Observability of Charged Higgs Through Triple or Double Higgs Production in a General 2HDM at an e^+e^- Linear Collider

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Dedicating to late Prof. Riazuddin (a great scientist of Pakistan and student of Prof. Abdus Salam)

Charged Higgs Searches and Constraints

LEP

Direct search lower limit on the $mH^{\pm} \sim 90$ GeV for all $\tan\beta$ value assuming $BR(H^+ \rightarrow \tau\nu) \simeq 1$.
Indirect search lower mass limit of $mH^{\pm} \sim 125$ GeV at $\tan\beta > 10$.

TEVATRON

Restrict $mH^{\pm}$ to be in the range $mH^{\pm} > 80$ GeV for $2 < \tan\beta < 30$.
($mH^{\pm} < mt - mb$) was searched in $H^{\pm} \rightarrow \tau\nu$, $\tau \rightarrow$ hadrons in the search mass range $125 < mH^{\pm} < 170$ GeV/c2

CLEO

Indirect lower limit from $b \rightarrow s\gamma$ studies exclude a $H^{\pm}$ mass below 300 GeV at 95 % C.L. in 2HDM Type II with $\tan\beta > 2$. In general in terms of 2HDM types the current conclusion is $mH^{\pm} > 300$ GeV in 2HDM Type II and III

CMS

The CMS collaboration restricts a neutral MSSM Higgs boson to be heavier than 200 GeV with $\tan\beta \leq 10$, assuming $mh^0 \sim 125$ GeV. [CMS PAS HIG-13-021]

ATLAS

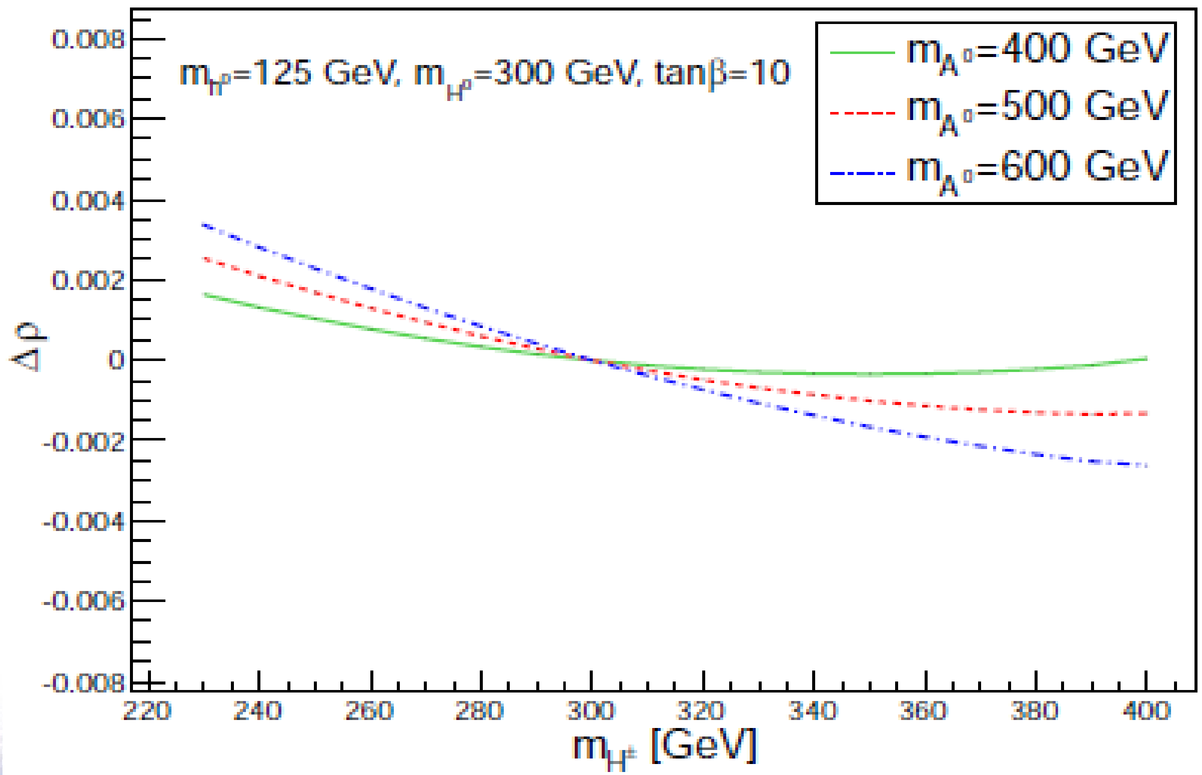
ATLAS based on direct searches for the charged Higgs indicate no charged Higgs lighter than 160 GeV with $\tan\beta > 20$. [ATLAS-CONF-2013-090]

No exclusion for a charged Higgs boson heavier than 170 GeV. Setting ($170 \leq mH^{\pm} \leq 400$ GeV)
CP-odd Higgs boson mass taken: $400 \leq mA \leq 600$ GeV,
Lightest Higgs boson mass: $mh^0 \sim 125$ GeV (known)
Heavy neutral Higgs boson mass: $mH^0 \sim 300$ GeV (τ pair decay)

$mH^{\pm}$ range is not sensitive to $B_s \rightarrow \mu^+\mu^-$ constraints. [Phys. ReV. D 87 (2013) 035026]

$\Delta\rho$ constraint

- The mass splitting of m_A among the neutral Higgs bosons may arise large terms for Feynman diagrams involved in EW measurements such as the Z boson self-energy.
- The global fit to SM electroweak measurements requires $\Delta\rho$ to be $O(10^{-3})$
- Set of chosen mass points of m_A are consistent with EW precision measurements.



Triple Higgs Couplings

- Triple Higgs study is a unique process for the charged Higgs
- **$e^+e^- \to H^+H^-H^0$ or $H^+H^-h^0$** (pair of charged Higgs with $H^0 \to bb$)
- This feature easy to be distinguished from the background.
- SM background events: WW, ZZ and $Z^{(*)}/\gamma^*$ and $t\bar{t}$

$$g_{H^+H^-H^0} = \frac{2m_W s_W}{e} \left[s_{\beta-\alpha}\left(\frac{1}{4}s_{2\beta}^2(\lambda_1+\lambda_2) + \lambda_{345}(s_\beta^4 + c_\beta^4) - \lambda_4 - \lambda_5 - s_{2\beta}c_{2\beta}(\lambda_6 - \lambda_7)\right) + c_{\beta-\alpha}\left(\frac{1}{2}s_{2\beta}(s_\beta^2\lambda_1 - c_\beta^2\lambda_2 + c_{2\beta}\lambda_{345}) - \lambda_6 s_\beta s_{3\beta} - \lambda_7 c_\beta c_{3\beta}\right)\right]$$

Phys. Lett. B 659 (2008) 297

$$g_{H^+H^-H^0} = \frac{m_W s_W s_{2\beta}}{e}[s_\beta c_\alpha \lambda_1 + c_\beta s_\alpha \lambda_2 - s_{\beta+\alpha}\lambda_{345}] + c_{\beta-\alpha}\lambda_3$$

Phys. Rev. D 67 (2003) 075019

$$\frac{g_{h_{2HDM}VV}}{g_{h_{SM}VV}} = s_{\beta-\alpha}, \quad \frac{g_{H_{2HDM}VV}}{g_{H_{SM}VV}} = c_{\beta-\alpha}$$

Phys. Rev. D 66 (2002) 095007

$$g_{H^+H^-H^0} = \frac{e}{m_W s_W s_{2\beta}^2}(c_\beta^3 s_{2\beta} s_\alpha m_H^2 + c_\alpha s_{2\beta} s_\beta^3 m_H^2 - 2 s_{\beta+\alpha} m_{12}^2 + c_{\beta-\alpha} s_{2\beta}^2 m_{H^\pm}^2)$$

Phys. Rev. D 72 (2005) 115013

$$g_{H^+H^-H^0} = \frac{e}{m_W s_W s_{2\beta}}\left[(m_{H^\pm}^2 - m_{A^0}^2 + \frac{1}{2}m_{H^0}^2)s_{2\beta}c_{\beta-\alpha} - (m_{H^0}^2 - m_{A^0}^2)c_{2\beta}s_{\beta-\alpha}\right]$$

arXiv:hep-ph/9812246

Assumption: $\lambda_5 = \lambda_6 = \lambda_7 = 0$ $\quad s_{\beta-\alpha} = 1$

$$\frac{g_{h_{2HDM}b\bar{b}}}{g_{h_{SM}b\bar{b}}} = -s_\alpha/c_\beta = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$$

Phys. Rev. D 80 (2009) 071102(R)20
Phys. Rev. Lett. 96 (2006) 042003

Triple Higgs Couplings

$$H^{\pm}H^{\pm}H^{0}: \quad \frac{-ie}{m_W s_W s_{2\beta}}\left[(m_{H^\pm}^2 - m_A^2 + \frac{1}{2}m_H^2)s_{2\beta}c_{\beta-\alpha} - (m_H^2 - m_A^2)c_{2\beta}s_{\beta-\alpha}\right]$$

$$H^{\pm}H^{\pm}h^{0}: \quad \frac{-ie}{m_W s_W s_{2\beta}}\left[(m_{H^\pm}^2 - m_A^2 + \frac{1}{2}m_h^2)s_{2\beta}s_{\beta-\alpha} + (m_h^2 - m_A^2)c_{2\beta}c_{\beta-\alpha}\right]$$

Signal: $e^+e^- \to H^+H^-H^0$ + $e^+e^- \to H^+W^-H^0$
Where $H^\pm \to \tau\nu$ and H^0 ->bb (convient choice for BG rejection)

Higgs-fermion Yukawa Coupling defined for the four types of 2HDM

	Type			
	I	II	III	IV
ρ^D	$\kappa^D t_\beta^{-1}$	$-\kappa^D t_\beta$	$-\kappa^D t_\beta$	$\kappa^D t_\beta^{-1}$
ρ^U	$\kappa^U t_\beta^{-1}$	$\kappa^U t_\beta^{-1}$	$\kappa^U t_\beta^{-1}$	$\kappa^U t_\beta^{-1}$
ρ^L	$\kappa^L t_\beta^{-1}$	$-\kappa^L t_\beta$	$\kappa^L t_\beta^{-1}$	$-\kappa^L t_\beta$

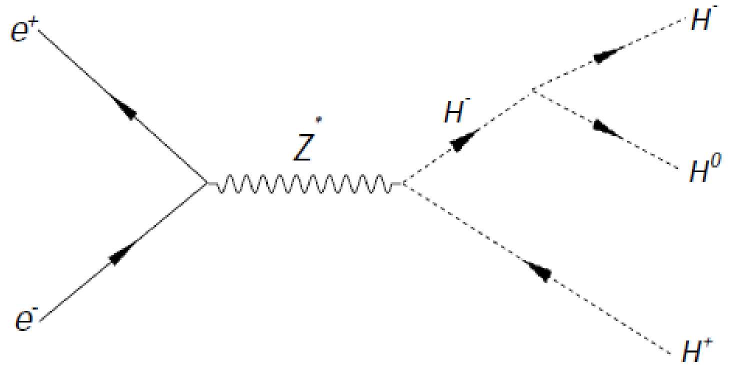
largest $H^+ \to \tau\nu$ and $H^0 \to \bar{b}b$ branching ratio of decays at high tanβ

Full Signal Production process

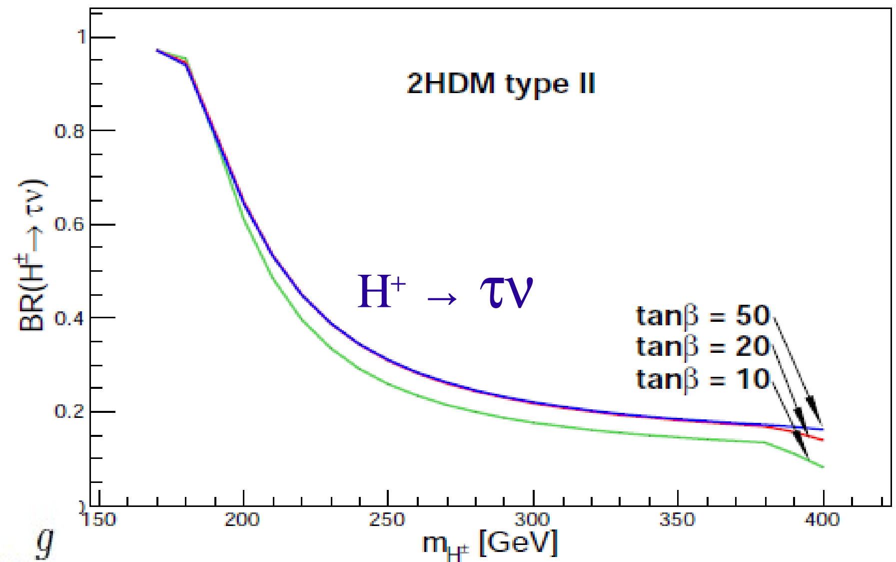
$$e^+e^- \to H^+H^-H^0\ (H^+W^-H^0) \to \tau^+\tau^-\bar{b}bE^T_{miss}$$

Triple Higgs Production at e⁻e⁺ Collider

$e^+e^- \rightarrow H^+H^-H^0\ (H^+W^-H^0) \rightarrow \tau^+\tau^- b^- b E^T_{miss}$

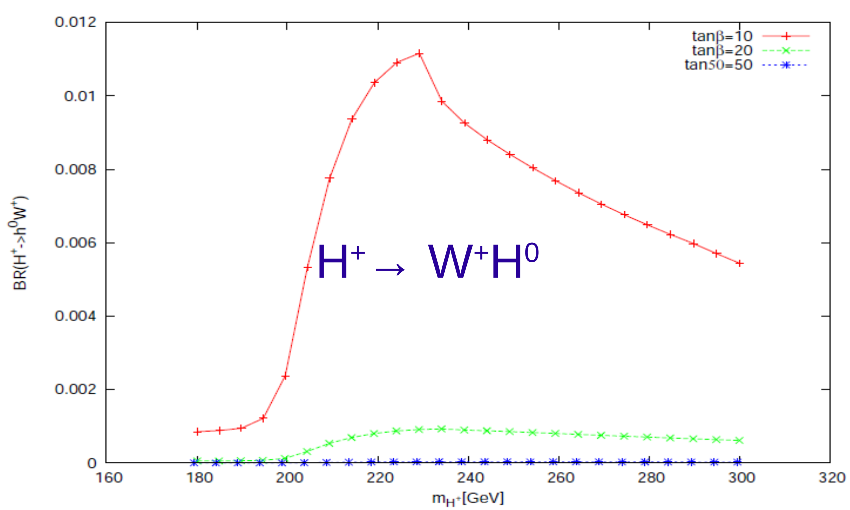


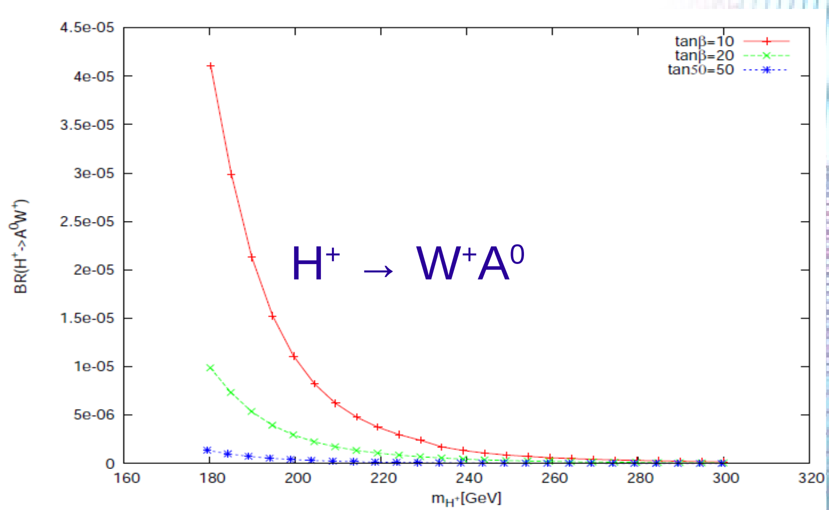
Possible scenario: CLIC (ILC)
SM Background: W^+W^-, ZZ, tt, and Drell-Yan $Z(*)/\gamma*$ production.



$H^+ \rightarrow W^+H^0$ and $H^+ \rightarrow W^+A^0$ lead to three to four particles for each charged Higgs decay and are not considered as their identification is difficult due to limited particle identification efficiencies and detector consideration

$$g_{H^\pm W^\mp h} \propto \frac{g}{2}\cos(\beta-\alpha) \qquad g_{H^\pm W^\mp H} \propto \frac{g}{2}\sin(\beta-\alpha) \qquad g_{H^\pm W^\mp A} \propto \frac{g}{2}$$

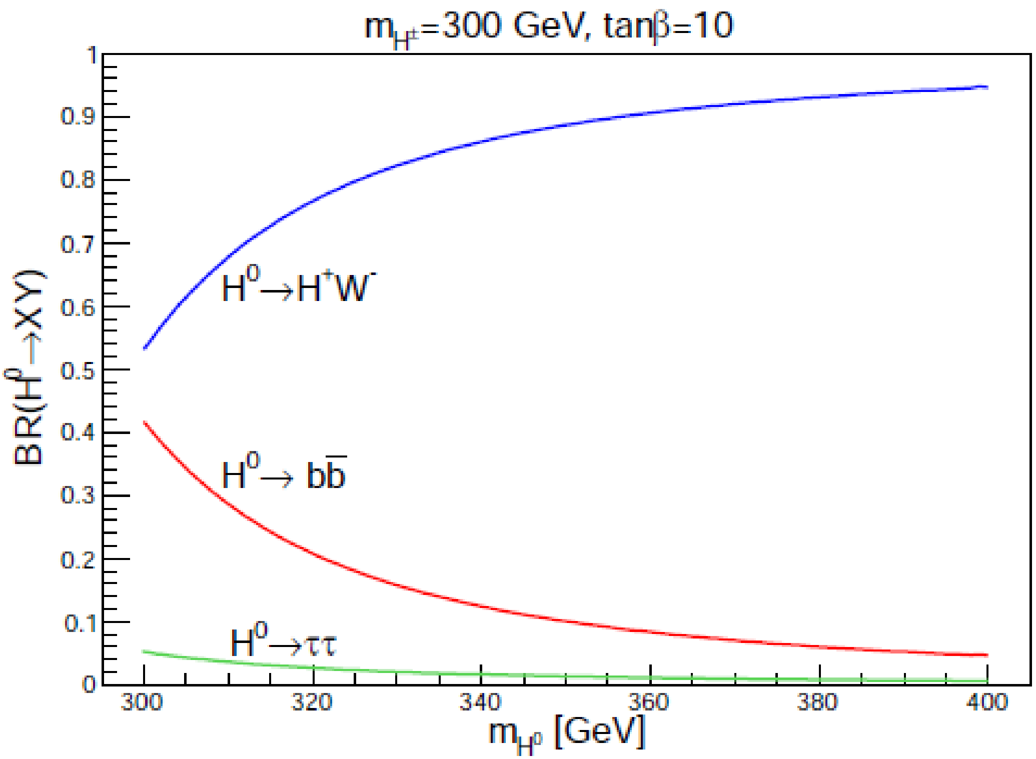




H^0 Decays

$H^0 \to h^0h^0$, $H^0 \to W^+W^-$ and $H^0 \to Z^0Z^0$ vanish as they are proportional to $c_{\beta-\alpha}$ and this analysis is based on $s_{\beta-\alpha} = 1$. Therefore as long as the lightest neutral Higgs is required to be SM-like with $s_{\beta-\alpha} = 1$, such decay channels do not play a role.

The neutral Higgs mass (mH0) has to be greater than mh0, and be small enough to allow for heavy charged Higgs masses to be produced at the linear collider



Background contribution

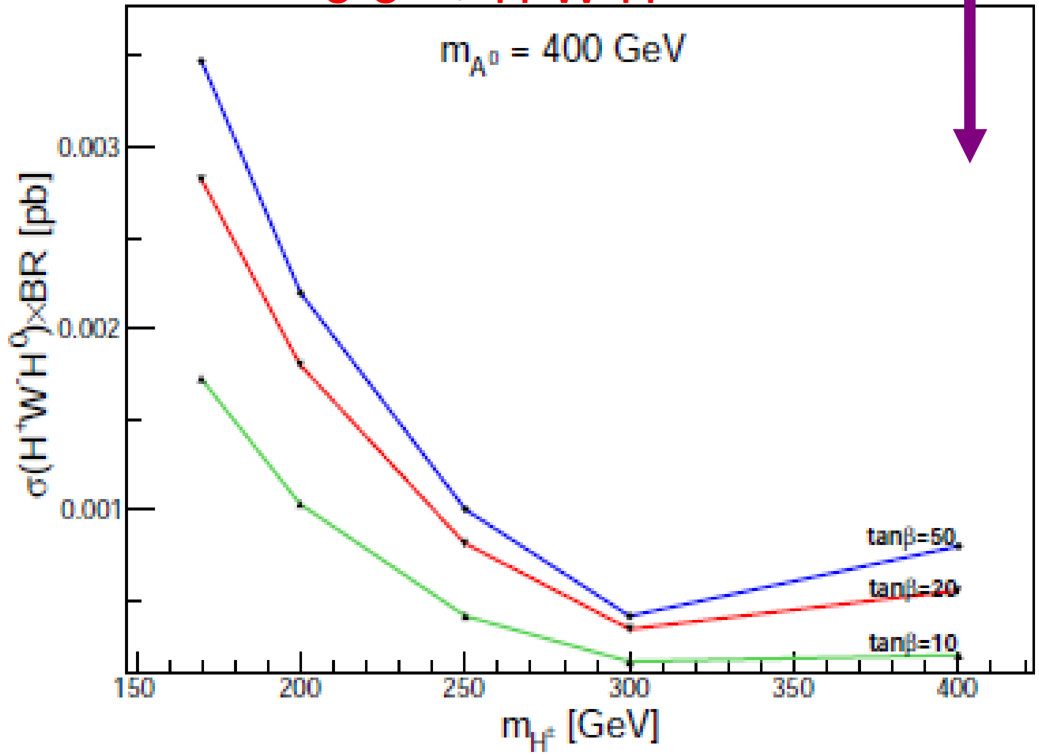
Double Higgs Production

- The double Higgs production originates from different decay chains, $e^+e^- \rightarrow A^0H^0 \rightarrow H^+W^-H^0$ and $e^+e^- \rightarrow H^+H^- \rightarrow H^+W^-H^0$.
- A double charged Higgs production through $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}\tau^+\nu \rightarrow W^+b\bar{b}\tau^+\nu \rightarrow \tau^+\nu\, b\bar{b}\tau^+\nu$ are also explicitly checked and turned out to make no contribution to the signal, as they are suppressed by the cut on the $b\bar{b}$ invariant mass.

Other Triple Higgs Processes:
$h^0H^+H^-$ and $A^0H^+H^-$ turn out to be negligiblev with a cross section of the order **10^{-6} pb.**

SM Processes:
ZZ (0.13 pb), WW (1.8 pb), $Z^{(*)}/\gamma^*$ (2.0 pb) and $t\bar{t}$ (0.1 pb) @ CMS = 1.5 TeV

$e^+e^- \rightarrow H^+W^-H^0$



Event Simulation

CompHEP 4.5.1
Triple Higgs coupling
signal events generation
Cross-section calculation
Double Higgs Production
(output in LHEF)

PYTHIA 8.1.53
Particle showering
ISR,FSR
mutiple interaction
Background processes

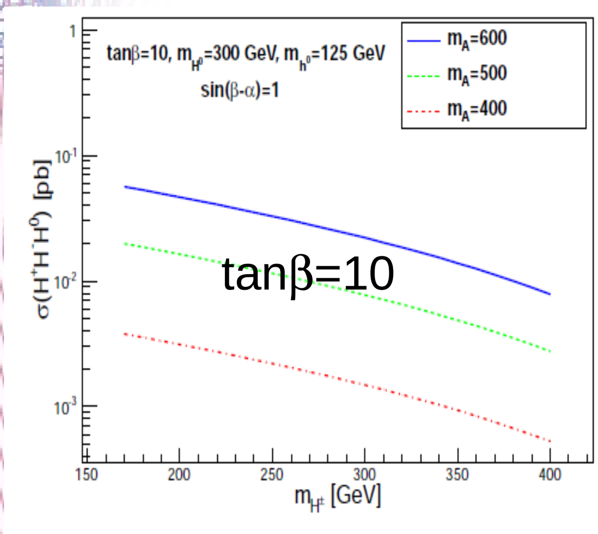
FASTJET 2a.4.1
Jet finding
sequential recombination
clustering algorithms,
plugins for access to a
range of cone jet finders

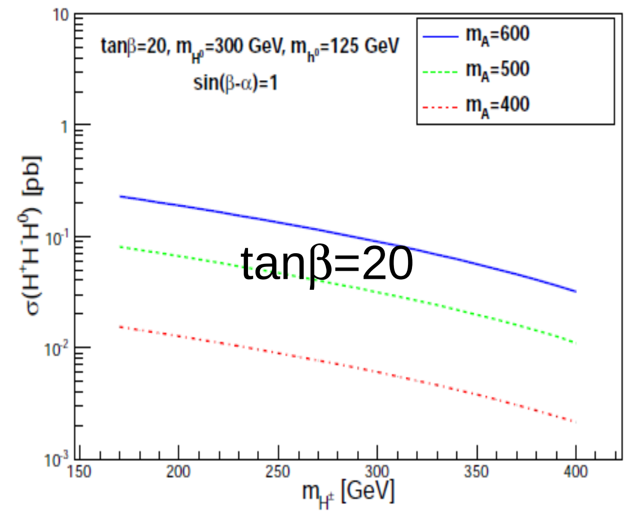
SuSpect
Particle spectrum
Renormalization group
eolution

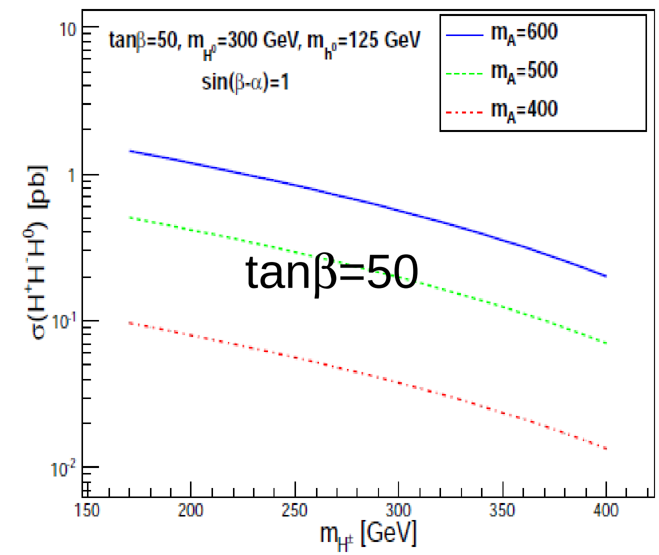
2HDMC 1.1
Evaluation of decay widths
Branching ratios

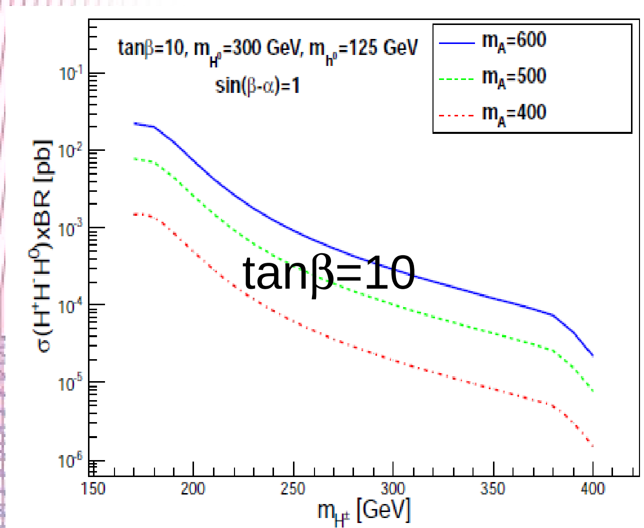
TAUOLA 1.0.7
Tau lepton production
Tau jets hadronic decay

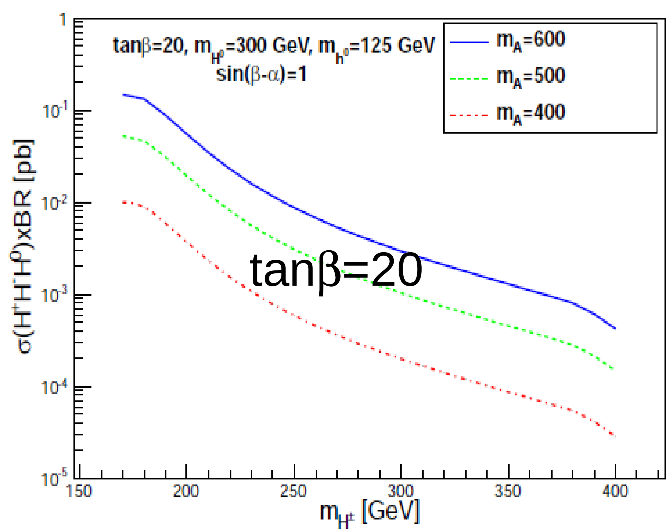
Results: Signal cross-section

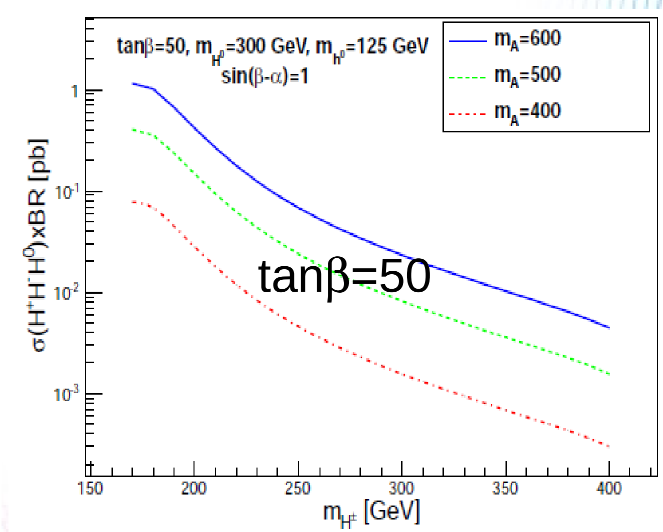




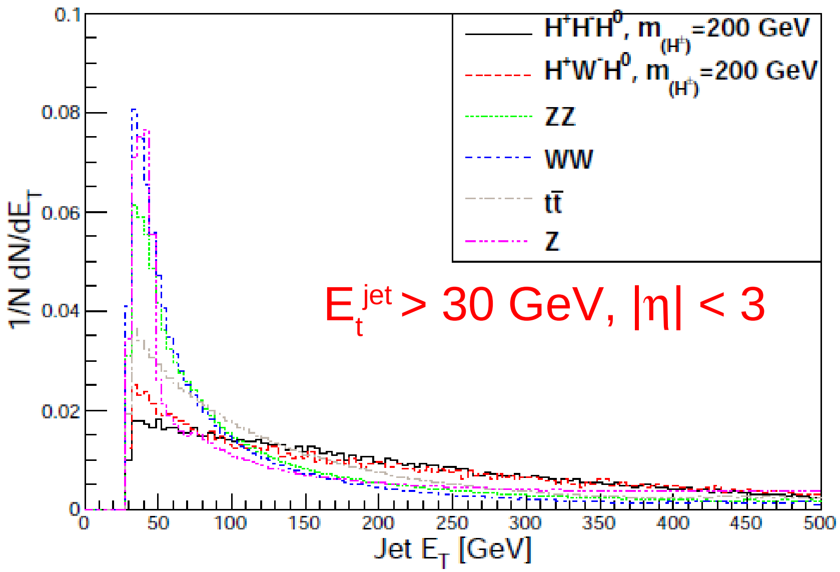


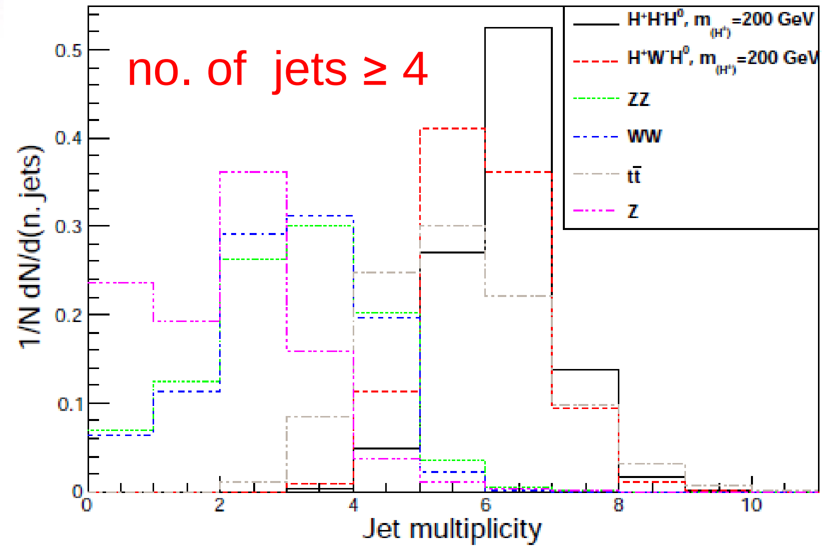






Results: Jets reconstruction

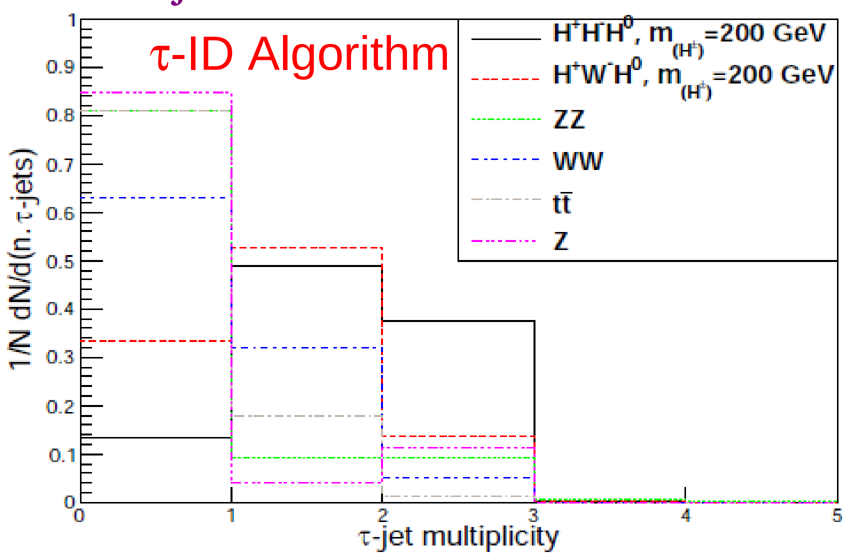


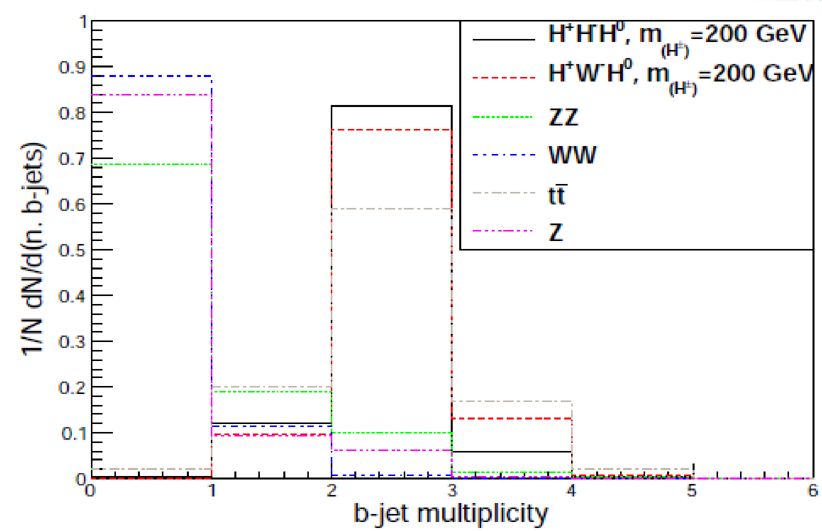


- ΔR(jets,tracks) < 0.1; E_T > 20 GeV
- Isolation: 0.1 < ΔR(ldtrk,tracks) <0.4 ;P_t^{tracks} > 1 GeV
- Signal tracks: ΔR(pion,tracks) < 0.07
- no. of τ-jets > 2

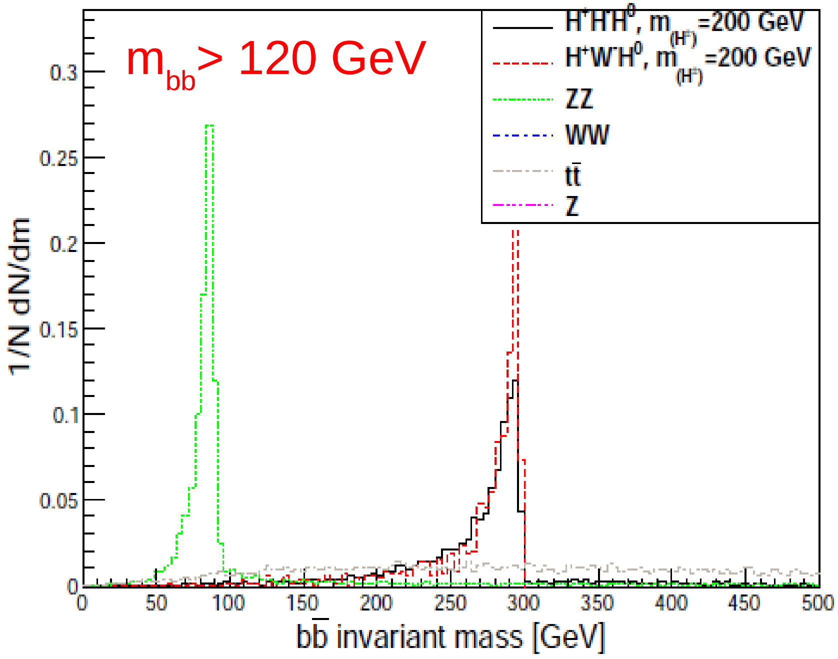
ΔR(jets,tracks) < 0.4 with respect to the generated b or c quarks. A jet is tagged as a b-jet with, a probability of 60% (10%) if it matches a b-quark (c-quark).

no. of b-jets > 2

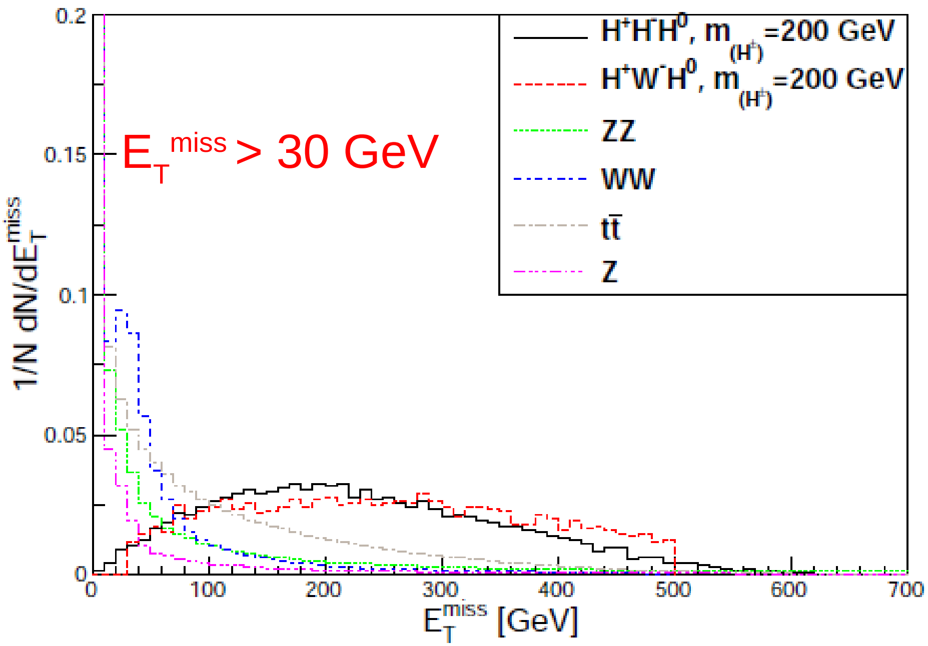




Results: m_{bb}, E^T_{miss}



- b-jet pair invariant mass tends to peak at 300 GeV (the neutral Higgs boson mass) in signal events.
- ZZ background the $b\bar{b}$ invariant mass obviously peaks at the Z mass.

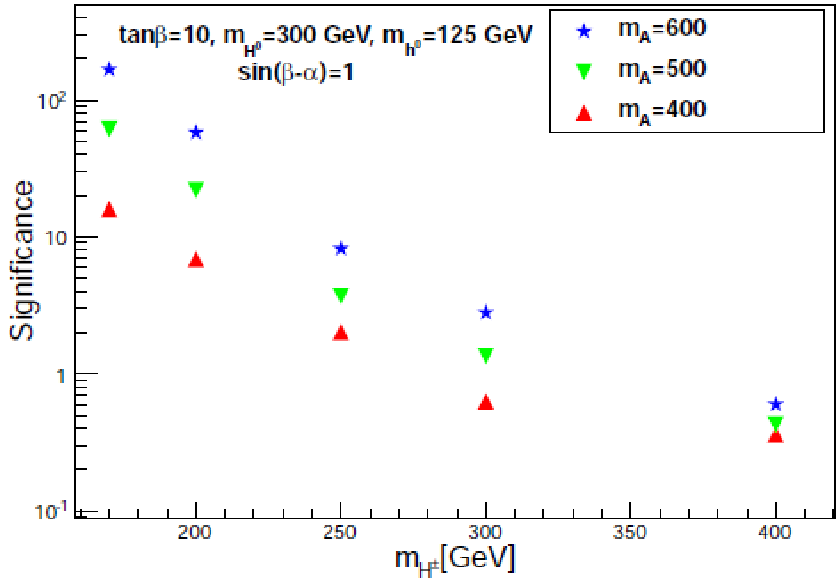


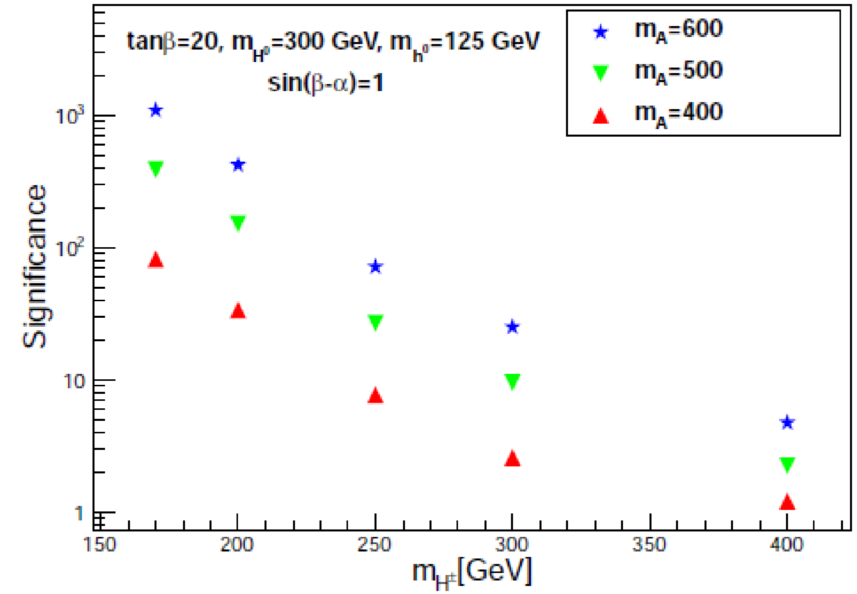
Signal/Background Effeciencies

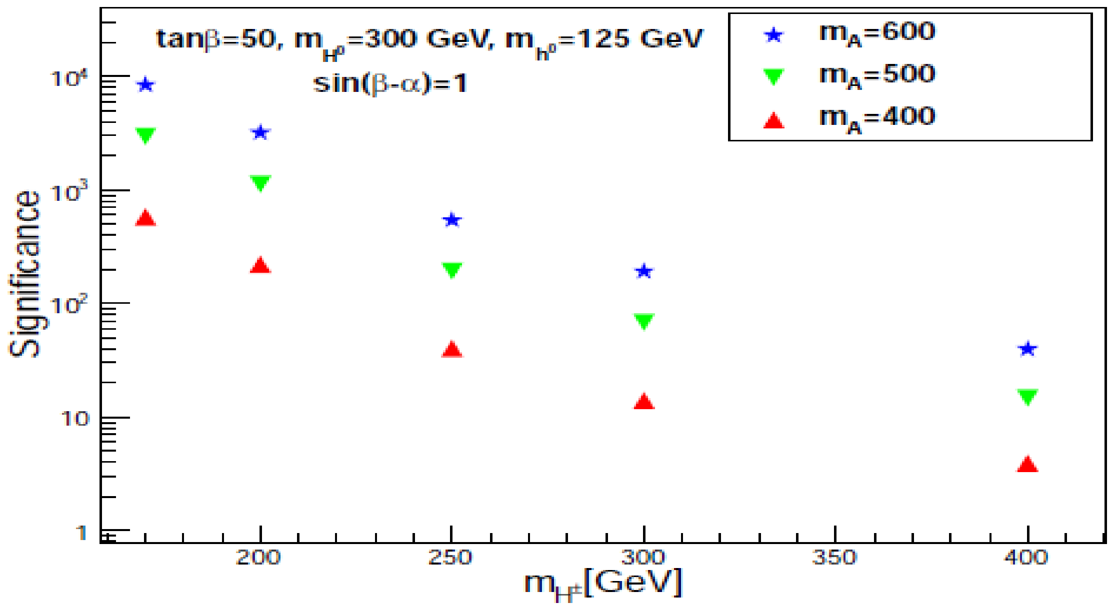
	Signal, $m_{H^\pm}$:													
	170 GeV		200 GeV		250 GeV		300 GeV		400 GeV		Background			
	HHH	HHW	HHH	HHW	HHH	HHW	HHH	HHW	HHH	HHW	ZZ	$Z^{(*)}/\gamma^*$	WW	$t\bar{t}$
Four jets	0.64	0.64	0.63	0.63	0.63	0.59	0.63	0.63	0.62	0.62	0.24	0.052	0.22	0.91
Leading track	0.99	1	0.99	1	0.99	1	0.99	1	0.99	0.99	0.87	0.95	0.92	0.96
Isolation	0.87	0.69	0.88	0.69	0.89	0.78	0.9	0.63	0.9	0.83	0.35	0.092	0.6	0.24
Number of signal tracks	0.99	0.97	0.99	0.97	0.99	0.97	0.99	0.96	0.99	0.99	0.87	0.37	0.95	0.87
Two τ-jets	0.41	0.2	0.43	0.21	0.45	0.28	0.47	0.22	0.5	0.1	0.68	0.6	0.19	0.071
τ-jet charge	1	0.99	1	0.99	1	1	1	0.99	1	0.99	1	1	1	0.97
Two b-jets	0.82	0.84	0.82	0.84	0.82	0.85	0.82	0.82	0.82	0.81	0.15	0	0	0.61
$b\bar{b}$ inv. mass	0.88	0.94	0.88	0.93	0.88	0.94	0.87	0.93	0.85	0.96	0.041	nan	nan	0.33
E_T^{miss}	0.99	0.98	0.98	0.99	0.98	0.83	0.99	1	0.98	0.99	0.28	nan	nan	0.9
Total eff.	0.16	0.064	0.17	0.067	0.18	0.082	0.18	0.063	0.19	0.039	7.7e-05	0	0	0.0023

The signal selection efficiencies are assumed to be independent of tanβ and m_A

Signal Significance







Conclusion

- The effect of the CP-odd neutral Higgs mass on the production cross section and the signal significance is studied.
- Increasing m_A Higgs could increase the signal significance very sizably.
- The significance depends on $\tan\beta$ and m_A due to the dependence of cross section to these parameters.
- A reasonable background suppression is achieved leading to high signal significance values for some areas of the parameter space which correspond to heavy CP-odd neutral Higgs and high $\tan\beta$.
- The analysis reveals the future linear colliders potential for a heavy charged Higgs observation if LHC fails to do so.
- If the charged Higgs is heavier than 300 GeV, it may escape from LHC experiments.
- In such a scenario a linear collider with enough integrated luminosity higher than 500 fb^{-1} would probably be the only option which could provide some news.