:

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

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)

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

For $M_{\text{soft}}^2 \gg \lambda v^2$, then $m_\Phi^2 \sim M_{\text{soft}}^2$

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

(Decoupling Theorem)

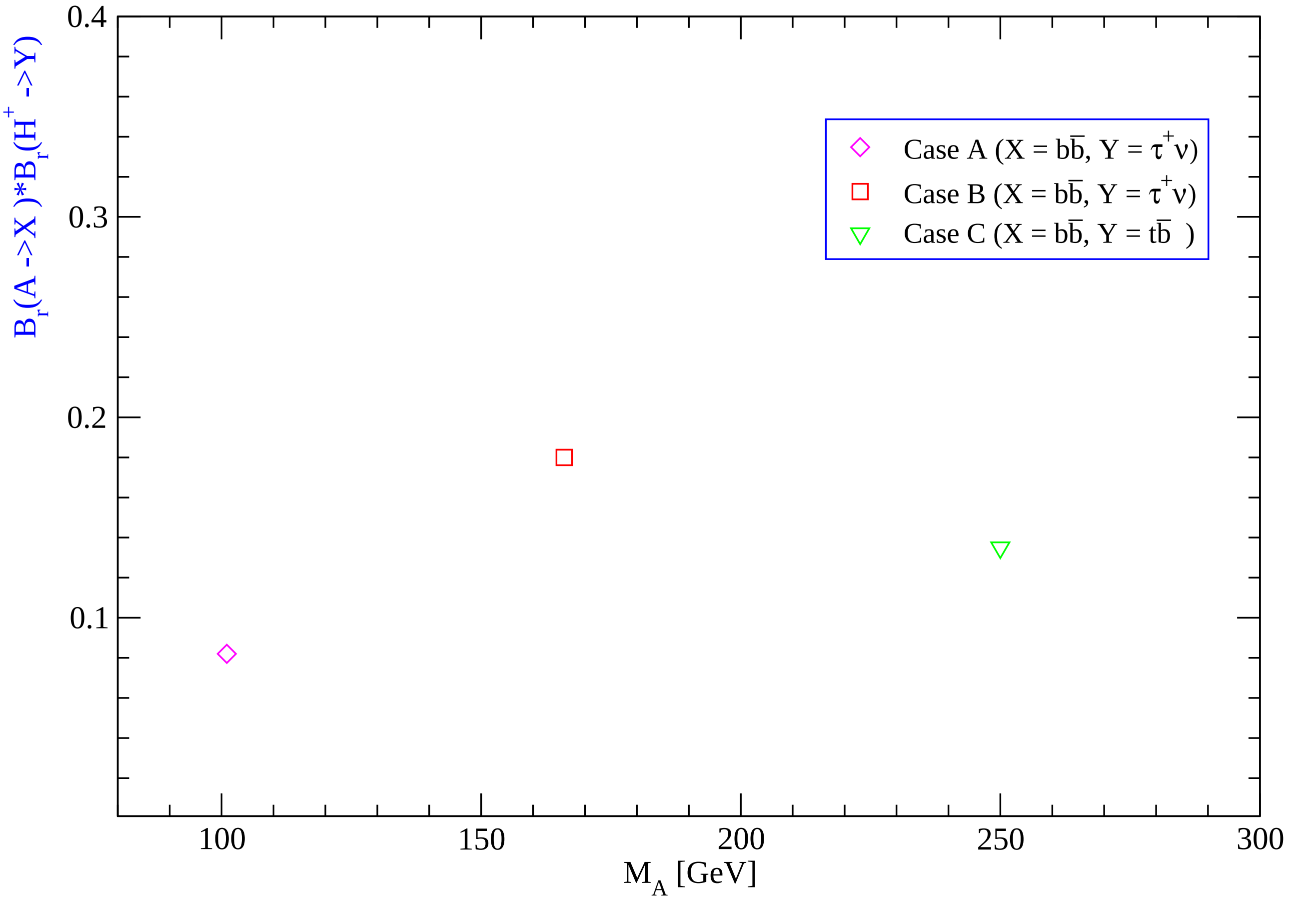
For $M_{\text{soft}}^2 \lesssim \lambda v^2$, then $m_\Phi^2 \sim \lambda_i v^2$

non-decoupling m_Φ^n terms appear
in the low energy observables

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

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.



Here is that promising process

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

- 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,

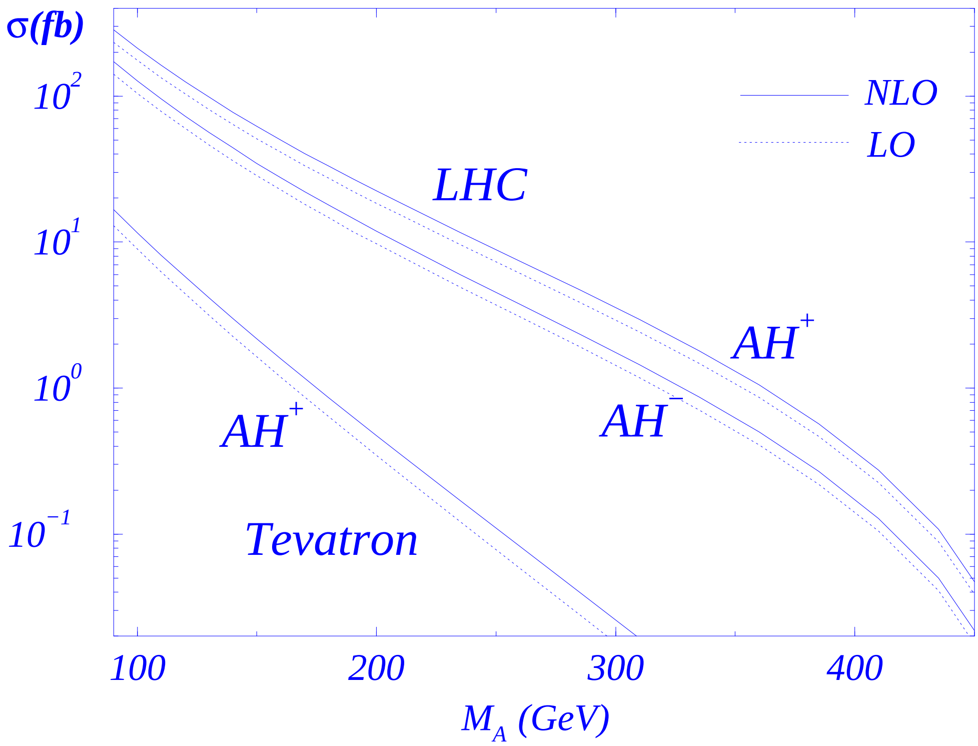
$$M^2_{H+} = M^2_A + m^2_W .$$

$\Rightarrow$ $\sigma(AH^{+})$ 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 $A \rightarrow b\bar{b}$.)

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 $M_A = 120\,\mathrm{GeV}$, 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.

Electroweak radiative corrections

- Calculated in the on-shell renormalization scheme in which M_A is an input parameter, but M_{H^+} is calculated.
- Dominated by t, b and $\tilde{t}_{1,2}, \tilde{b}_{1,2}$ loops due to their potentially large couplings to Higgs bosons.
- The one-loop effective WAH^+ coupling

$$-\frac{\bar{g}}{2}(p_A - p_H)^\mu \left[1 + F^{(1)}(q^2)\right], \qquad (1)$$

- From t, b loops,

$$F^{(1)}_{\text{quark}} \sim \frac{N_c}{16\pi^2}\left[-\frac{1}{4}y_t^2 + \frac{1}{2}\left(\frac{3}{2} - \ln\frac{m_t^2}{m_b^2}\right)y_b^2\right],$$

where $N_c = 3$,

$$y_t^2 = 2m_t^2 \cot^2\beta/v^2$$

$$y_b^2 = 2m_b^2 \tan^2\beta/v^2.$$

- From $\tilde{t}_{1,2}, \tilde{b}_{1,2}$ loops,

$$F^{(1)}_{\text{squark}} \sim \frac{-N_c}{16\pi^2}\left[\left(\frac{3}{4} - \ln 2\right)\left(\frac{Y_{\tilde{t}}}{M}\right)^2 + \left(\frac{13}{6} - 3\ln 2\right)\left(\frac{Y_{\tilde{b}}}{M}\right)^2\right],$$

where

$$Y_{\tilde{t}} = \tfrac{m_t}{v}(A_t \cot\beta + \mu)$$

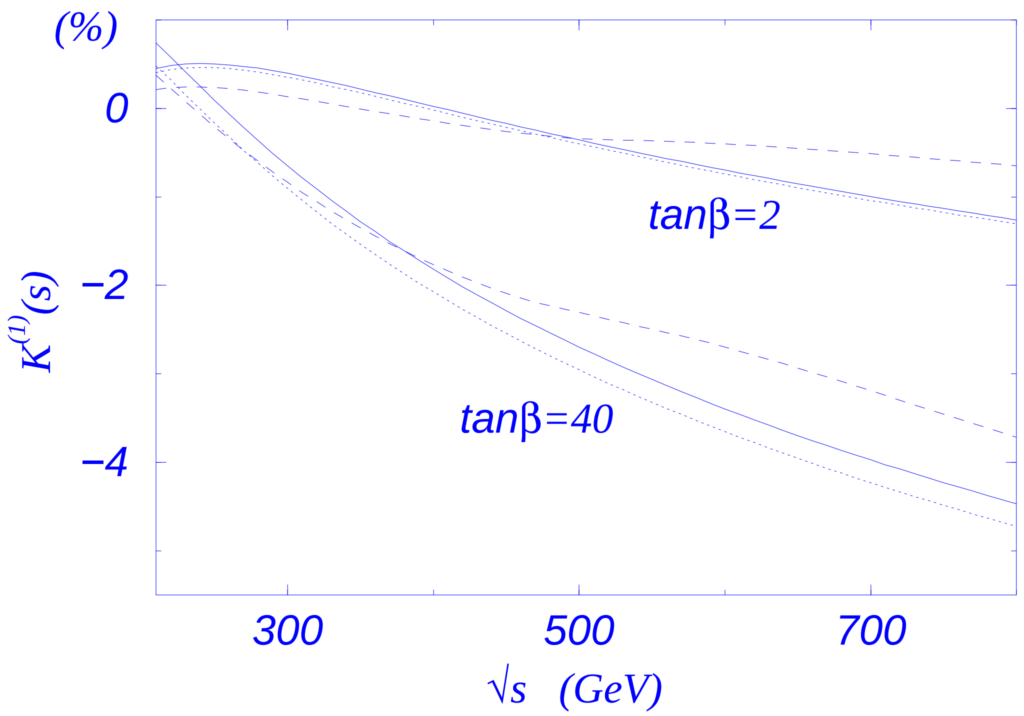
$$Y_{\tilde{b}} = \tfrac{m_b}{v}(A_b \tan\beta + \mu),$$

and $\qquad M \equiv M_{\tilde{Q}} \simeq M_{\tilde{U}} \simeq M_{\tilde{D}}.$

Constrained by ρ parameter and the direct search of squarks.

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 uncern-tainties.

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.

- Define δ by

$$M_{H^\pm} = \sqrt{M_A^2 + m_W^2}\,(1+\delta)\ .$$

- When $A_{t,b}$ and μ are zero (i.e., no-mixing case),

$$\delta \;\sim\; \frac{N_c}{8\pi^2 v^2}\left(\frac{m_t^2 m_b^2}{M_A^2 + m_W^2}\right)\frac{1}{\sin^2\beta\cos^2\beta}\left(1+\ln\frac{M^2}{m_t^2}\right)$$

  which can be large for $\tan\beta \simeq m_t/m_b$ and $M^2 \gg m_t^2$.

- For $2 < \tan\beta < 40$, $M < 2\,\text{TeV}$ and $M_A > 90$ GeV, δ is found to be less than 5%, which is smaller than the typical mass resolution of measuring M_A (about 10% at 100 GeV).

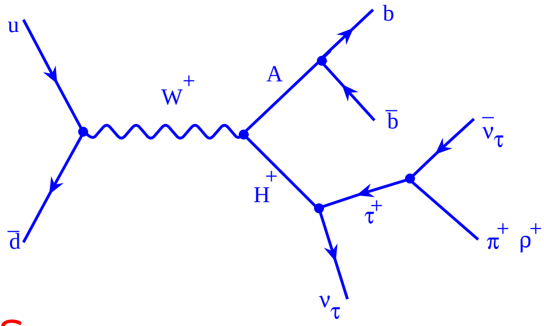
  $\Rightarrow$

  The MSSM mass relation between A and $H^\pm$ holds well beyond tree level.

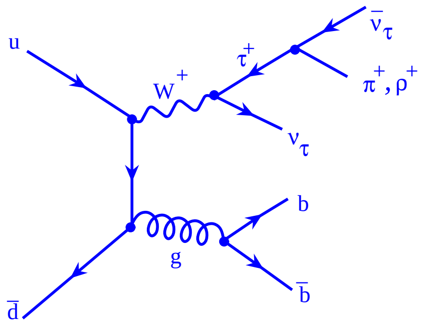
  Thus, to a very good accuracy, the production rate of $AH^\pm$ beyond tree level is also determined by g and M_A.

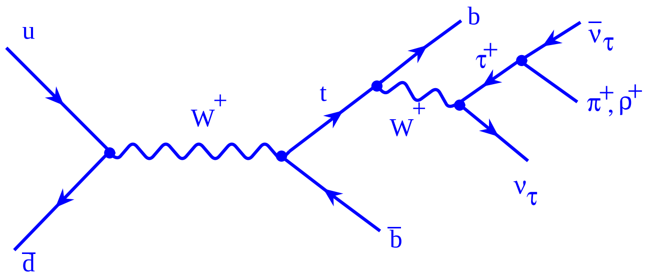
Detecting the Signal Event

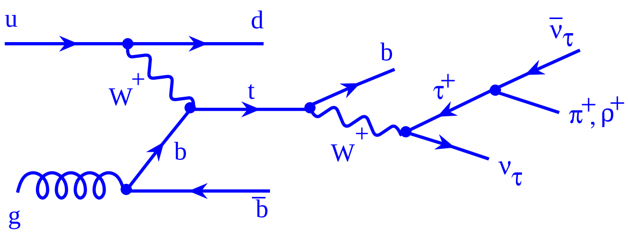
- Signal

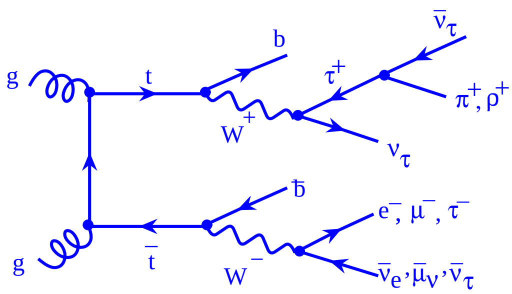


- Backgrounds









- 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)

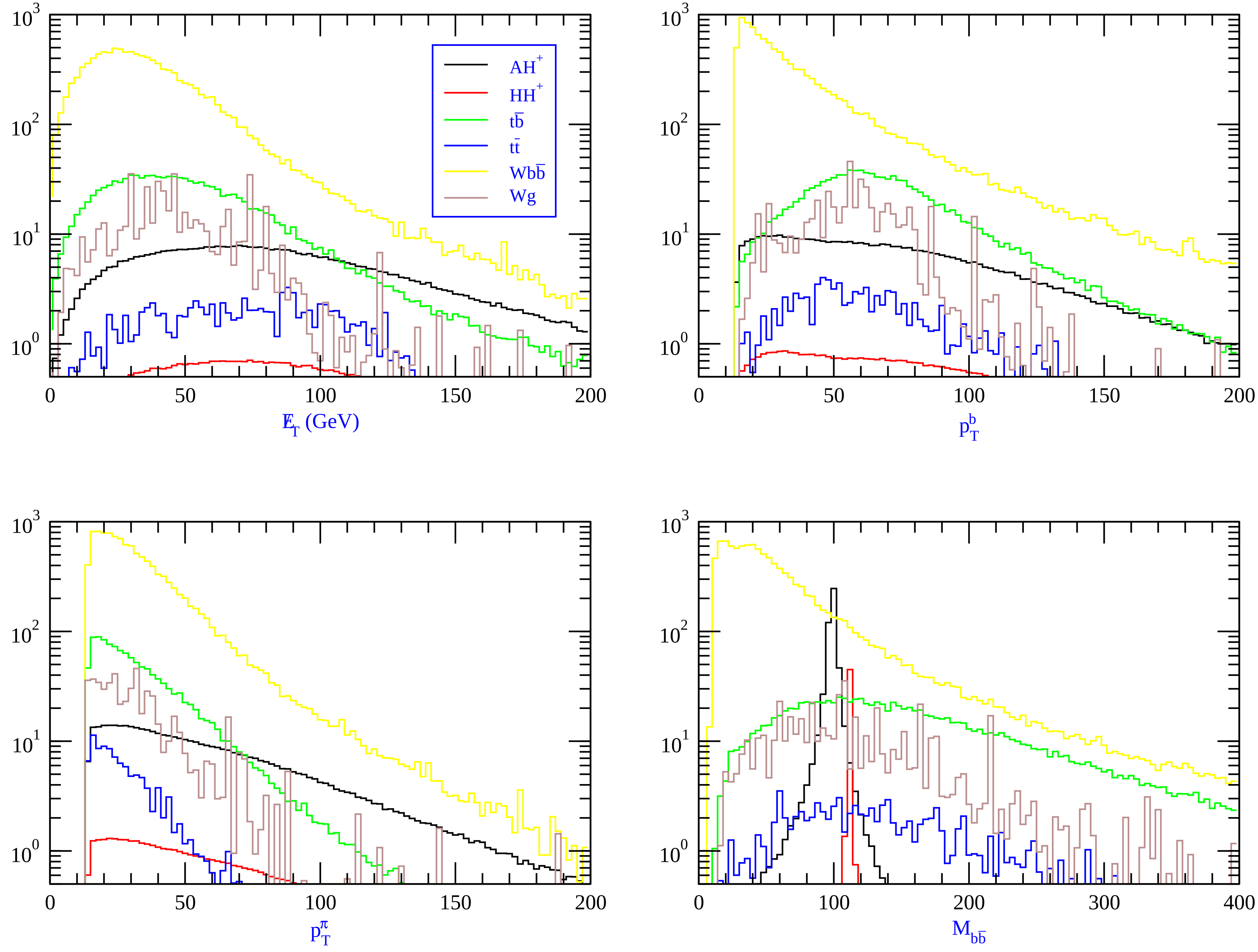
- Numbers of signal and background events at the LHC with 100 fb^{-1}. The b-tagging efficiency (50%, for tagging both b and $\bar{b}$ jets) is included, and the kinematic
cuts listed in each column are applied sequentially.

- 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^+

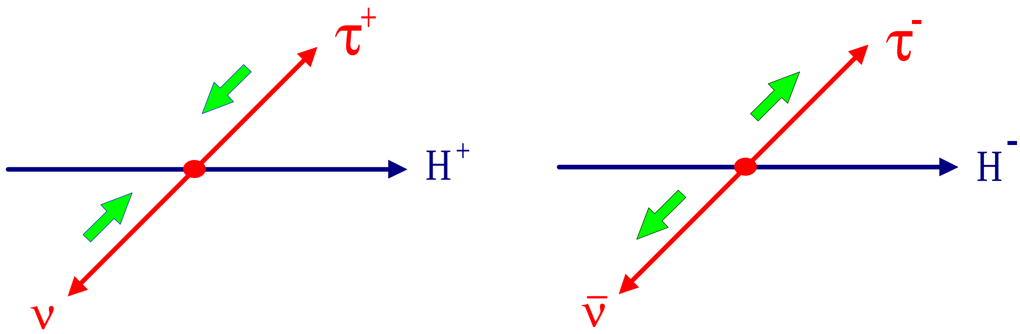
	Basic Cuts	$\not{E}_T > 50$	$P_T^\pi > 40$	$105 < M_{b\bar{b}} < 125$ [GeV]
HH^+	48	38	24	24
AH^+	507	391	241	26
$Wb\bar{b}$	11555	3111	864	58
$t\bar{b}$	1228	614	163	11
Wg	567	236	68	13
$t\bar{t}$	110	80	17	2
Signal (S)	48	38	24	24
Bckg (B)	13966	4431	1352	101
S/B	0.003	0.008	0.018	0.22
$S/\sqrt{B}$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


AH+
HH+
tb̄
tt̄
Wbb̄
Wg
Ɇ_T (GeV)
p_T^b
p_T^π
M_bb̄

Tau is polarized

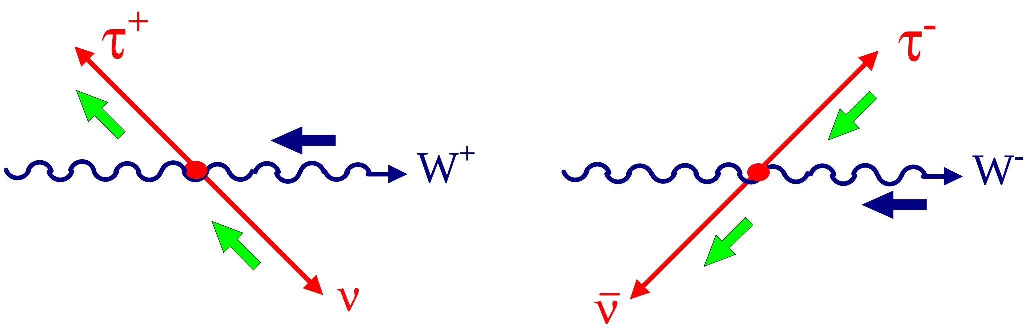
- In the signal event ($H^+ \to \tau^+\nu$), τ^+ is

  left-handedly polarized

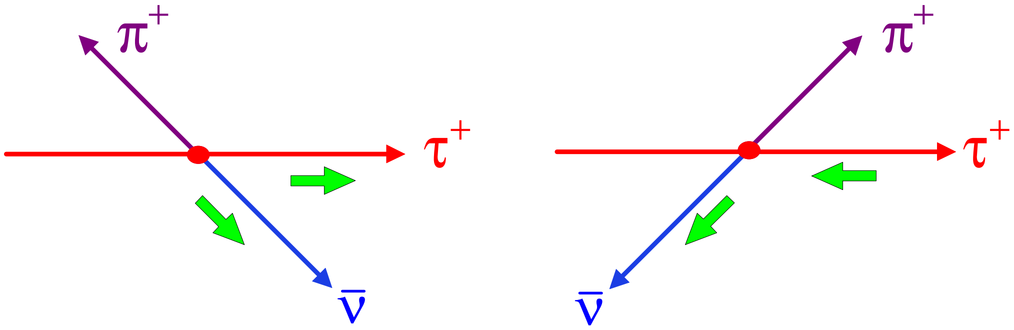


- In the background event ($W^+ \to \tau^+\nu$), τ^+ is

  right-handedly polarized



Pion momentum depends on Tau polarization

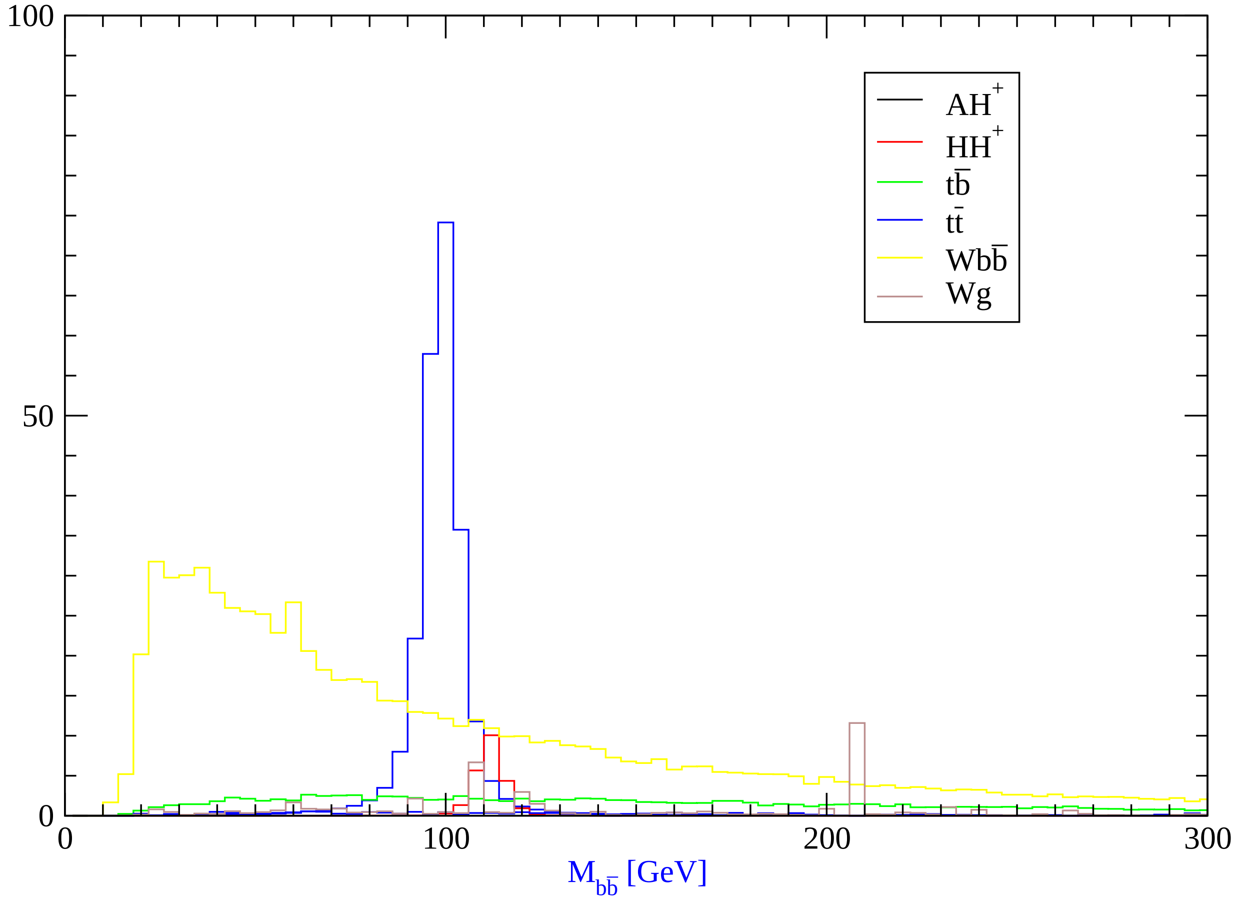


A left-handed τ^+ produces a harder π^+.

A right-handed τ^- produces a harder π^-.

The signal event produces either a left-handed τ^+ or a right-handed τ^-.

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

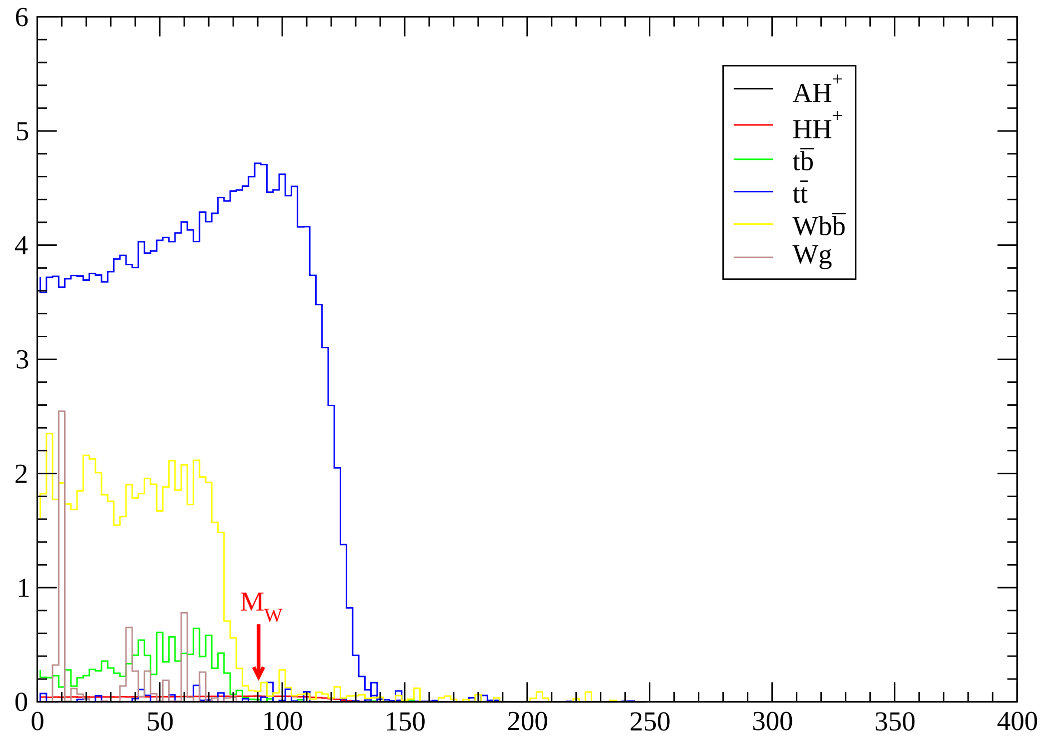


- The transverse mass of π^+ and $\not{E}_T$, i.e. of H^+ in the signal event, after imposing the additional cuts:

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

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 for Case A

- Assuming the double b-tagging efficiency to be 50%, there will be about 200 signal events,

  $$pp \to A(\to b\bar{b})\, H^+(\to \tau^+(\to \pi^+\bar{\nu})\, \nu)$$

  detected at the LHC (with a $100\,\text{fb}^{-1}$ integrated luminosity) for $m_A \sim 100$ GeV.

- 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.

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

$\Rightarrow$

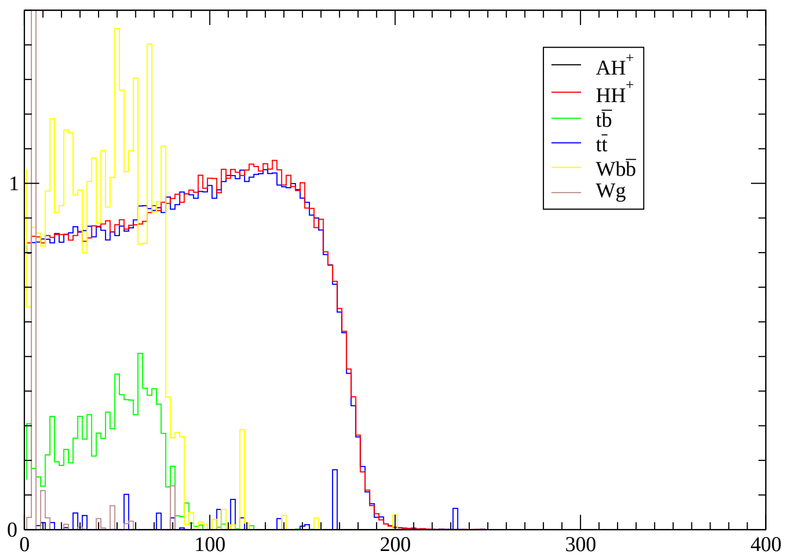
The $AH^\pm$ signal is a promising one, indeed.

Set B ($m_A = 165$GeV)

- Numbers of signal(AH^+/HH^+) and background events at the LHC with an integrated luminosity of 100 fb^{-1}.

	Basic Cuts	$\not{E}_T > 50$	$P_T^\pi > 40$	$155 < M_{b\bar{b}} < 175$ [GeV]
AH^+	126	111	85	71
HH^+	129	114	87	72
$Wb\bar{b}$	11560	3102	840	33
$t\bar{b}$	1221	607	163	10
Wg	783	318	11	5
$t\bar{t}$	108	79	18	1
Signal (S)	255	225	171	143
Bckg (B)	13672	4106	1031	48
S/B	0.02	0.05	0.17	3.0
$S/\sqrt{B}$	2.18	3.51	5.33	20.8
$\sqrt{S+B}/S$	0.46	0.29	0.20	0.09

- The transverse mass distribution of of π^+ and $\not{E}_T$.



Set C ($M_A = 250$GeV)

- Number of ($b\bar{b}b\bar{b}l^+/E_T$) events for the signal and background at the LHC with an integrated luminosity 100 fb^{-1}. The b-tagging efficiency (50% $\times$ 50%, for tagging four b-jets) is included.

	Basic Cuts	Second Cuts
WAH^+	18	18
WHH^+	18	18
$gg \rightarrow t\bar{t}b\bar{b}$	1632	3
$qq' \rightarrow t\bar{t}b\bar{b}$	105	0
Signal	36	36
Bckg	1737	3

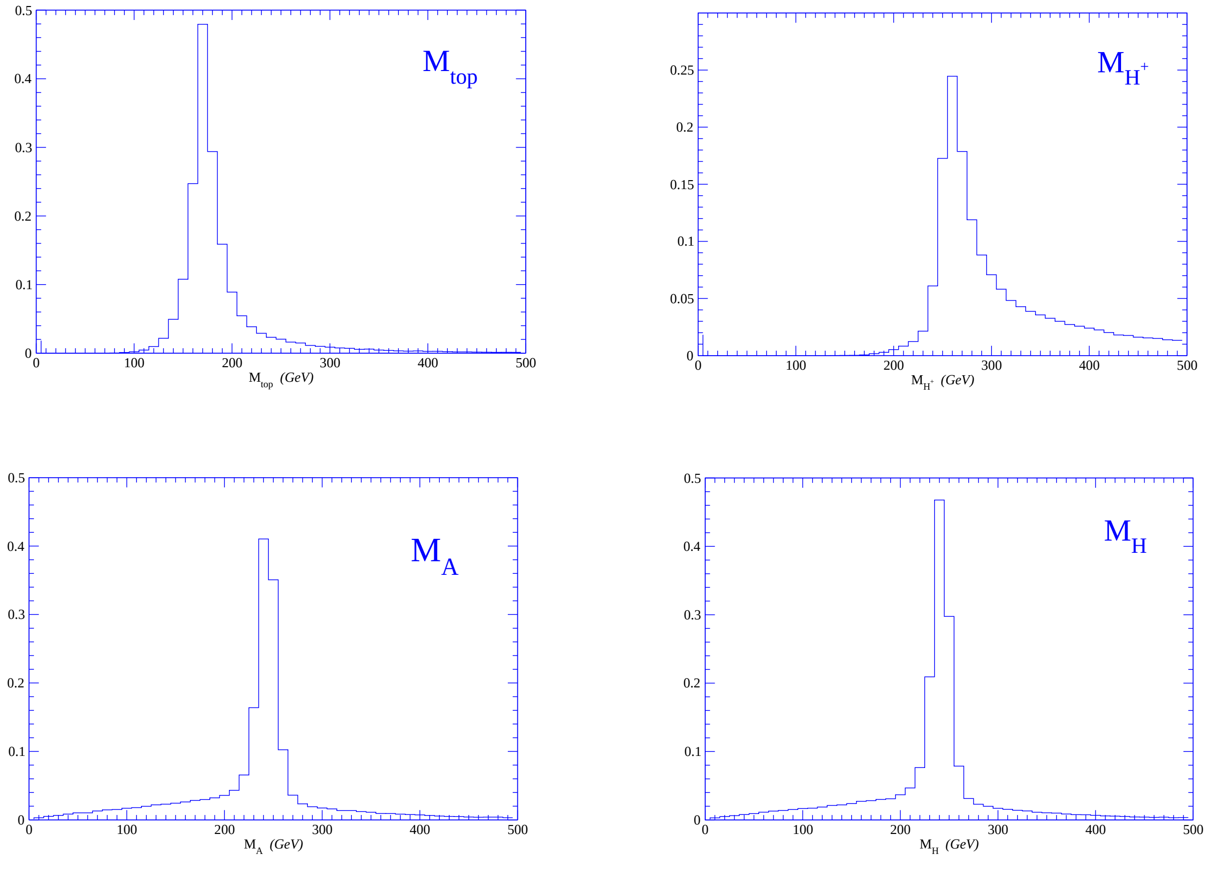
Basic cuts:

$$p_T^l > 15.0, |\eta^l| < 3.0,$$
$$p_T^b > 20.0, |\eta^b| < 2.0.$$

Second Cuts: (veto additional lepton)

$$|p_T^l| < 10.0, \eta^l| > 3.5$$

The invariant mass distributions of the reconstructed t, H^+, A, and H



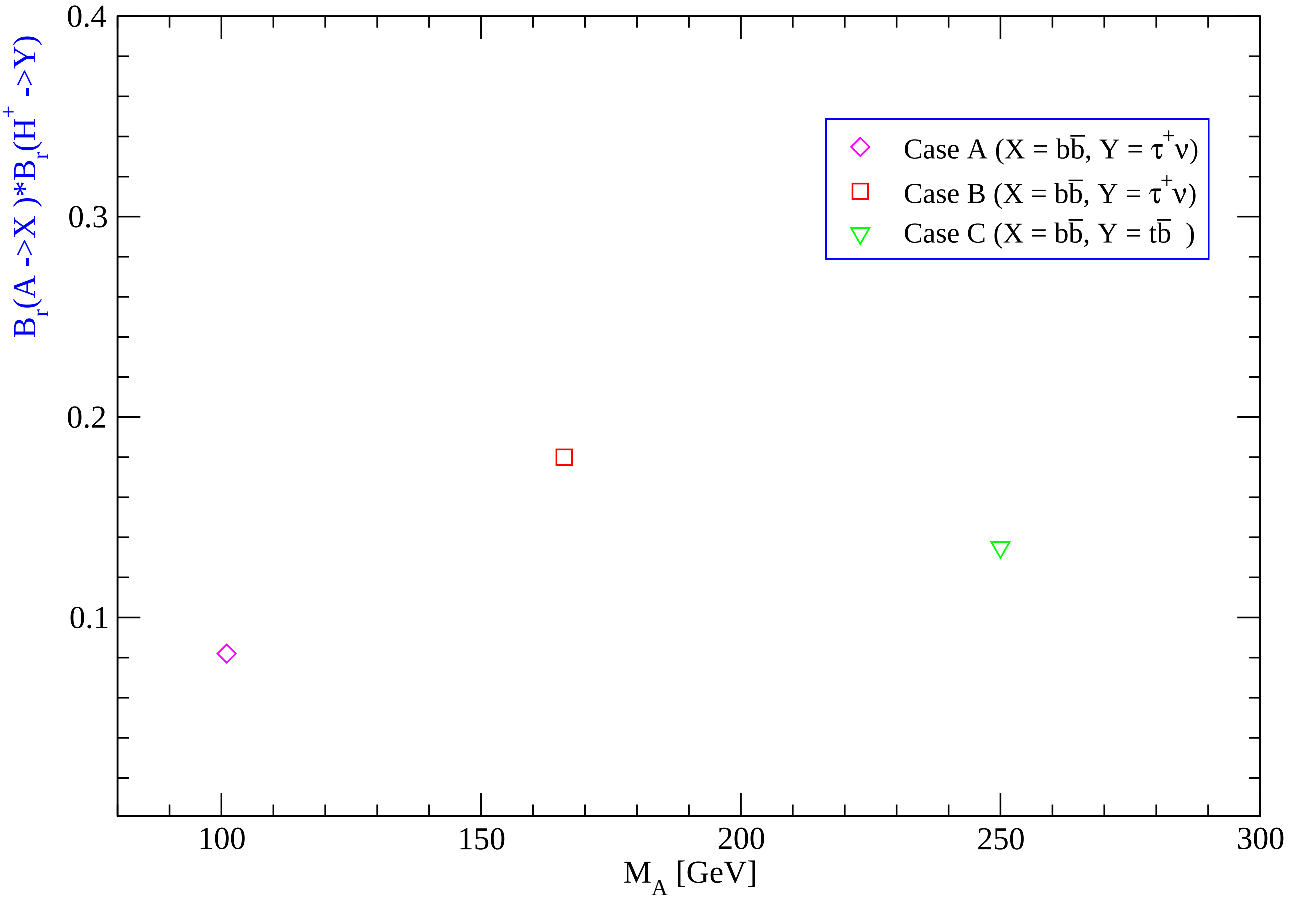
$H^+ \to \tau\nu$ Channel @ Tevatron

- Numbers of signal and background events at the Tevatron with an integrated luminosity of 30 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.

	Basic Cuts	$\not{E}_T > 50$	$P_T^{\pi} > 40$
AH^+	10	7	4
HH^+	8	6	3
$Wb\bar{b}$	543	135	29
$t\bar{b}$	38	18	4
Wg	1	1	0
$t\bar{t}$	0	0	0

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.



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.)

Rates at VLHC

The LO (dotted lines) and NLO QCD (solid lines) cross sections of the AH^+ and AH^- pairs as a function of M_A at the VLHC (a 200 TeV pp collider).