2HDM Searches at the ILC in the 4-top events

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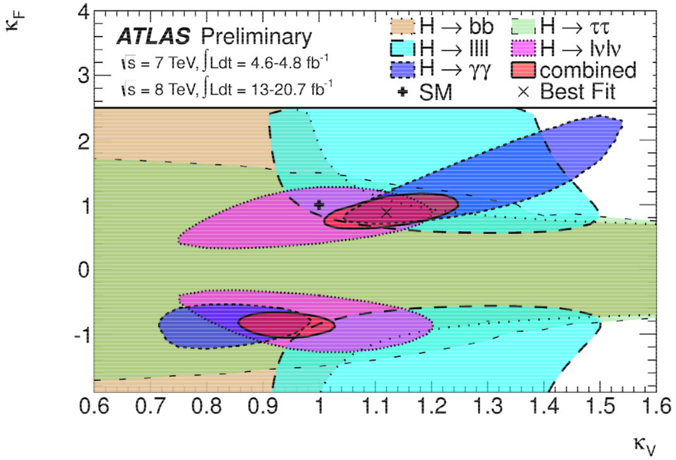
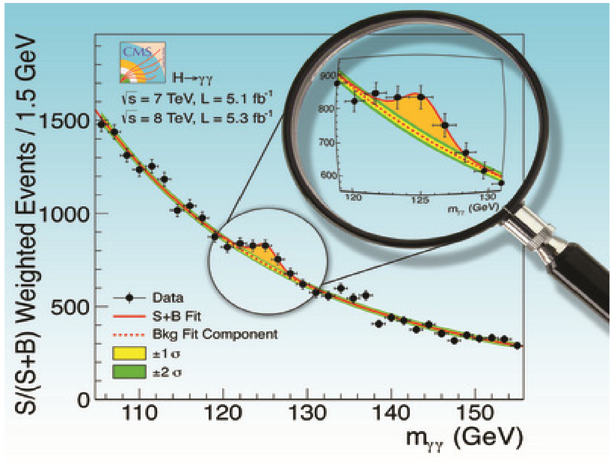
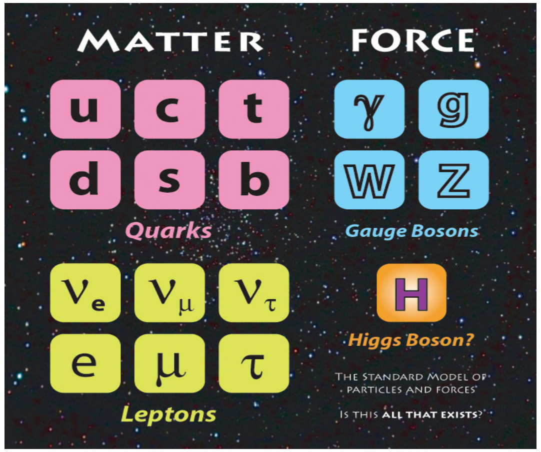
Introduction :

A Higgs boson was found at the LHC,

which seems mostly the SM one.







- But, we don't know whether this is the only one or there are more.
- Extended Higgs sectors are often introduced in the physics beyond the SM, to explain unsolved problems, such as dark matter, neutrino mass, baryon asymmetries ,,

Two Higgs Doublet Model (2HDM):

$$\Phi_1 + \Phi_2 \qquad \Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i\, z_i) \end{pmatrix}$$

i=1,2

- ρ = 1 at tree-level
- In general, FCNCs occur → discrete symmetry, aligned Yukawa,,,
- New sources of CP phases (assumed to be zero in this talk)

8 – 3 = 5 physical states:

$$h,\ H,\ A,\ H^{\pm}$$

VEVs: $v = \sqrt{v_1^2 + v_2^2} \simeq 246\ \mathrm{GeV}$

$\tan\beta = v_1/v_2$

Mixing angles:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

Softly-broken discrete symmetry

- To avoid FCNCs, we consider models with a discrete symmetry

Glashow,Weinberg ('77)

$$\Phi_1 \to \Phi_1, \ \Phi_2 \to -\Phi_2$$

so that each fermion has Yukawa couplings to one Higgs bosons:

$$\mathcal{L} = \overline{L}\,(Y_{\ell 1}{\color{red}\Phi_1} + {\color{blue}\times})\,\ell_R + \mathrm{H.c.}$$

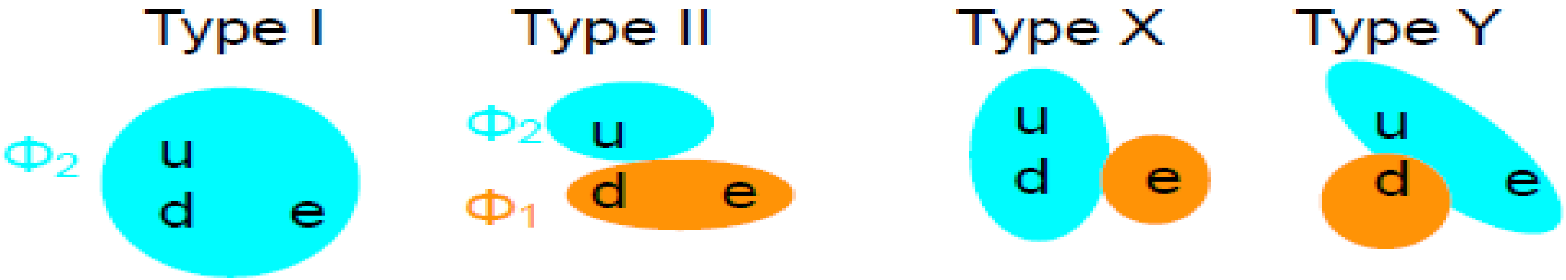
or vice versa

- 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

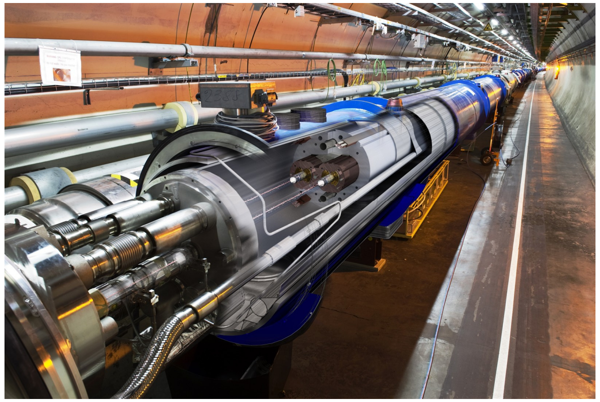
flipped

Direct searches at future colliders

LHC /s = 13-14TeV

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

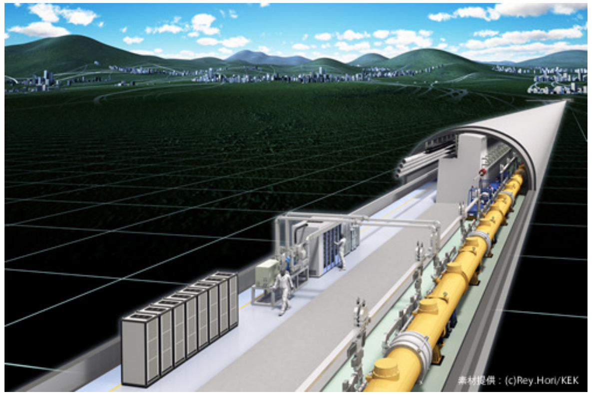
3000fb^{-1} (HL-LHC) 2025(?) ~



ILC

/s = 250GeV, 2025(?) ~

(~350GeV), 500GeV, 1TeV



For the direct searches, basically the LHC is better than the ILC.

But, there are still possibilities that the LHC cannot find/identify new Higgs bosons.

If their masses are within the ILC reaches, the ILC can help to explore them.

We study the complementarity of the direct searches of additional Higgs bosons at the LHC and ILC, in the context of the 2HDM with discrete symmetry.

Direct searches at the LHC

- There exist many extensive studies for the searches of the MSSM Higgs bosons.

e.g. ATLAS TDR

- We interpret their results to the general 2HDMs

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

- H, A : $gg \to H/A$, $gg(q\bar{q}) \to Q\bar{Q}H/A$ $\Big\}$ $H/A \to b\bar{b}$ or $\tau^+\tau^-$

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

- In the case where only couplings to lepton are large (Type-X in large tanβ) :

$$q\bar{q} \to HA \quad q\bar{q}' \to HH^\pm, AH^\pm$$

$$H/A \to \tau^+\tau^-,\ H^\pm \to \tau^\pm\nu$$

Aoki,Kanemura,Tsumura,
Yagyu('09),
Kanemura,Tsumura,HY('11)

Direct searches at the LHC

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

Reaches of direct searches for additional Higgs boson(95% CL), interpreted from the ATLAS TDR.

Kanemura,HY,Zheng ('14)

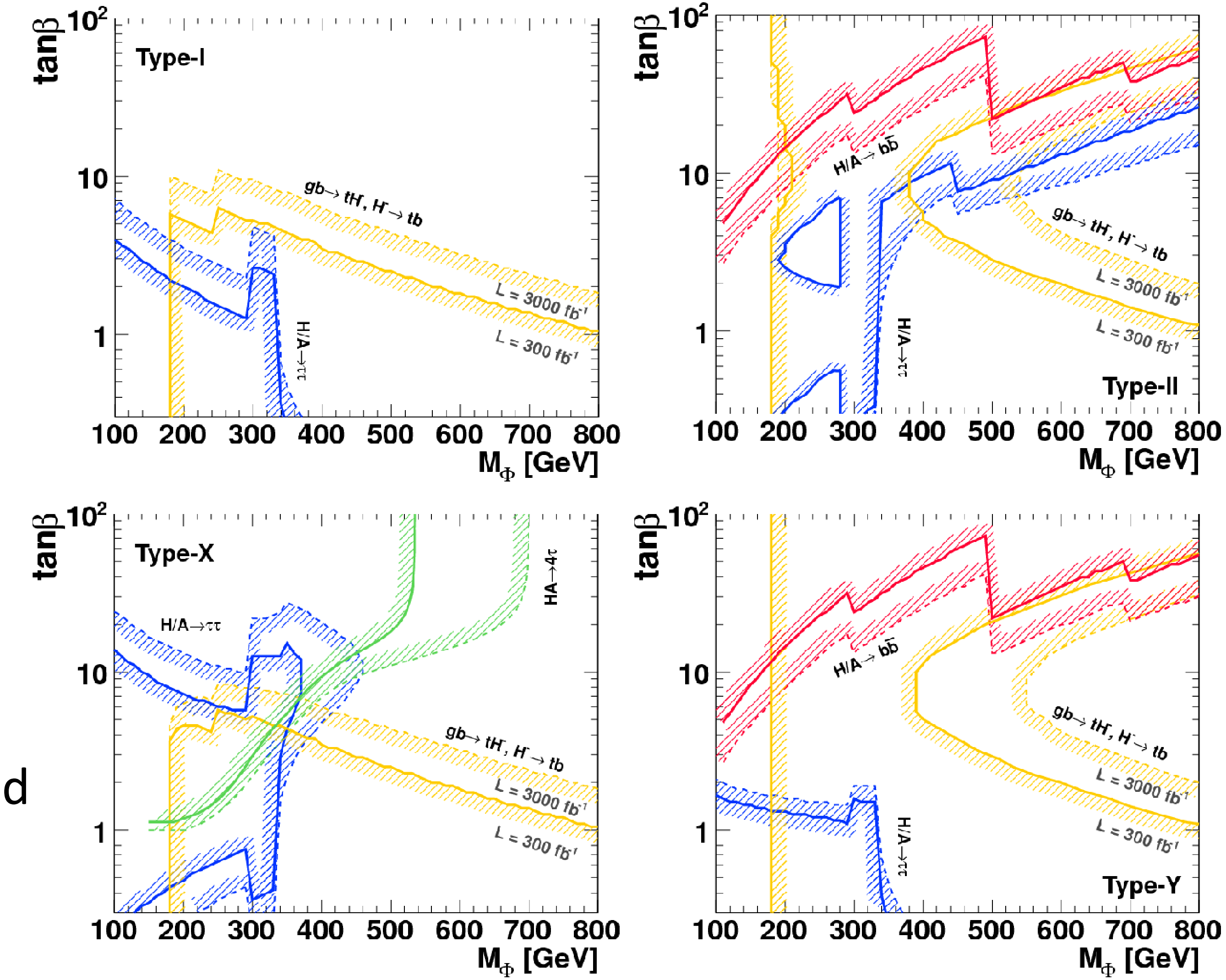
solid:300fb^{-1}, dashed:3000fb^{-1}

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

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

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

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



Extensive regions are covered up to M$_\Phi$~600GeV.

Direct searches at the ILC

Pair and single productions
of additional Higgs bosons

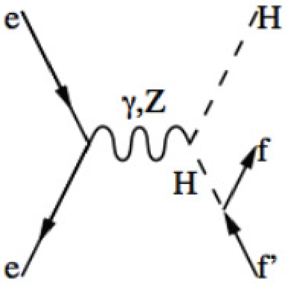
Kanemura,Moretti,Odagiri(01),
Kiyoura et al. (06),,,
Kanemura,HY,Zheng ('14)

At lepton colliders, heavy particle production is limited by the collision energy.

Pair production needs /s > 2m, while single production needs /s > m.

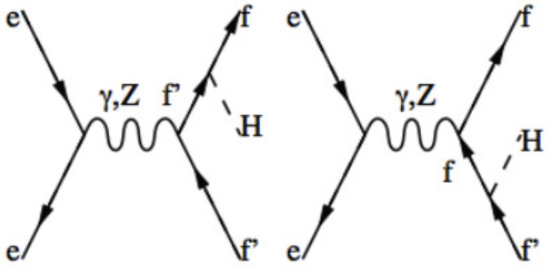
- /s > $m_H + m_A$ or $2m_{H+}$

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



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

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



- Single production can be enhanced by large Yukawa couplings,
  and extend the mass reach at lepton collider (a bit).

Direct searches at the ILC

Contour plot at σ = 0.1 fb

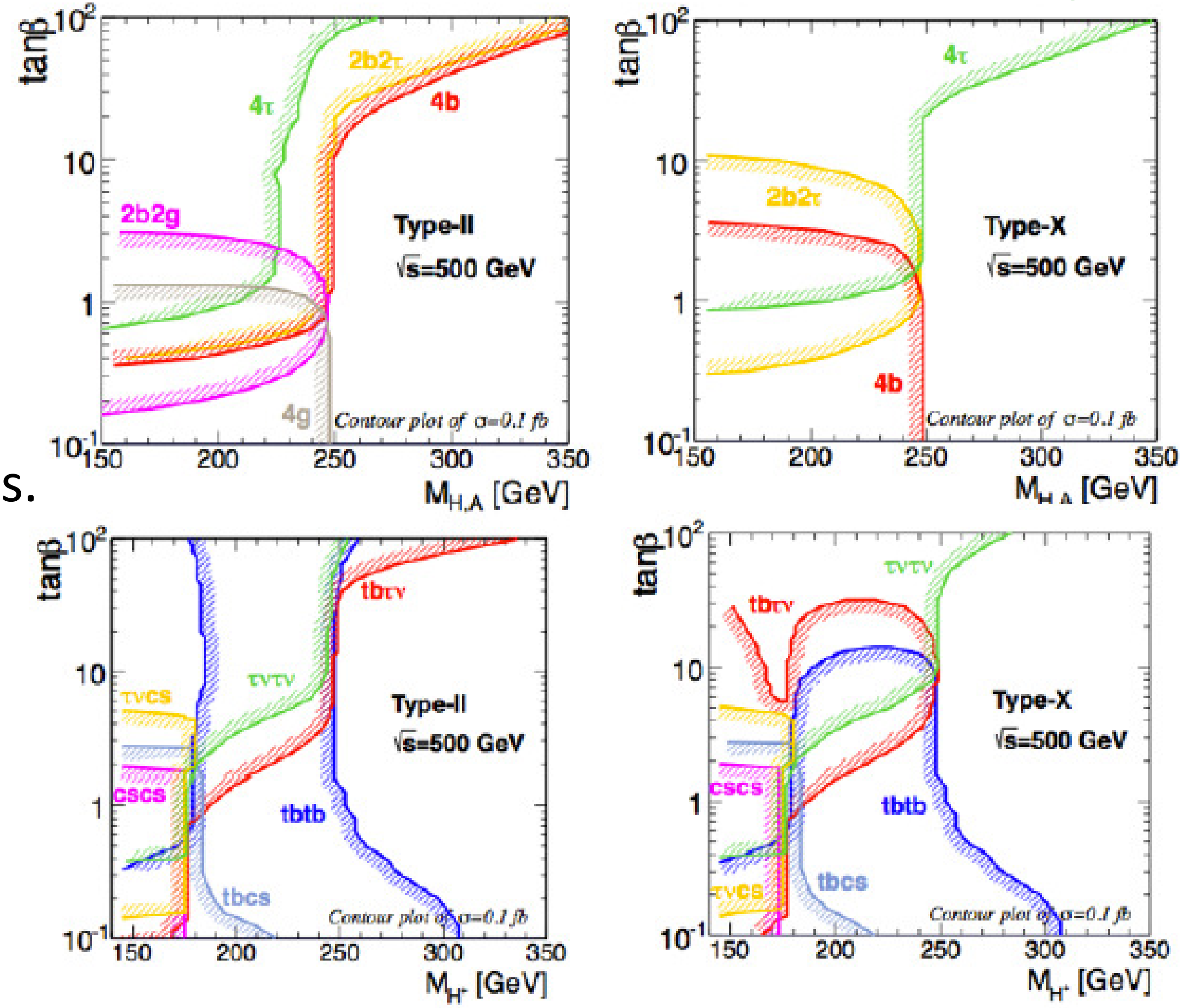
(as a typical order of cross-sections
Efficiency for each channel is not considered)

/s = 500 GeV Type-II & X

- In the pair production regions, we expect at least one kind of signature for any types/parameters.

- For most of the cases, by the combination of the signatures, the type of Yukawa can be distinguished.

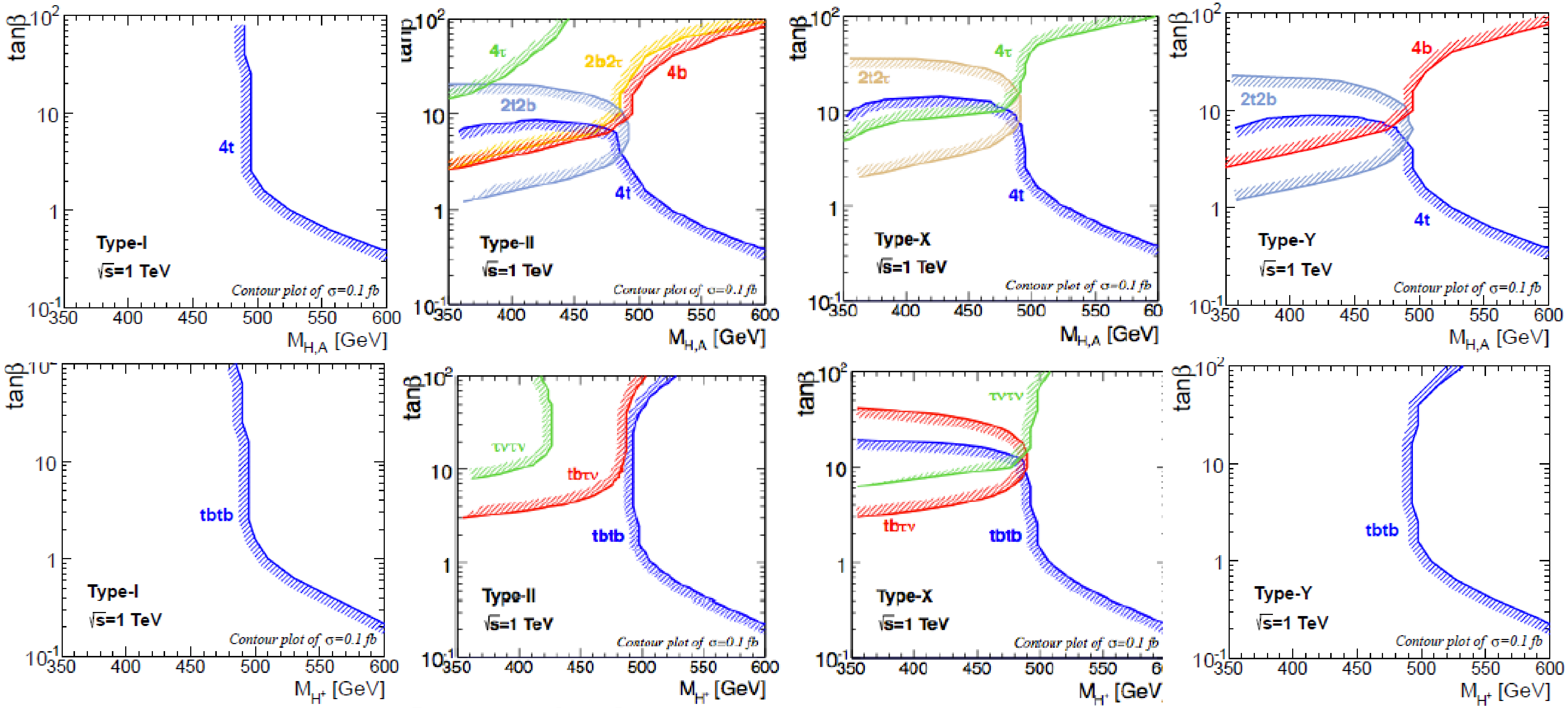
Kanemura,HY,Zheng (14)



Direct searches at the ILC

/s = 1 TeV tt, tb decay modes are dominant → tttt, tbtb signatures.

Kanemura,HY,Zheng (14)



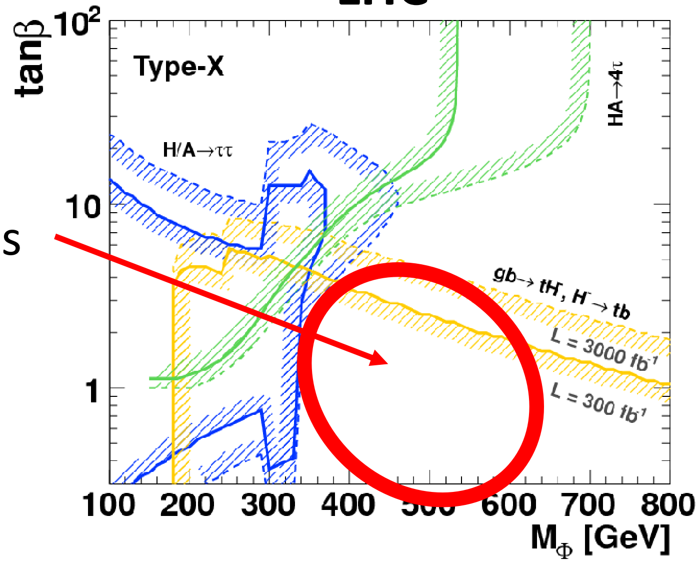
Complementarity of the LHC and ILC

Scenarios in which the ILC is useful for the direct searches

① LHC cannot find new Higgs, but ILC can find it.

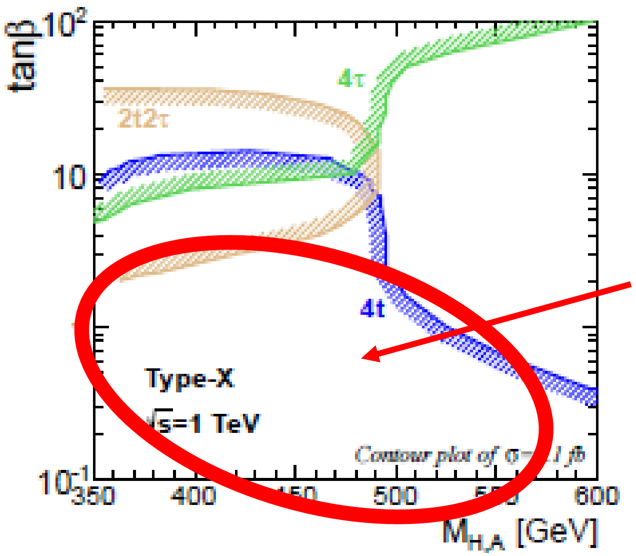
② LHC can find new Higgs, but models/types cannot be distinguished.
ILC then distinguish the models, determine the parameters.

LHC



Neutral Higgs cannot be discovered

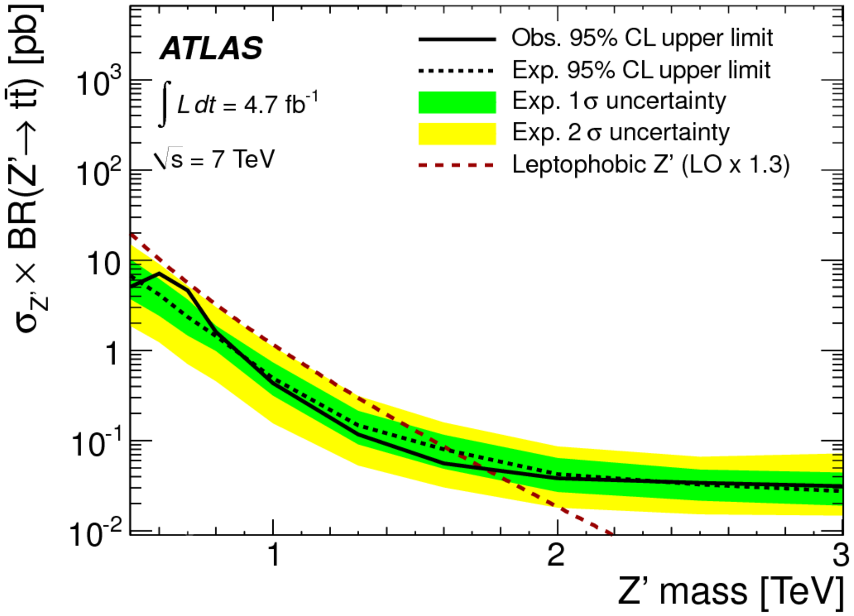
ILC 1TeV



ILC can find it !

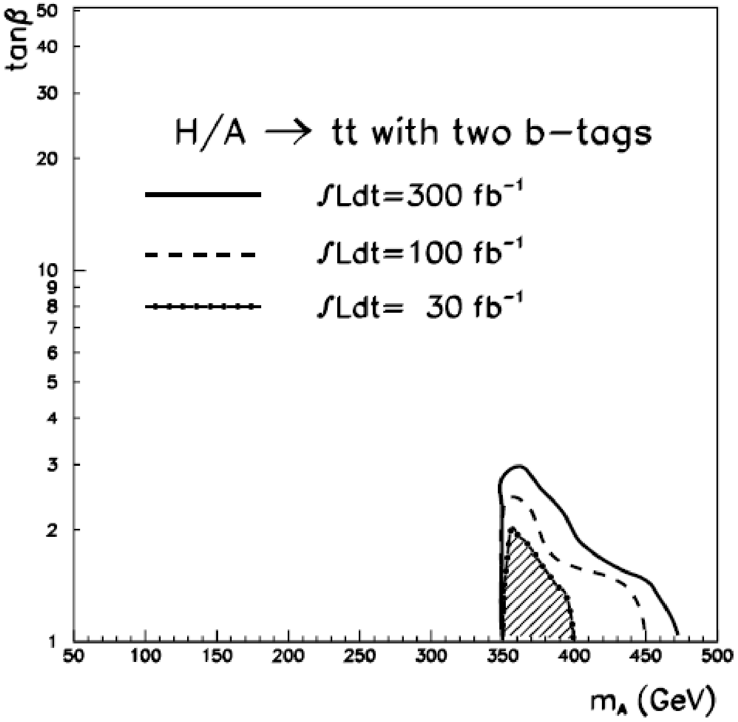
Searches for H/A → tt

- 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.



Limits on the cross-section ~ O(pb)

ATLAS TDR



Searches for H/A → tt

- It might be even easier to see **multi-top signals (same-sign top)**.

limits on the 4-top cross-section is already **63 fb @ 8TeV,20fb^{-1}**

CMS-TOP-13-002

At the LHC,

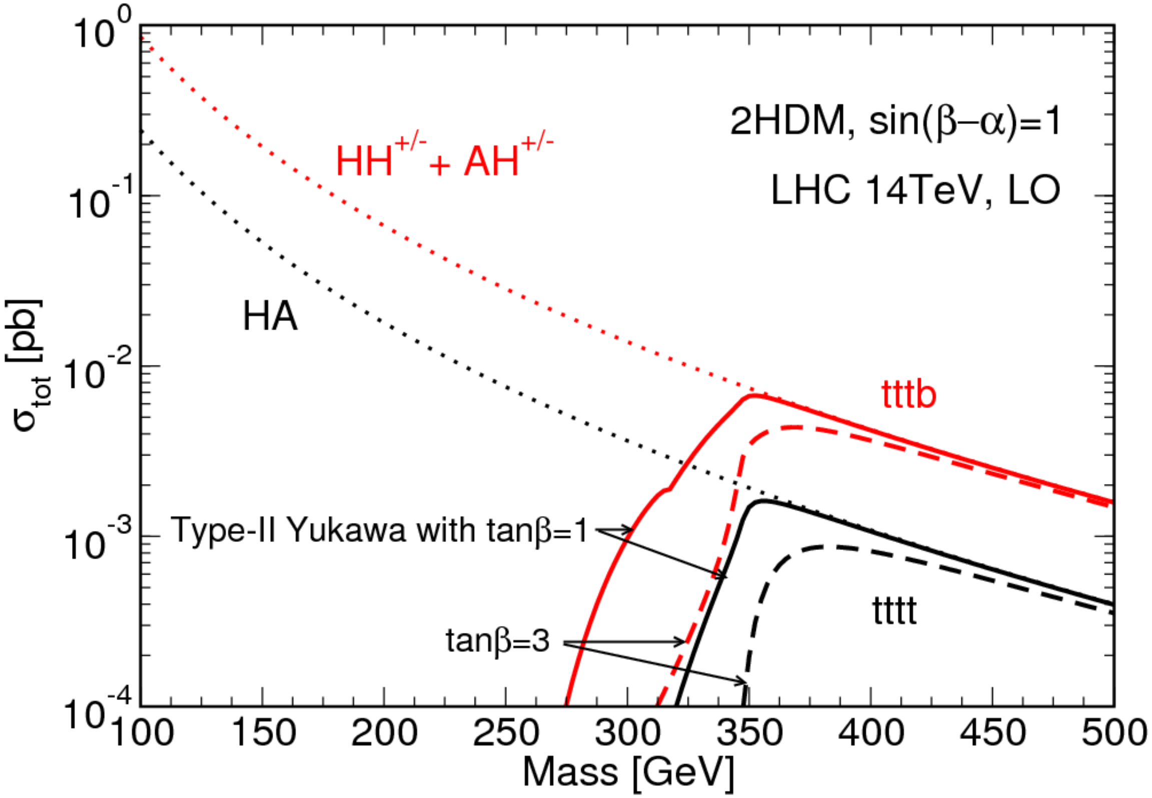
- Multi-top production in the 2HDM can reach

$$\sigma(3t/4t) \sim 10/10\ \mathrm{fb}^{-1}$$

(4t from ttH + ttA)

- while, SM contribution

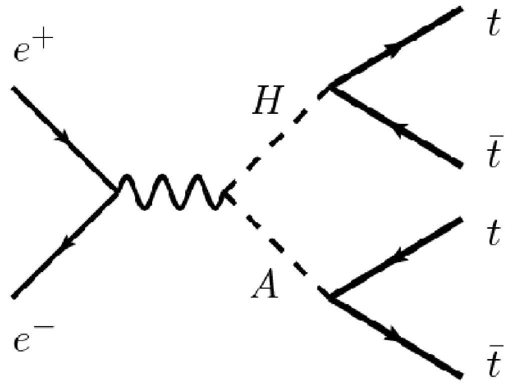
$$\sigma_{\mathrm{SM}}(3t/4t) \sim 2/10\ \mathrm{fb}^{-1}$$



4 top events at the ILC

- At the ILC 1TeV, $e^+e^- \rightarrow HA \rightarrow t\bar{t}t\bar{t}$

  is a promising process.

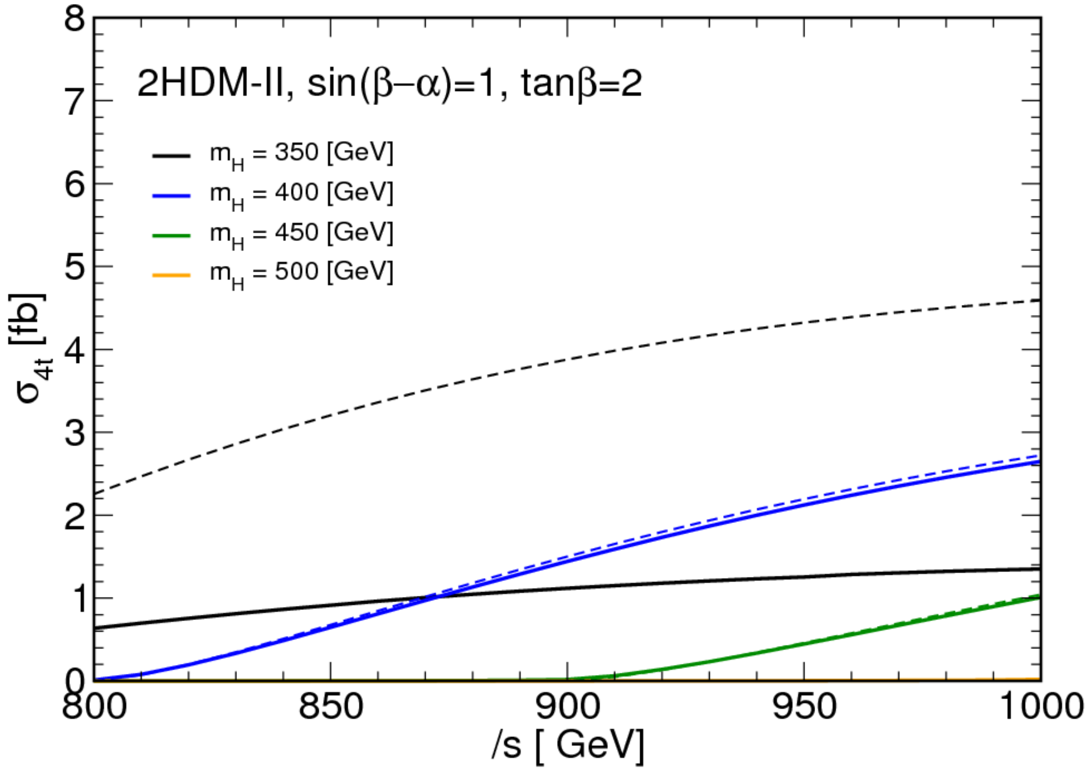


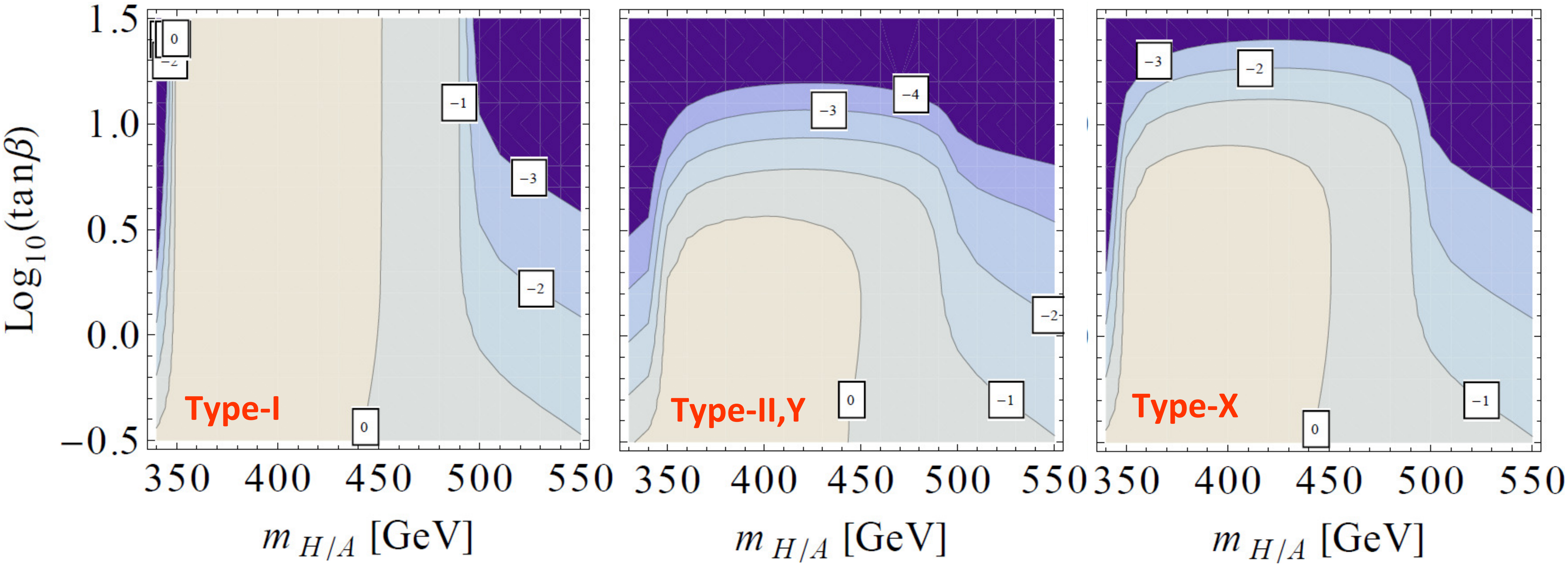
- SM 4-top cross-section ~ 2ab @ 1TeV

- 2HDM : pair production
  & single production of H/A

  - O(1) fb cross-section
    for M=350 ~ 450 GeV.

  - O(0.1) fb cross-section
    for M=450~550GeV.



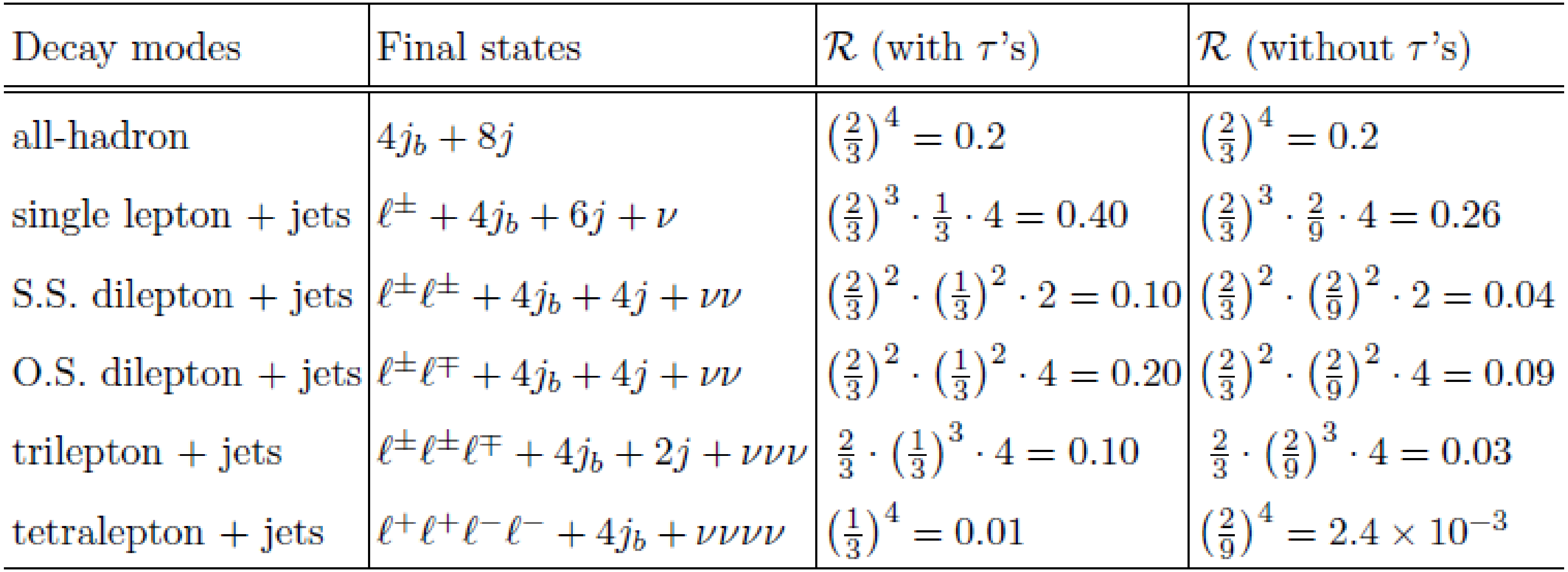


- The cross-section depends on the mass and tanβ for each Yukawa type.
- Type of Yukawa may be discriminated by the associated processes (e.g., 2t2b, 2t2τ).
- By measuring the mass, tanβ can be determined from the cross-section (i.e., branching ratio).

⇒ We are interested in the 4 top events; methods for detection and mass measurement at the ILC (and then LHC).

(At the ILC, photon collider is also an important option: $\gamma\gamma \to H/A \to t\bar{t}$)

Decay modes :



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:

- Leptons + jets(4 b-jets) + missing energy
- **$2n_l + n_j = 12$** (neglecting tau's decay)
- Small thrust events due to heavy particle decays.

Simulation (by theorists) :

- Event generation by PYTHIA.
- Hadron-level list with momentum smearing.
- (Tentative) Event analysis:
  - First, find Isolated leptons with high p_T (e,μ).
  - Then, jet clustering to classify event topology.

  → Next, event reconstruction for each decay modes.

- Problems:
  - ✓ How to define the number of jets?
  - ☐ How to reconstruct the mass of H/A?
  - ☐ Background analysis

Simulation : N_{jet} distributions

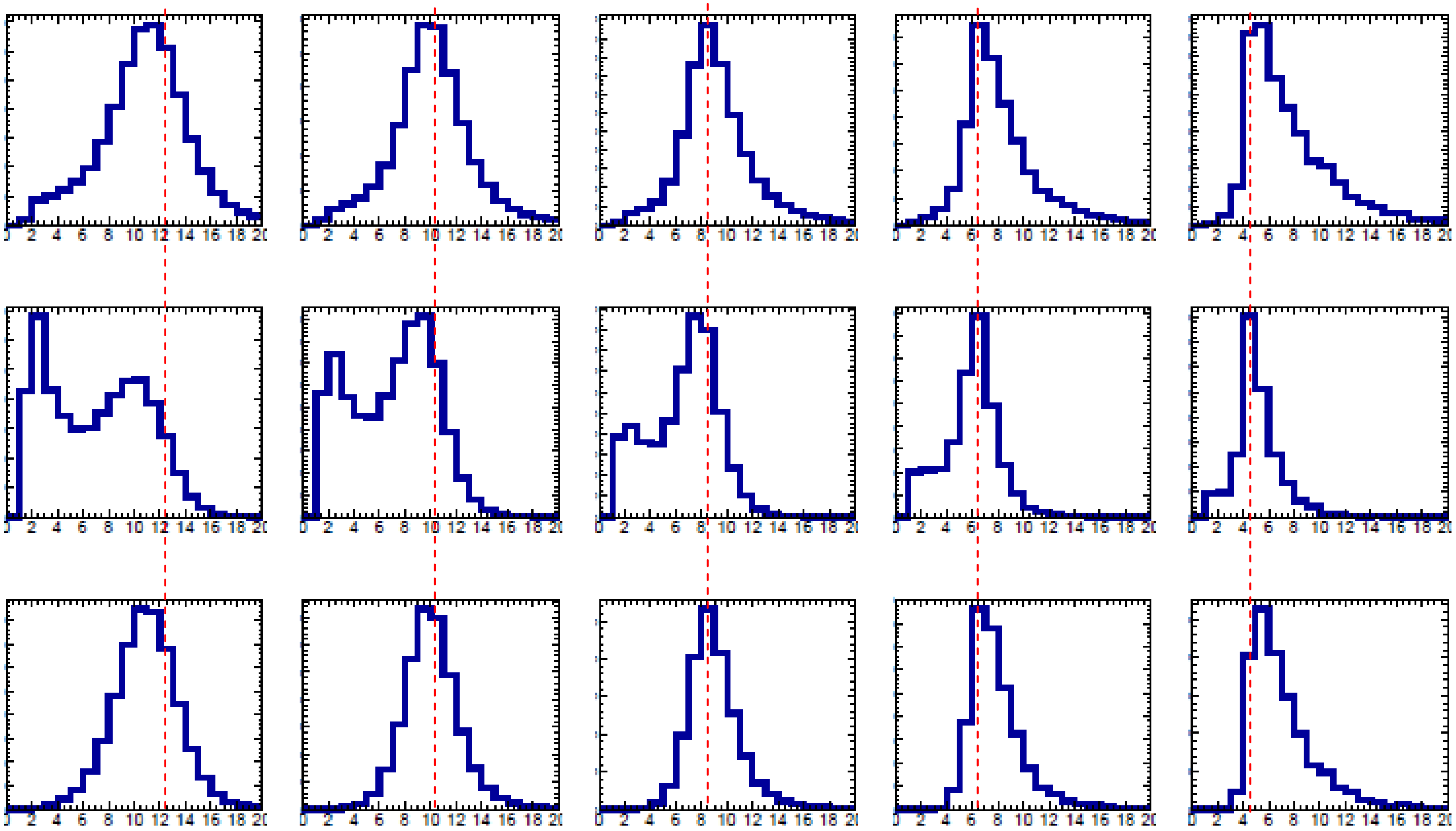
(exclusive)
Durham alg.

$n_\ell = 0$ $n_\ell = 1$ $n_\ell = 2$ $n_\ell = 3$ $n_\ell = 4$

$$\frac{Y_{n-1,n}}{Y_{n,n+1}} > 2$$

$$\frac{Y_{n-1,n}}{Y_{n,n+1}} > 3$$

$$\frac{Y_{n-1,n}Y_{n+1,n+2}}{(Y_{n,n+1})^2} > 2.5$$



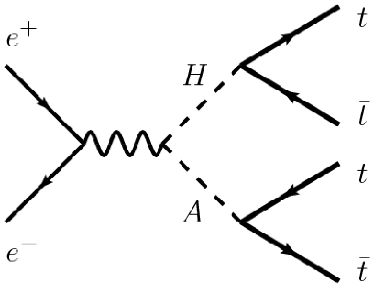
- $2n_l + n_j = 12$ relation can be seen. → to be refined by τ-tag and b-tag

Summary

- For the direct searches for 2HDM at the LHC and ILC,
  the unclear regions are maybe…

  M > 350 GeV and low tanβ → Multi-top signals.

- At the ILC, $e^+e^- \to HA \to t\bar{t}t\bar{t}$



- Cross-section measurements and mass reconstruction
  → determination of the mass & tanβ

- Simulation study for this process

  ☐ how to reconstruct the mass? (Endpoint method, Weight function method,,,)

  ☐ how to study the realistic background?