Direct Searches of 2HDM Bosons in Multi-top Events

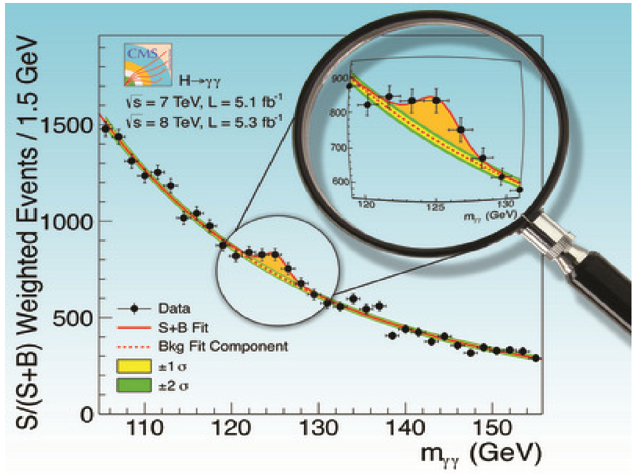
Hiroshi Yokoya (U. of Toyama)

Collaborators: Shinya Kanemura (U. of Toyama),
Ya-Juan Zheng (NTU)

LCWS2014, Belgrade, Serbia, Oct. 5-10, 2014

Introduction : Discovery of Higgs Boson

- A Higgs boson was found at the LHC !
- Within current errors, its properties are consistent with the SM (J^{CP}, cross-sections, branching ratio into WW,ZZ,YY,bb,ττ,,,)



- However, whole structure of the Higgs sector is still unknown.
We have to determine the Higgs sector by future experiments.

- **Direct measurements** → **this talk,,**
  find second Higgs at colliders; clear evidence; need high energy to produce
- **Indirect measurements** → **see talks by Kakizaki, Kanemura,,**
  find deviations in Higgs couplings from the SM; need precision; distinguish models by fingerprinting

Two Higgs Doublet Model (2HDM):

In this talk, we consider the 2HDM with discrete symmetry (Z_2) as a typical benchmark model of extended Higgs sectors

- ρ=1 is preserved at the tree-level. (ρ_{exp}=1.00040±0.00024)
- Tree-level FCNC can be avoided by Z_2 symmetry
- 5 Higgs bosons (h & H, A, $H^\pm$)
- Additional CP phases provided, etc.

Glashow,Weinberg ('77)

Higgs potential in the 2HDM with softly-broken Z_2 symmetry

$$
\begin{aligned}
V(\Phi_1,\Phi_2) \; = \; & m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - \left(m_3^2\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}|\Phi_1|^4 \\
& + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]
\end{aligned}
$$

Parameters in the model

$$(m_{1-3}, \lambda_{1-5}) \rightarrow (v, m_h, \alpha, \beta, m_H, m_A, m_\pm, m_3)$$

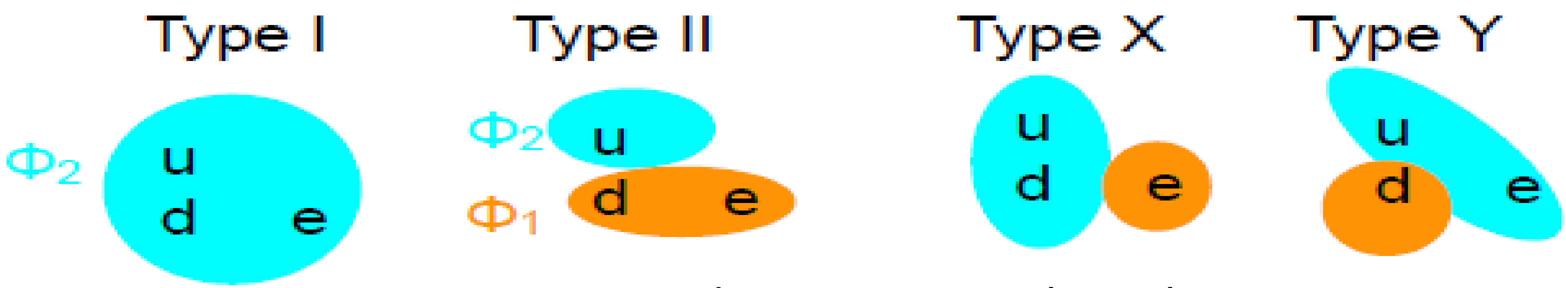
Two Higgs Doublet Model (2HDM):

<u>Z_2-parity of Fermions</u> → Type of Yukawa interactions

Four kinds of Z_2-parity assignment to fermions :

▶ Four types of Yukawa models

V.Barger et.al. ('90),Y.Grossman ('94), A.Akeroyd,W.Stirling ('95),,, Aoki,Kanemura,Tsumura,Yagyu ('09)



all fermion couples to one Higgs boson

up v.s. down (MSSM)

quark v.s. lepton

flipped

<u>We consider the SM-like limit (alignment)</u>

$$\kappa_V^h = \sin(\beta-\alpha),\ \kappa_V^H = \cos(\beta-\alpha)$$
$$\kappa_f^h = \sin(\beta-\alpha) + \cos(\beta-\alpha) F_f^h(\beta),$$
$$\kappa_f^H = \cos(\beta-\alpha) + \sin(\beta-\alpha) F_f^H(\beta)$$

In the $\sin(\beta-\alpha) \to 1$ limit,

- No deviation in the couplings of light Higgs(h) with SM particles,
- Mass scale of additional Higgs bosons can be still as low as TeV scale

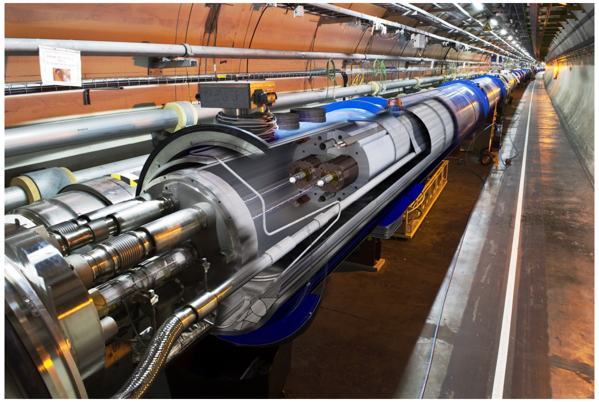
→ Indirect method is difficult, only the direct method is available

Direct searches at future colliders

LHC /s = 13-14TeV

L = 300fb^{-1} 2015 - 2022

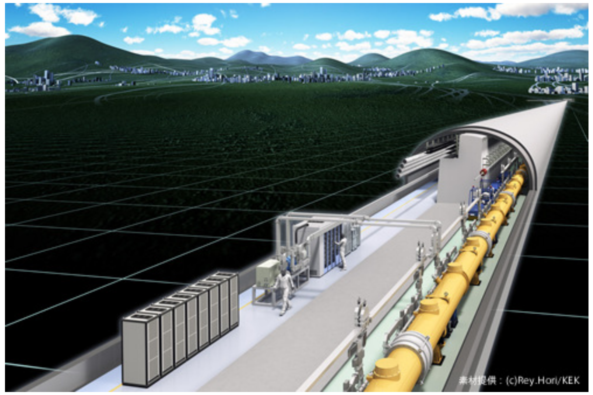
3000fb^{-1} (HL-LHC) 2025(?) ~



ILC

/s = 250GeV, 2025(?) ~

(~350GeV), 500GeV, 1TeV



Because the energy reach is higher at LHC than at ILC, basically LHC is better than ILC for the direct search.

However, there is still possibility that LHC cannot find/identify new Higgs bosons, but ILC can help to clarify them, as long as the ILC energy is enough to produce them.

Direct search is another important program to be performed at the ILC.

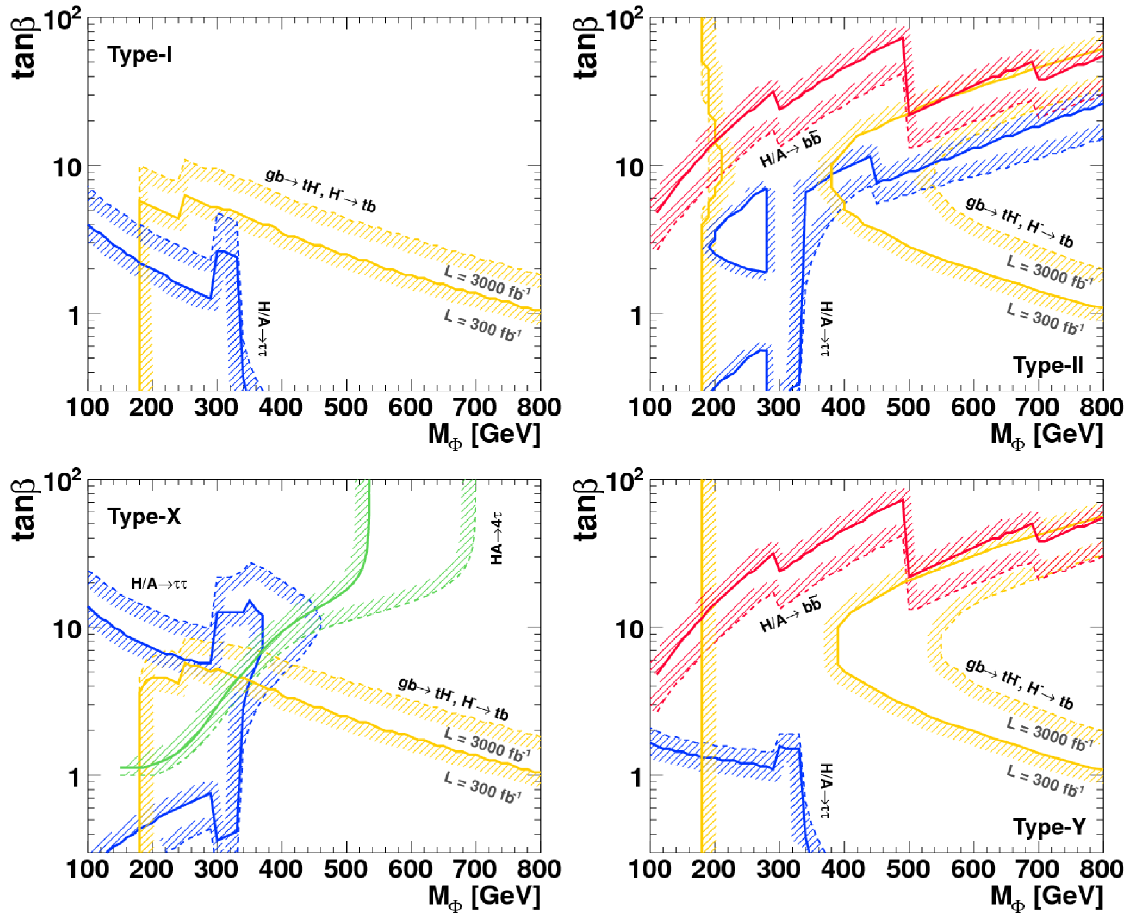
Direct searches at the LHC

ILC Higgs White paper (13),
Kanemura,Tsumura,Yagyu,HY (14)

Discovery reaches of additional Higgs boson interpreted from the MSSM Higgs search in the ATLAS TDR.

Kanemura,HY,Zheng (14)

Contours for 95% C.L., Solid:300fb^{-1}, dashed:3000fb^{-1}



Useful processes:

QCD+ Yukawa

$$(b\bar{b}+)H/A \to \tau^+\tau^-$$

$$b\bar{b} + H/A \to b\bar{b}b\bar{b}$$

$$gb \to tH^-;\, H^- \to \bar{t}b$$

EW

$$q\bar{q} \to HA \to 4\tau$$

In wide parameter regions,
M_Φ up to ~ 500GeV can be covered

Direct searches at the ILC

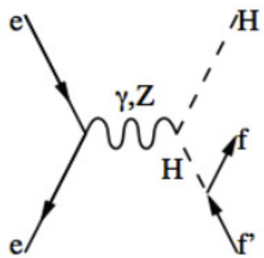
- At the ILC, there are pair and single production processes which can have large cross-section.

Kanemura,Moretti,Odagiri(01), Kiyoura et al.(02)
Kanemura,HY,Zheng(14),,,

Pair production

(/s > m_H + m_A or $2m_{H+}$)

$$e^+e^- \to HA$$
$$e^+e^- \to H^+H^-$$



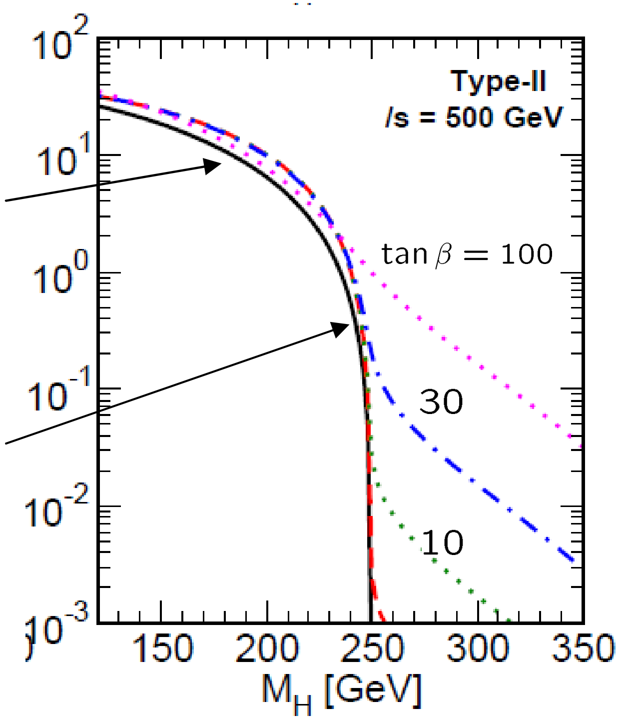
σ_{bbH} [fb]

pair production

$\sigma_{bbH} = \sigma_{HA} \times \mathcal{B}r(A \to bb)$

single production

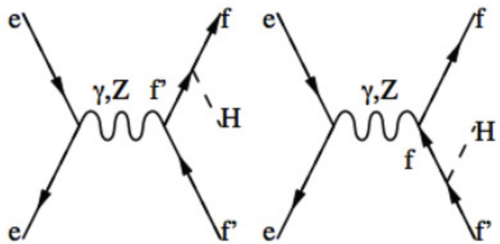
$\sigma_{bbH} \propto (y_b^H)^2$



Single production

(/s < m_H + m_A or $2m_{H+}$)

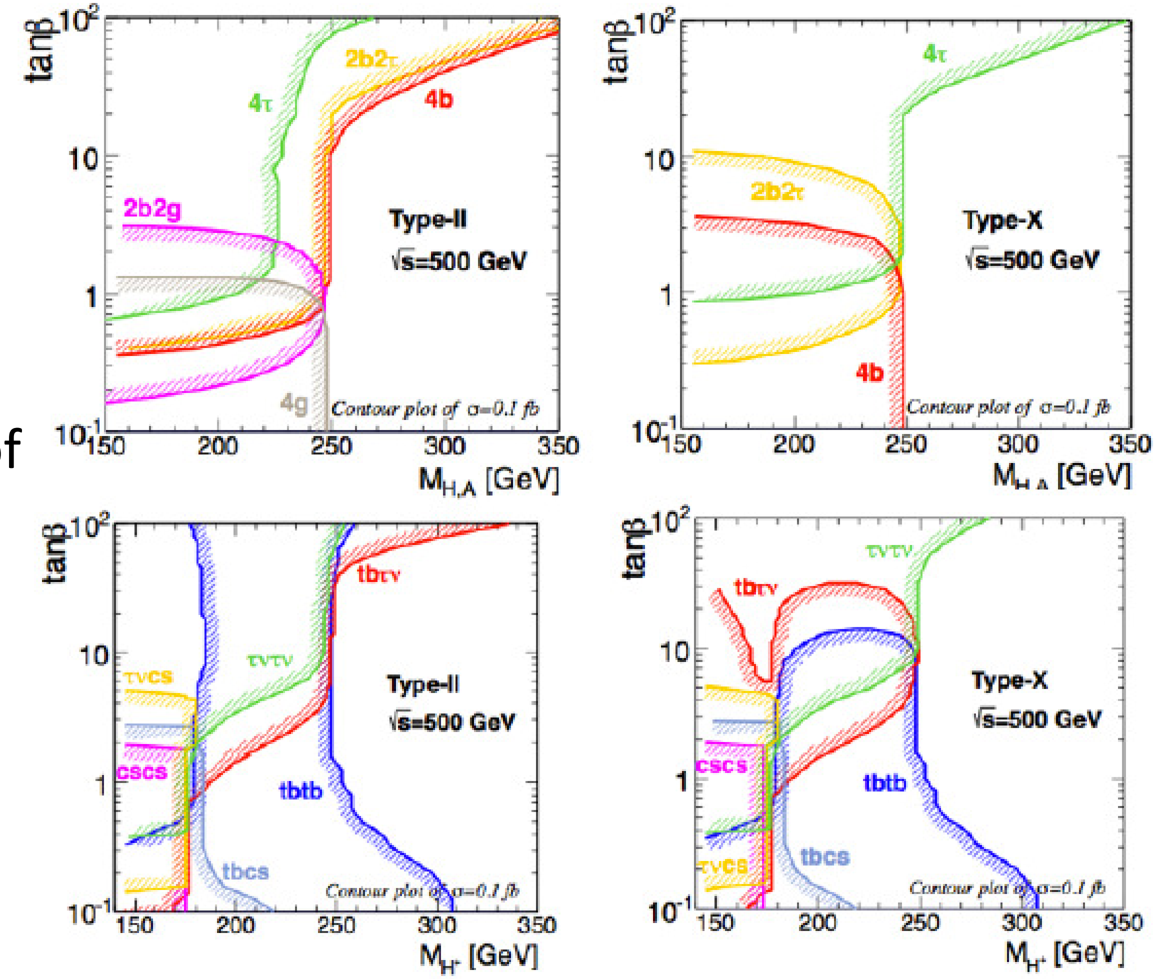
$$e^+e^- \to f\bar{f}H/A$$
$$e^+e^- \to f\bar{f}'H^\pm$$



Direct searches at the ILC

- Contour plot at $\sigma = 0.1$ fb for various final-state signals (as a typical order of detectable cross-section)

/s = 500 GeV Type-II & X Kanemura,HY,Zheng (14)



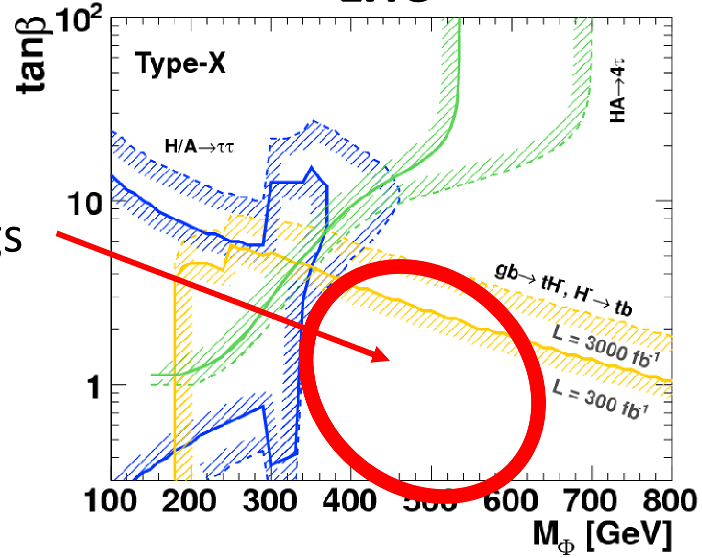
- Because of the clean environment, signals can be detectable in various final-states.

- Type of Yukawa models can be discriminated from the combination of the signals.

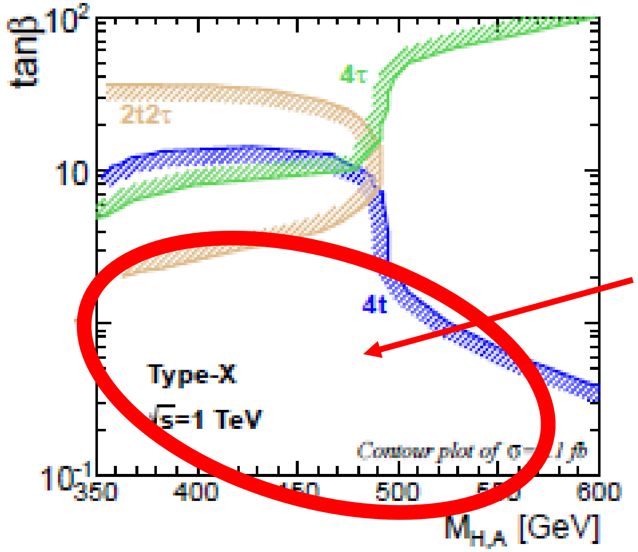
- Single production process can be useful in very large or small tanβ regions.

Multi-Top events at the ILC

LHC



ILC 1TeV



Neutral Higgs cannot be discovered

ILC can find it !

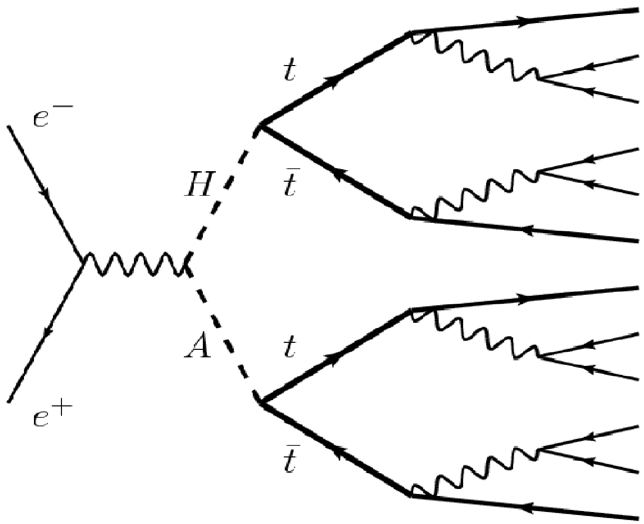
We focus on the parameter regions of $M_{H,A} \gtrsim 350\ \mathrm{GeV}\ \&\ \mathrm{small}\ \tan\beta$ where H/A decay into tt.

- At the LHC, $pp \to H/A \to t\bar{t}$ difficult to find tt resonance
- At the ILC, $e^+e^- \to HA \to t\bar{t}t\bar{t}$ detectable at /s = 1 TeV stage

→ We study the collider signature of the 4 top events at the ILC1TeV

Four-top signal structure

$$e^+e^- \to HA \to t\bar{t}t\bar{t} \to bW\bar{b}WbW\bar{b}W \to bf\bar{f}\bar{b}f\bar{f}bf\bar{f}\bar{b}f\bar{f}$$



Decay modes	Final states	$\mathcal{R}$ (with τ's)	$\mathcal{R}$ (without τ's)
all-hadron	$4j_b + 8j$	$\left(\frac{2}{3}\right)^4 = 0.2$	$\left(\frac{2}{3}\right)^4 = 0.2$
single lepton + jets	$\ell^\pm + 4j_b + 6j + \nu$	$\left(\frac{2}{3}\right)^3 \cdot \frac{1}{3} \cdot 4 = 0.40$	$\left(\frac{2}{3}\right)^3 \cdot \frac{2}{9} \cdot 4 = 0.26$
S.S. dilepton + jets	$\ell^\pm\ell^\pm + 4j_b + 4j + \nu\nu$	$\left(\frac{2}{3}\right)^2 \cdot \left(\frac{1}{3}\right)^2 \cdot 2 = 0.10$	$\left(\frac{2}{3}\right)^2 \cdot \left(\frac{2}{9}\right)^2 \cdot 2 = 0.04$
O.S. dilepton + jets	$\ell^\pm\ell^\mp + 4j_b + 4j + \nu\nu$	$\left(\frac{2}{3}\right)^2 \cdot \left(\frac{1}{3}\right)^2 \cdot 4 = 0.20$	$\left(\frac{2}{3}\right)^2 \cdot \left(\frac{2}{9}\right)^2 \cdot 4 = 0.09$
trilepton + jets	$\ell^\pm\ell^\pm\ell^\mp + 4j_b + 2j + \nu\nu\nu$	$\frac{2}{3} \cdot \left(\frac{1}{3}\right)^3 \cdot 4 = 0.10$	$\frac{2}{3} \cdot \left(\frac{2}{9}\right)^3 \cdot 4 = 0.03$
tetralepton + jets	$\ell^+\ell^+\ell^-\ell^- + 4j_b + \nu\nu\nu\nu$	$\left(\frac{1}{3}\right)^4 = 0.01$	$\left(\frac{2}{9}\right)^4 = 2.4 \times 10^{-3}$

Event characteristics:

- Jets(4 b-jets + light jets) + leptons + missing energy
- **$2N_{lep} + N_{jet} = 12$** (at the parton-level)
- Small thrust events, due to heavy particle decays

SM BG:

- $t\bar{t},\ t\bar{t}\ell\ell,\ t\bar{t}b\bar{b}$ — reducible
- $t\bar{t}t\bar{t}$ — irreducible, but negligible XS

Simulation Analysis

Details of simulation analysis:

- Event generation by **MadGraph5 + Pythia6**
- Event analysis framework :

  Acceptance cuts; $|\eta| \leq 1.5$ & $p_T^{\rm chg} > 0.3$ GeV
  Momentum smearing according to the detector resolution;
  Lepton isolation requirement; Jet clustering by Durham algorithm with $Y_{cut} = 5\times10^{-4}$; (pseudo-)b-tag with loose criteria (ILC TDR); tau-tagging,,

$$N_{\rm lep} = N_e^{\rm iso} + N_\mu^{\rm iso} + N_{\tau_j},\ N_{\rm jet} = N_{Bj} + N_{Lj}$$

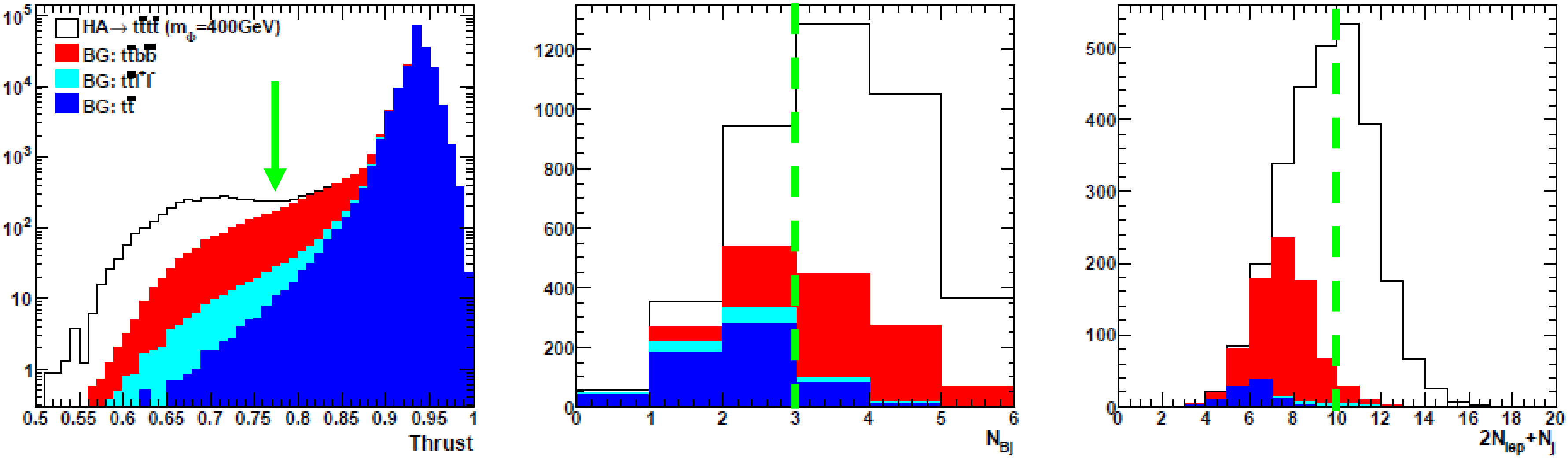
- **Selections Cuts**:

  We do not separate events by N_{lep}, N_{jet}, etc., but just collect events with

① Thrust: T<0.77, ② $N_{Bj} \geqq 3$, ③ $2N_{lep} + N_{jet} \geqq 10$

Simulation results

Event distributions in cut variables:



Signal selection/BG rejection efficiencies

- Signal efficiency: 40~50%
- BG rejection: 0.7% [ttbb], 1.4% [ttll], <10^{-6} [tt]

⇒ **Only ~40 BG events for 1ab^{-1}**

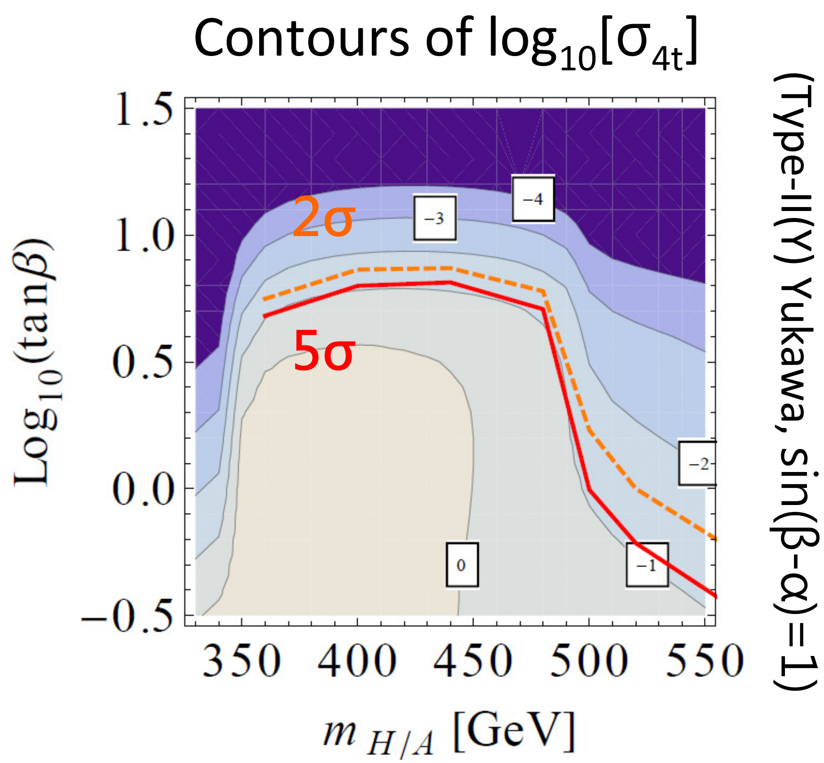
Processes	Cross-sections	Accumulated efficiencies		
	$\sigma_{\rm tot}$ [fb]	$T \leq 0.77$	$N_{b_j} \geq 3$ (tight/loose)	$2N_\ell + N_j \geq 10$
$e^+e^- \to HA \to t\bar{t}t\bar{t}$				
$m_{H,A} = 360$ GeV	$\sim 4.2 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	79%	44%/77%	25%/44%
400 GeV	$\sim 2.7 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	92%	50%/74%	30%/43%
440 GeV	$\sim 1.4 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	96%	52%/93%	30%/53%
480 GeV	$\sim 0.28 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	96%	51%/93%	30%/53%
500 GeV		95%	52%/77%	31%/42%
520 GeV		95%	52%/77%	31%/45%
560 GeV		93%	51%76%	31%/44%
$e^+e^- \to t\bar{t}$	166.	3.6×10^{-3}	$1.5/5.6 \times 10^{-4}$	$1.0/2.0 \times 10^{-6}$
$e^+e^- \to t\bar{t}b\bar{b}$	5.0	19%	8.8%/14%	0.44%/0.66%
$e^+e^- \to t\bar{t}\ell^+\ell^-$	0.76	23%	1.0%/3.8%	0.36%/1.4%
$e^+e^- \to t\bar{t}t\bar{t}$ (SM)	2.2×10^{-3}	-	-	-

Discovery Reach at the ILC

Discovery potential

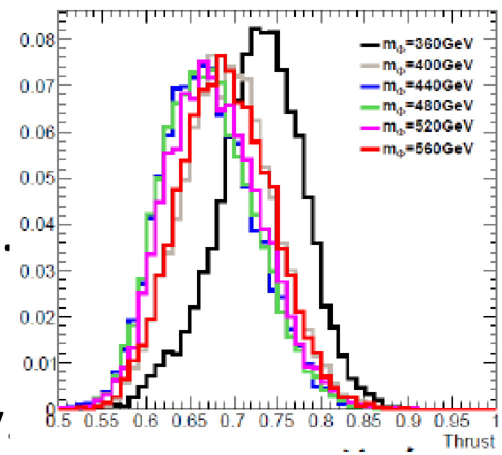
contours in the ($m_{H/A}$, $\tan\beta$) plane

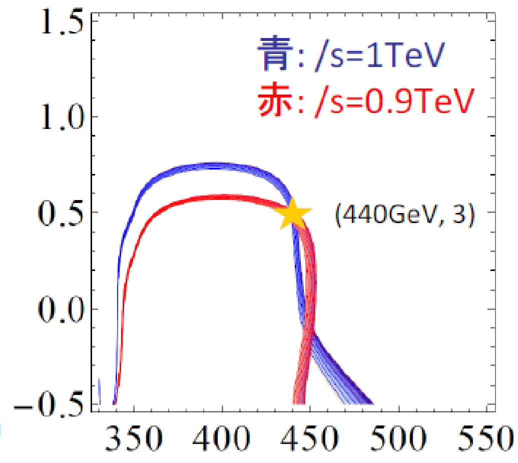
4-top cross-sections of about 0.08 (0.03) [fb] can be probed at the 5σ(2σ) CL.



Mass determination

- Kinematically, it is difficult to reconstruct the invariant-mass.
- Fitting of Thrust dist. may be performed.
- Energy scan of 4-top cross-section can determine ($m_{H/A}$, $\tan\beta$) simultaneously.





Summary

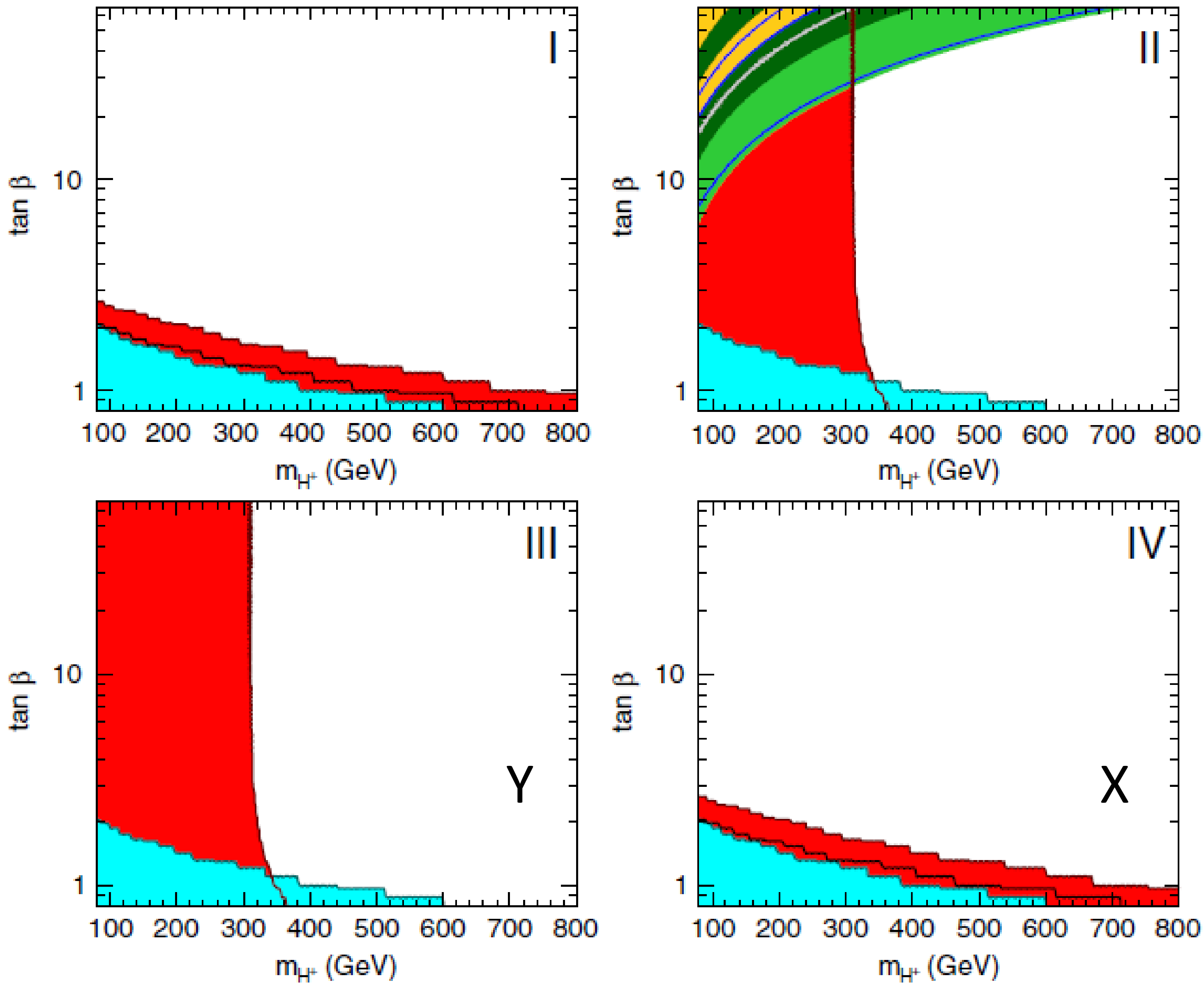
- For the direct searches of additonal Higgs bosons, difficult parameter regions may be… **M > 350 GeV and low tanβ → H/A > tt.**
- At the ILC, the signal is

$$e^+e^- \to HA \to t\bar{t}t\bar{t} \ (e^+e^- \to Ht\bar{t}/At\bar{t} \to t\bar{t}t\bar{t})$$

- We studies event structure of 4-top events at the ILC with MC simulation.
- Cuts on Thrust<0.77, $N_{Bj} \geqq 3$ and $2N_{lep}+N_{jet} \geqq 10$ work well to reduce SM BG.
- σ_{4t} of 0.08 (0.03)[fb] can be probed with $1ab^{-1}$ data.
- Mass and parameter determination can be possible by using distributions and energy scan.
- (Discrimination of the type of Yukawa, H/A mass difference are underway.)

Flavour constraints

Mahmoudi, Stal (10)



red : b->sγ

cyan : B-Bbar mixing

green : D_s->τν

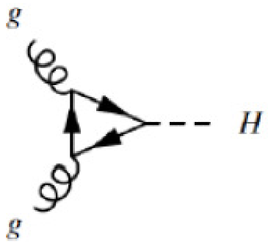
Golden channels: a la SUSY Higgs searches

$$pp \to H/A(b) \to \tau^+\tau^-(b)$$

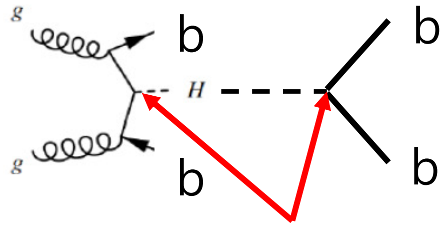
type-II

$$pp \to bH/A;\, H/A \to b\bar{b}$$

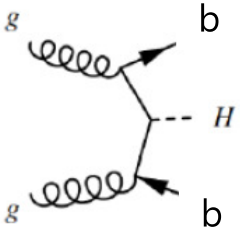
type-II, Y



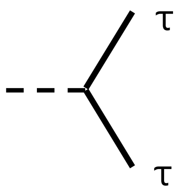
$\kappa_g \propto \tan\beta$ in large tanβ by bottom-loop



$\kappa_b \simeq \tan\beta$

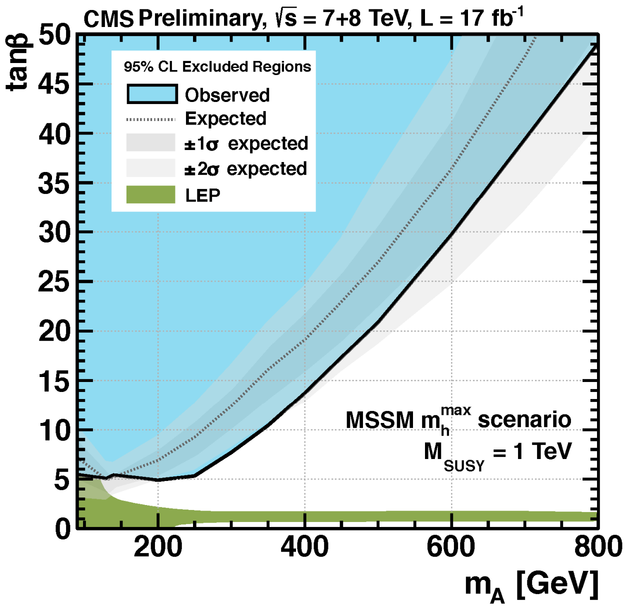


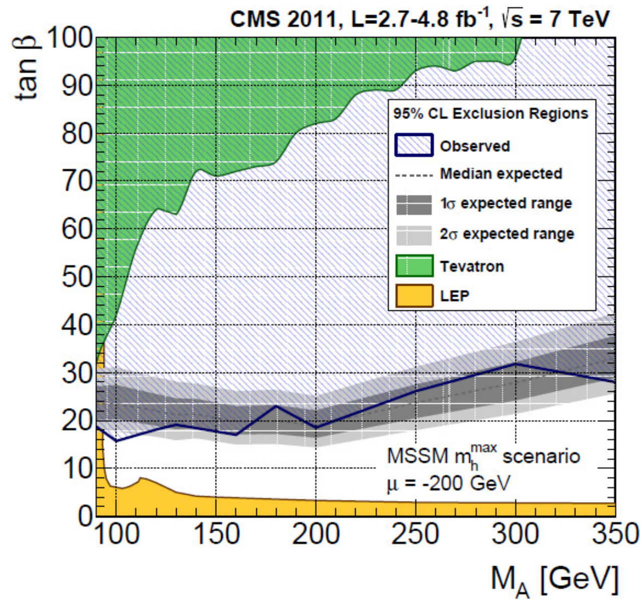
$\kappa_b \simeq \tan\beta$



$\kappa_\tau \simeq \tan\beta$

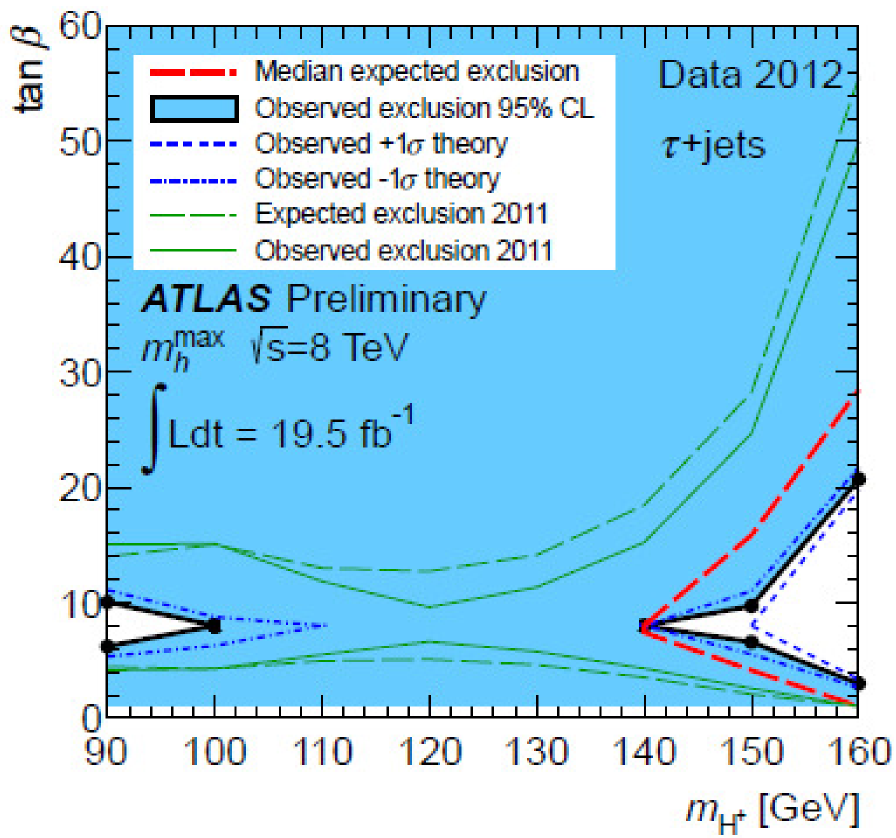
$(\mathcal{B}(\tau\tau) \sim 10\%)$

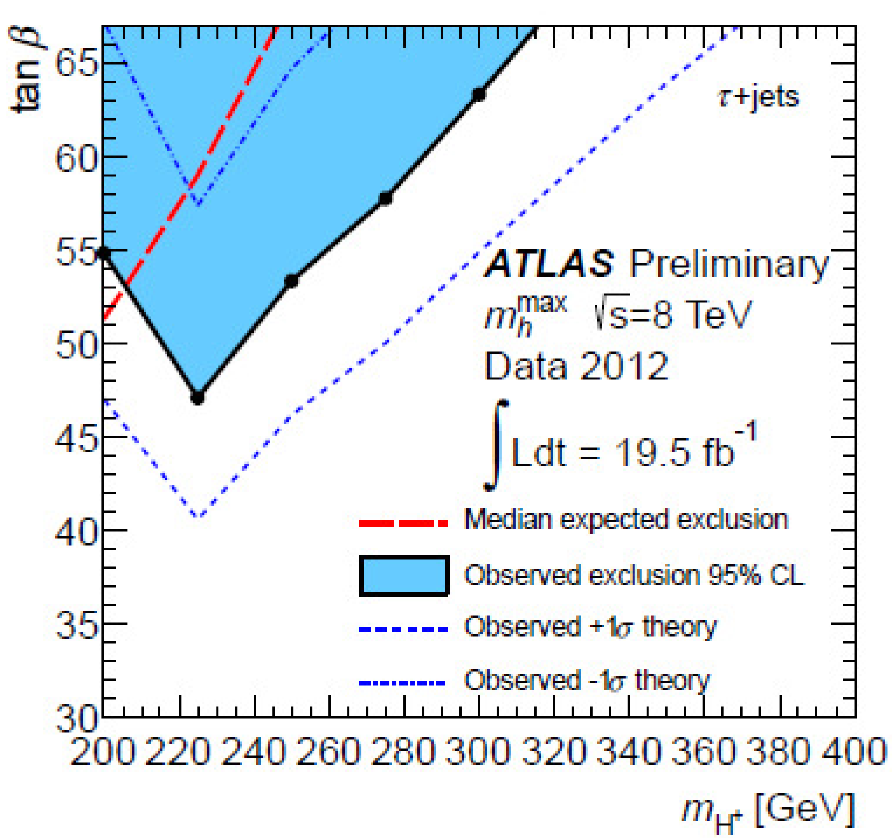




Charged Higgs search in the top quark decay :

$$t \to bH^{+} \to b\tau^{+}\nu$$

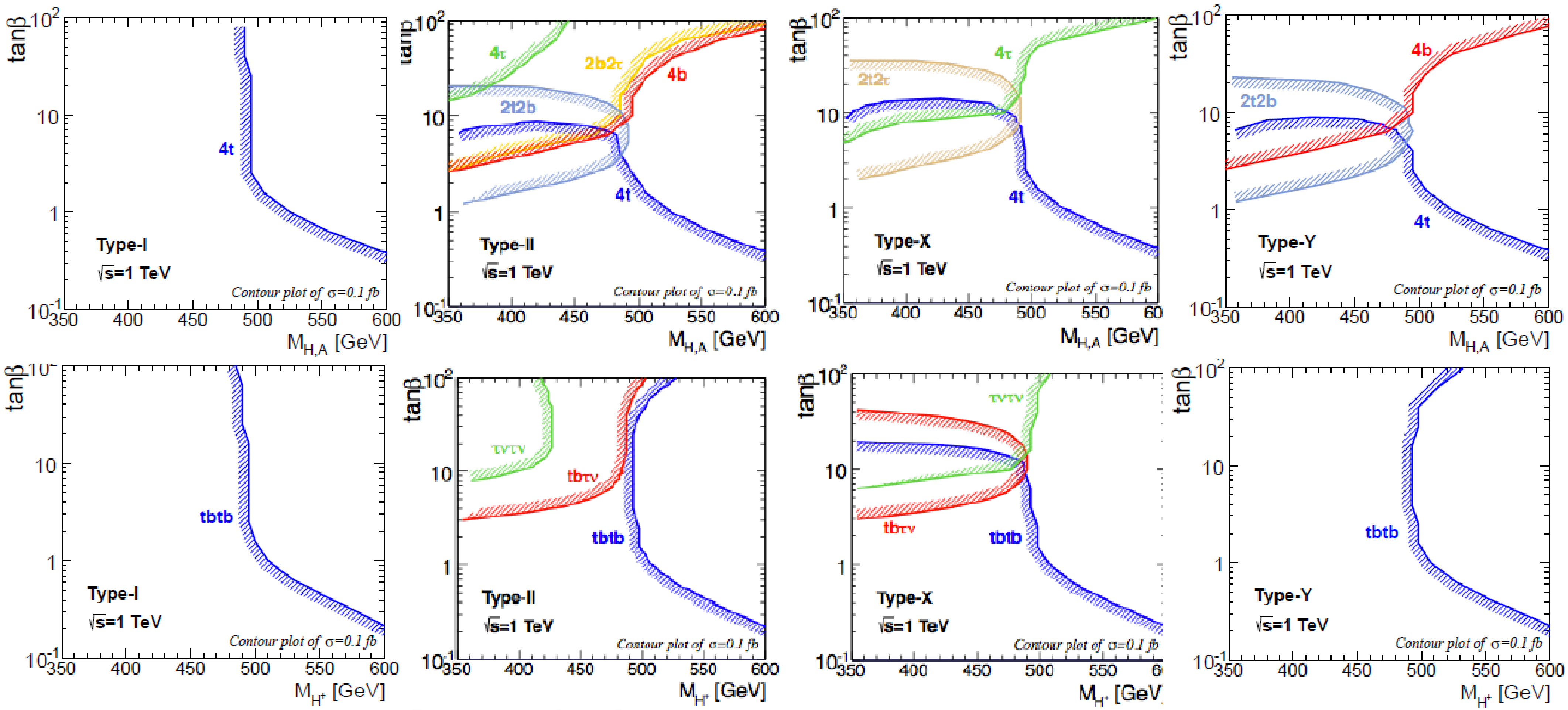




Direct searches at the ILC

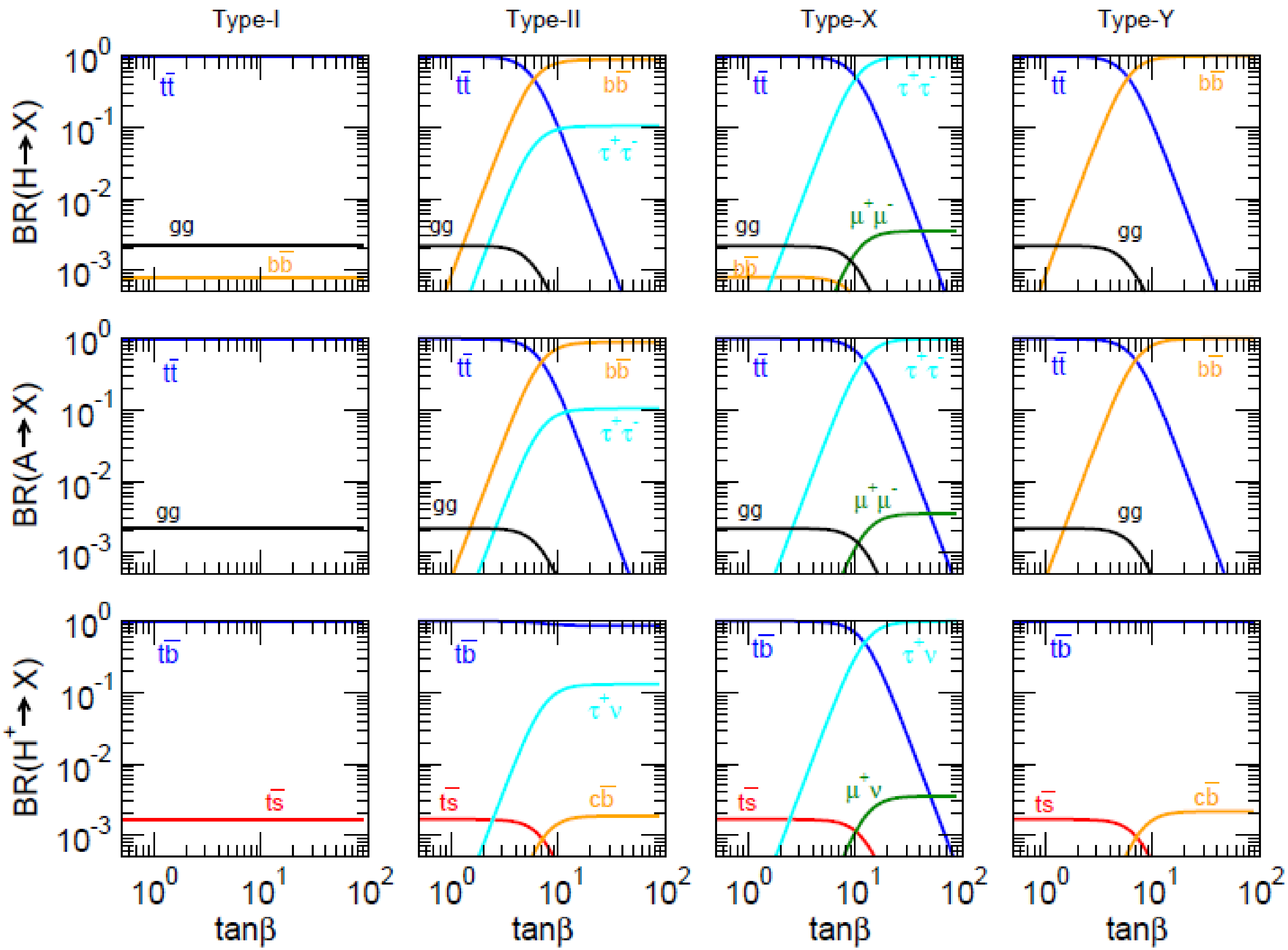
$\sqrt{s}$ = 1 TeV tt, tb decay modes are dominant → tttt, tbtb signatures.

Kanemura,HY,Zheng (14)



Decay Branching ratios

$m_H = m_A = m_{H+} = 500$ GeV, $\sin(\beta - \alpha) = 1$

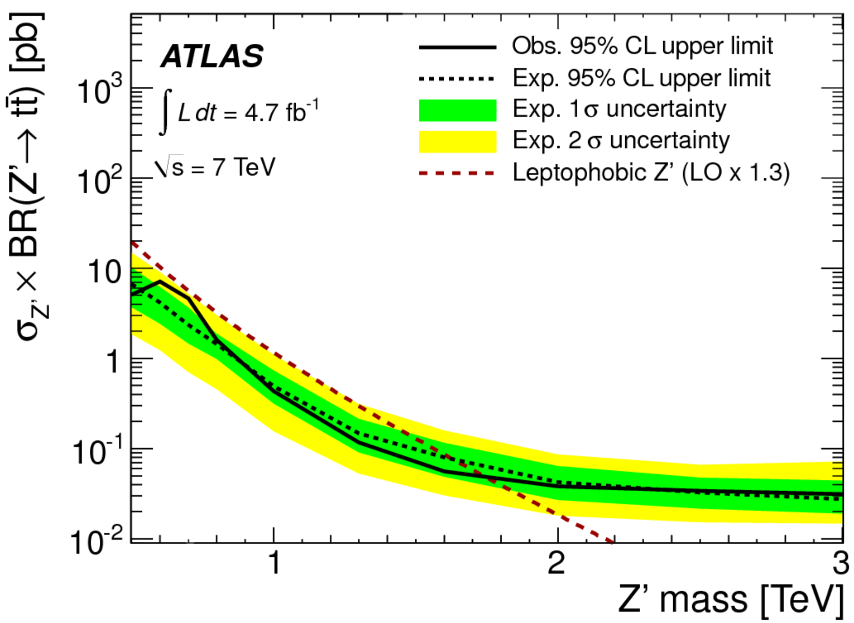


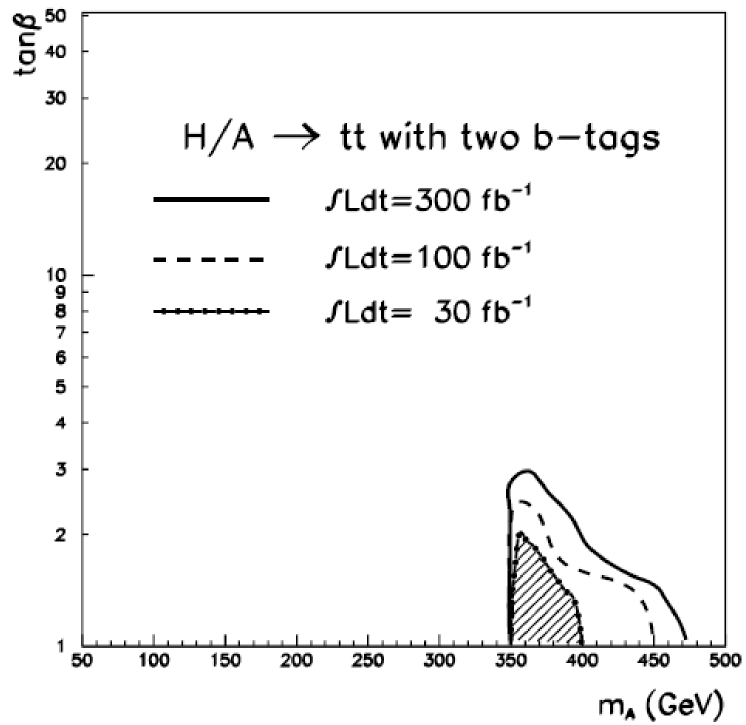
Searches for H/A → tt

- For M_{Φ}>350GeV, neutral Higgs bosons detection is difficult at the LHC, because they decay dominantly into top-quark-pair.

- At the LHC, $pp \to H/A \to t\bar{t}$ detection is limited, because of huge SM tt production cross-section.

ATLAS TDR





Limits on the cross-section ~ O(pb)

Expected signatures at the LHC and ILC (benchmark points with M=220 GeV)

$(M, \tan\beta)$		Type-I		Type-II		Type-X		Type-Y	
		H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$
(220 GeV, 20)	LHC300	-	-	$\tau\tau$, bb	tb	4τ	-	bb	tb
	LHC3000	-	-	$\tau\tau$, bb	tb	4τ	-	bb	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, 4τ	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	4τ	$tb\tau\nu$, $\tau\nu\tau\nu$	$4b$	$tbtb, tbcb$
(220 GeV, 7)	LHC300	-	-	$\tau\tau$	tb	4τ	-	-	tb
	LHC3000	-	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, 4τ	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	$2b2\tau, 4\tau$	$tbtb, tb\tau\nu$, $\tau\nu\tau\nu$	$4b$	$tbtb, tbcb$
(220 GeV, 2)	LHC300	-	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	tb	-	tb
	LHC3000	$\tau\tau$	tb	$\tau\tau$	tb	$\tau\tau, 4\tau$	tb	-	tb
	ILC500	$4b, 2b2\tau$	$tbtb$	$4b, 2b2\tau$, $4\tau, 2b2g$	$tbtb$, $tb\tau\nu$	$4b, 2b2\tau$, 4τ	$tbtb$, $tb\tau\nu$	$4b, 2b2\tau$, $2b2g$	$tbtb$

Expected signatures at the LHC and ILC (benchmark points with M=400 GeV)

$(M, \tan\beta)$		Type-I		Type-II		Type-X		Type-Y	
		H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$	H, A	$H^\pm$
(400 GeV, 20)	LHC300	-	-	$\tau\tau$	tb	4τ	-	-	tb
	LHC3000	-	-	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC1TeV	$4t$	$tbtb$	$4b, 2b2\tau,$ $2t2b$	$tbtb, tb\tau\nu,$ $\tau\nu\tau\nu$	$4\tau, 2t2\tau$	$tb\tau\nu,$ $\tau\nu\tau\nu$	$4b, 2t2b$	$tbtb$
(400 GeV, 7)	LHC300	-	-	-	-	-	-	-	-
	LHC3000	-	-	$\tau\tau$	tb	$\tau\tau, 4\tau$	-	-	tb
	ILC1TeV	$4t$	$tbtb$	$4b, 2b2\tau,$ $2t2b, 4t$	$tbtb, tb\tau\nu$	$4t, 2t2\tau$	$tbtb,$ $tb\tau\nu$	$4b, 2t2b, 4t$	$tbtb$
(400 GeV, 2)	LHC300	-	tb	-	tb	-	tb	-	tb
	LHC3000	-	tb	-	tb	-	tb	-	tb
	ILC1TeV	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$	$4t$	$tbtb$	$4t, 2t2b$	$tbtb$