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

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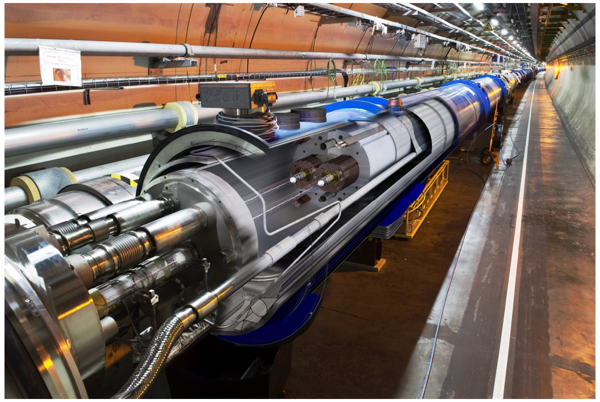
Direct searches at future colliders

LHC /s = 13-14TeV

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

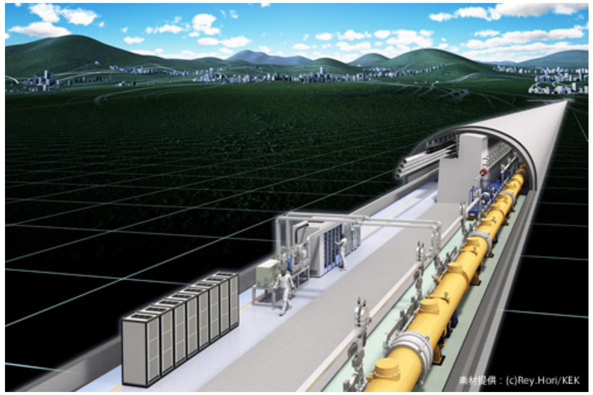
$3000fb^{-1}$ (HL-LHC) 2025(?) ~



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.

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: $v = \sqrt{v_1^2 + v_2^2} \simeq 246$ 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)

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

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

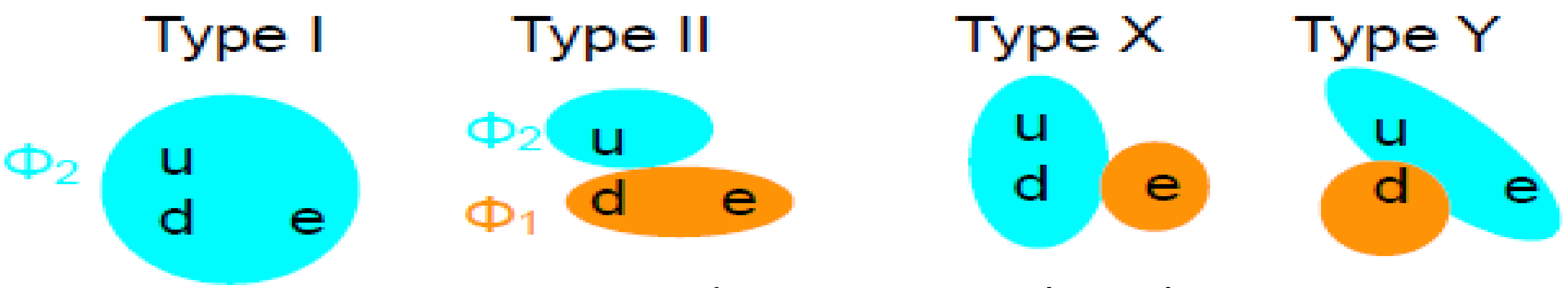
$$\mathcal{L} = \overline{L}\,(Y_{\ell 1}\Phi_1 + \times\,)\,\ell_R + \mathrm{H.c.}$$ or vice versa

- 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

Searches for extended Higgs sectors

2HDMs (with discrete symmetry) have more degree of freedom than e.g. the Higgs sector in the MSSM

(models of Yukawa sector, wide parameter regions)

- Model parameters : $(v,\ m_h)\ \ M^2,\ m_H,\ m_A,\ m_{H^\pm},\ \alpha,\ \beta$

  soft breaking scale

- Theoretical constraints : perturbative unitarity, vacuum stability, triviality
- Experimental constraints : EW precision, flavor, collider searches

We take $\sin(\beta-\alpha)=1$ SM-like limit [Alignment limit]

where no effect on SM Higgs couplings, i.e. indirect search impossible

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 : $gg \to H/A$, $gg(q\bar{q}) \to Q\bar{Q}H/A$ } $H/A \to b\bar{b}$ 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)

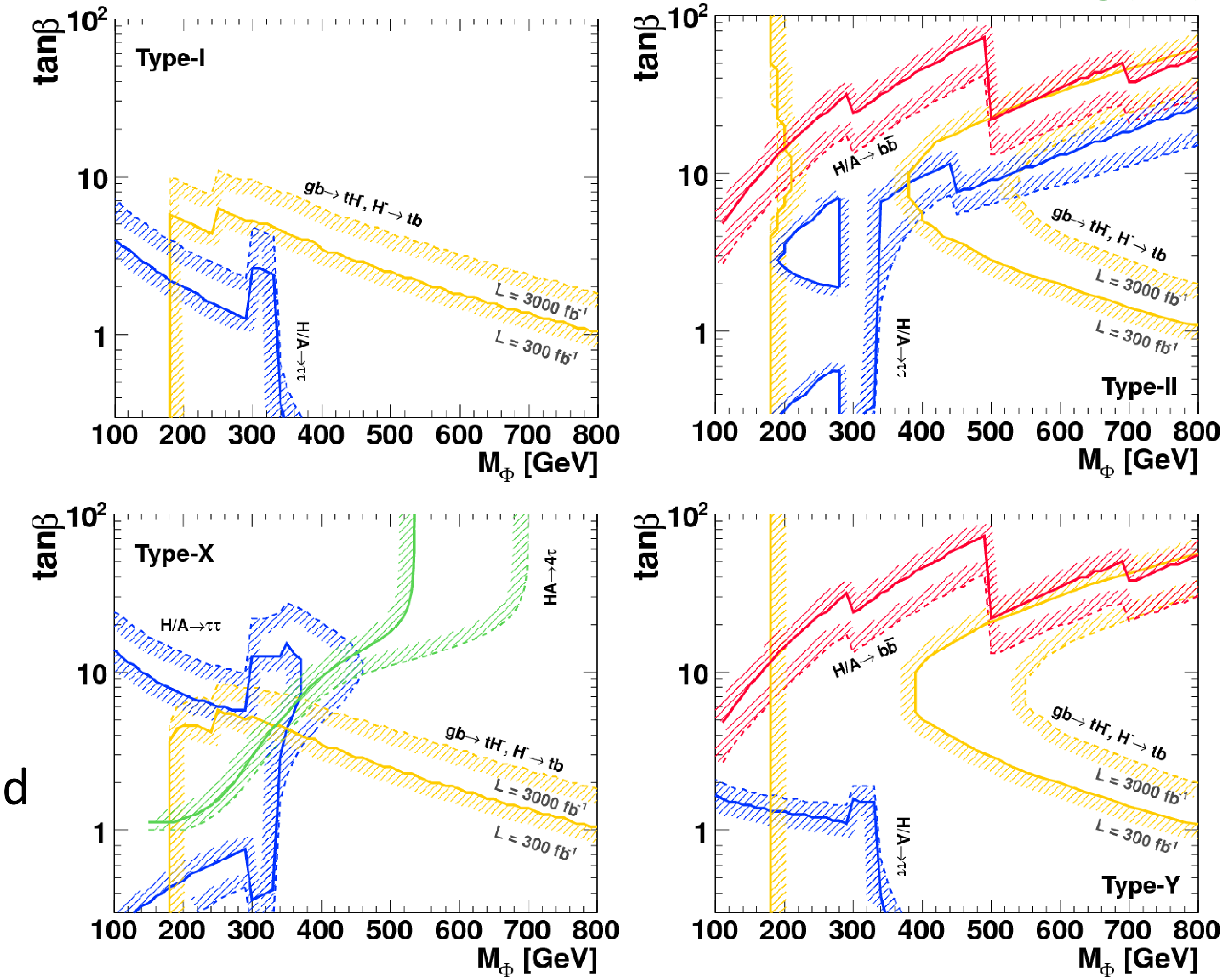
solid:300fb^{-1}, dashed:3000fb^{-1}

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

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

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

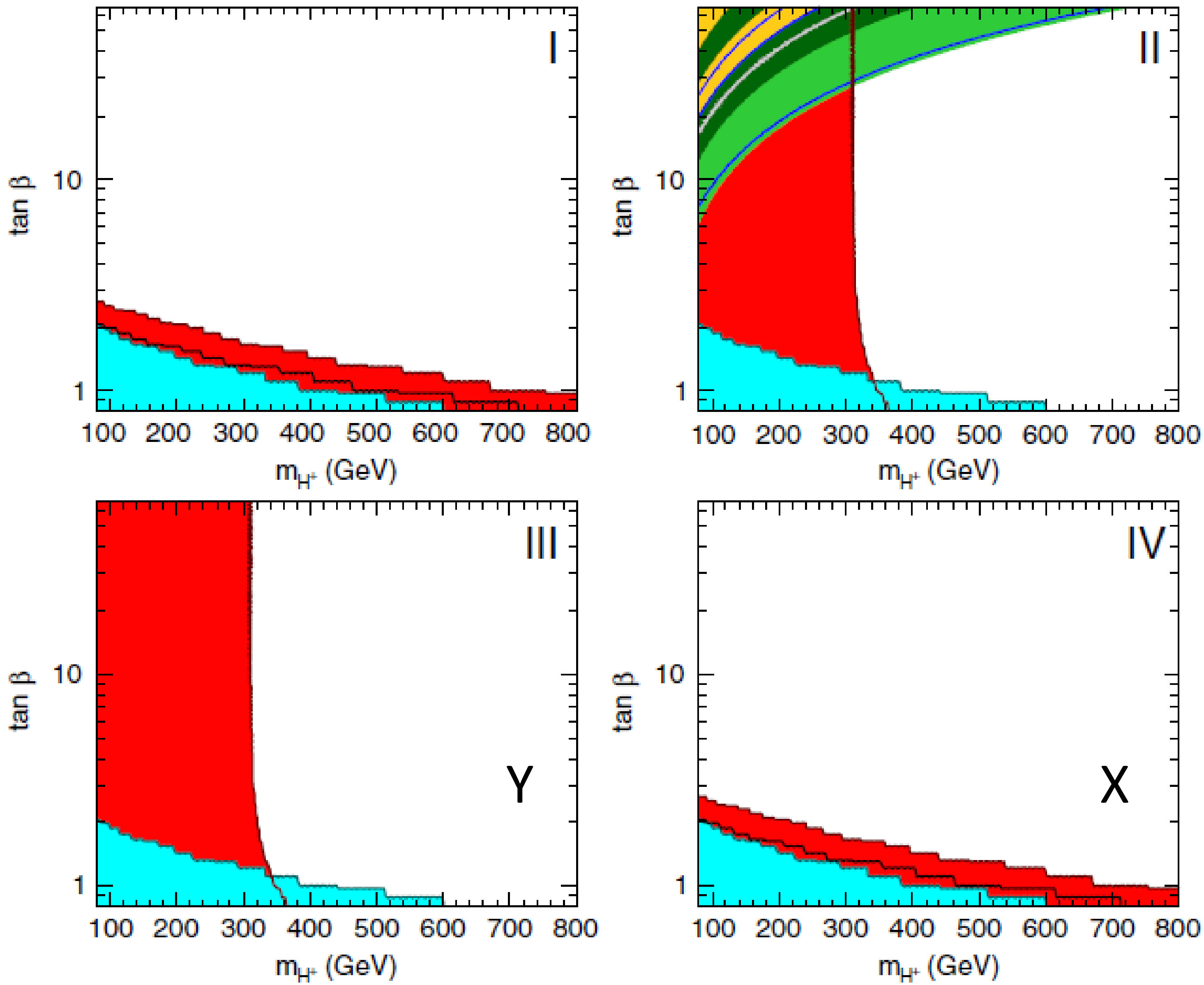
$q\bar{q} \to HA \to 4\tau$



Extensive regions are covered up to M_Φ~600GeV.

Flavour constraints

Mahmoudi, Stal (10)



red : b->sγ
cyan : B-Bbar mixing
green : D_s->τν

Direct searches at the ILC

Pair and single productions
of additional Higgs bosons

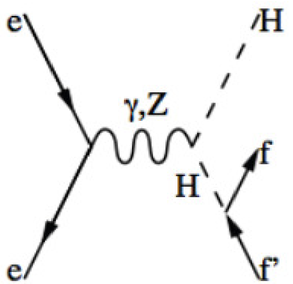
Kanemura,Moretti,Odagiri(01),
Kiyoura et al. (06),,,
Kanemura,HY,Zheng ('14)

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

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

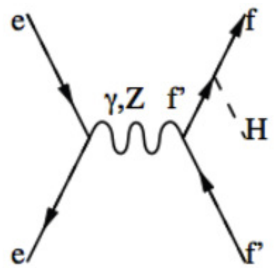
- /s > m_H + m_A or $2m_{H+}$

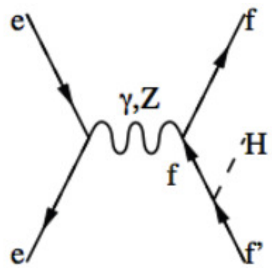
$$e^+e^- \to HA$$
$$e^+e^- \to H^+H^-$$



- /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).

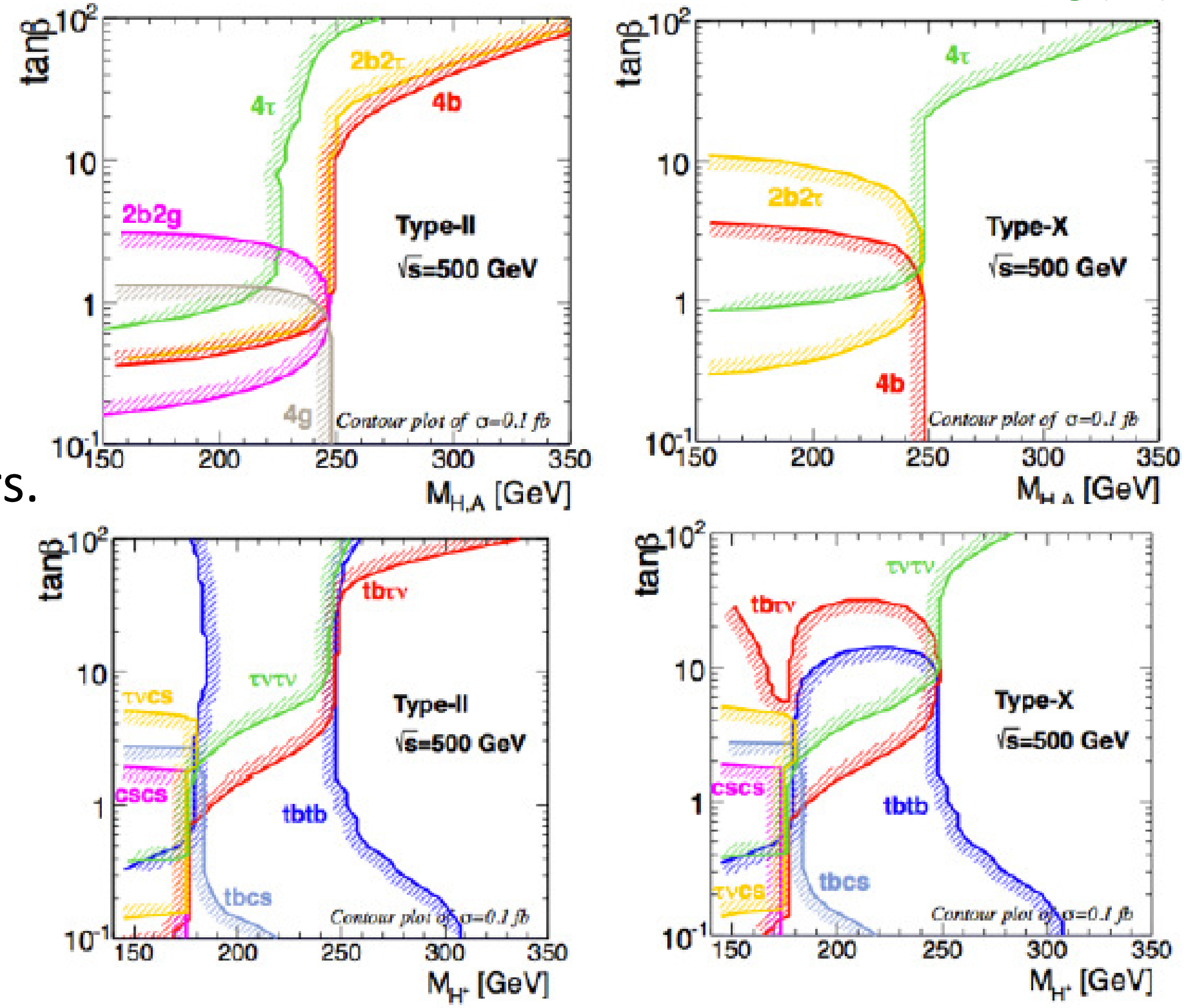
Direct searches at the ILC

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

Kanemura,HY,Zheng (14)



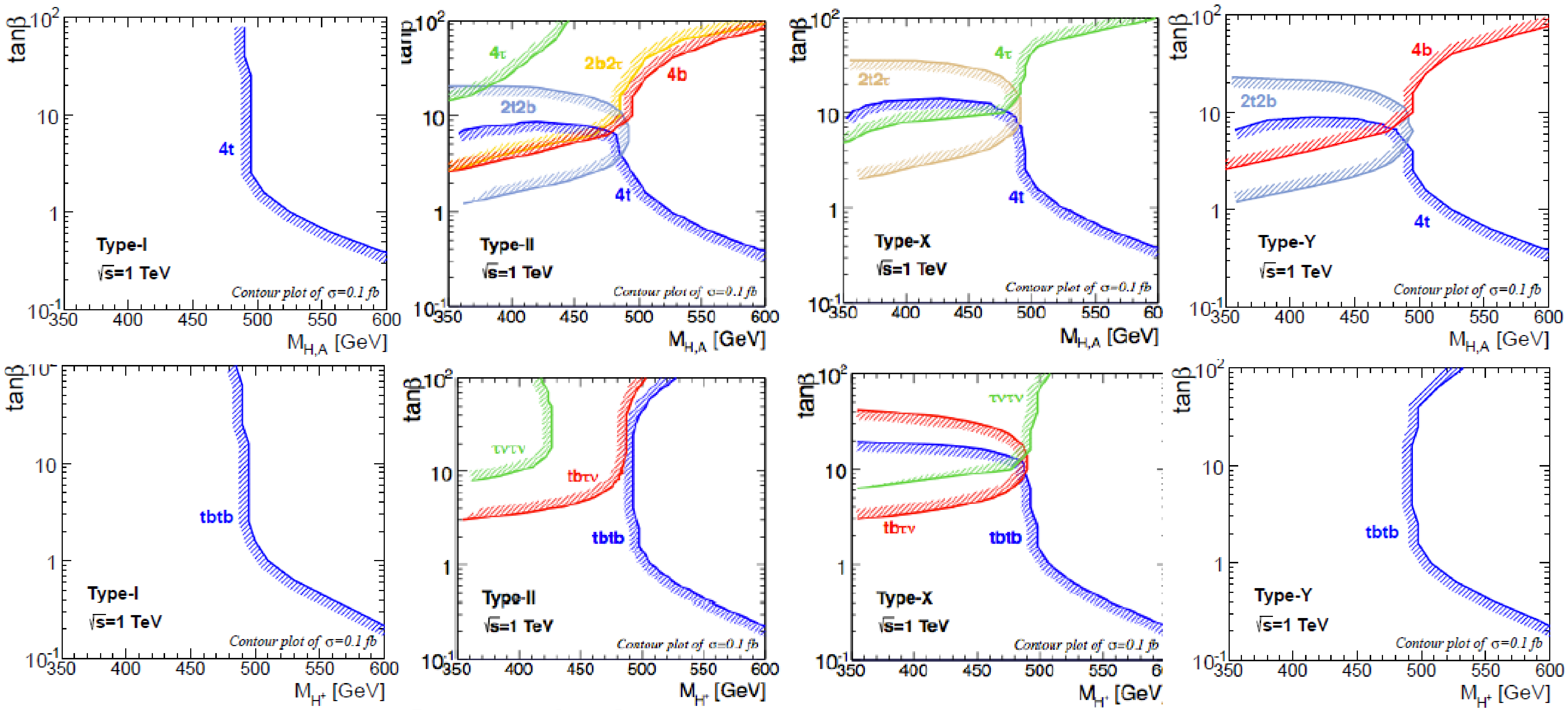
- In the pair production regions, we expect at least one kind of signature for any types/parameters.

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

Direct searches at the ILC

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

Kanemura,HY,Zheng (14)



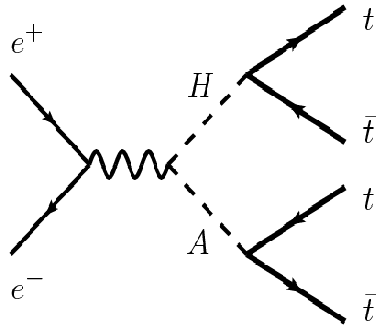
4 top events at the ILC

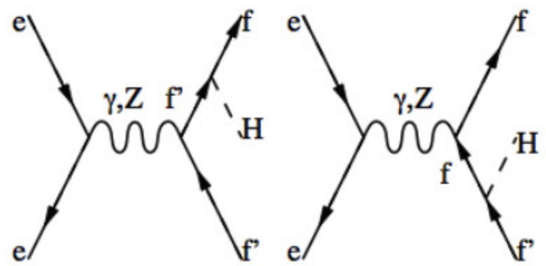
- For heavier H/A with smaller tanβ,

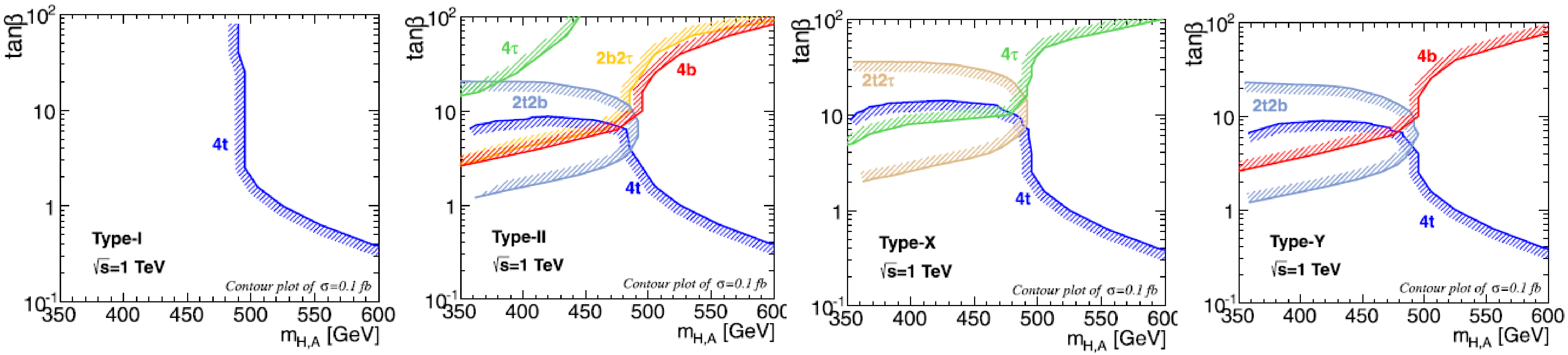
  four top event is the signal of direct production.

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

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







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
- **$2N_l + N_j = 12$** (at the parton-level)
- Small thrust, because of the heavy particle decays

Simulation

- Event Generation:

  MadGraph+Pythia +Tauola+FastJet

  Signal process : $e^+e^- \to HA \to t\bar{t}t\bar{t},$

  $e^+e^- \to Ht\bar{t}/At\bar{t} \to t\bar{t}t\bar{t},$

  BG processes : $e^+e^- \to t\bar{t}t\bar{t}, t\bar{t}b\bar{b}, t\bar{t}$

  $(t\bar{t}b\bar{b} = t\bar{t}g^*, h^*, Z^*, \gamma^*/tbW^*/W^*W^*)$

- Event Analysis:

  - Particles with $|\eta| \leq 1.5$ & $p_T^{\text{chg}} > 0.3$ GeV
  - Momentum smearing for chg track, neutral hadron and photon

    $\sigma_{p_T}^{\text{chg}}/p_T = 10^{-4} p_T \oplus 10^{-3},$

    $\sigma_E^{\text{ntrl}}/E = 0.4/\sqrt{E} \oplus 0.02,$

    $\sigma_{pE}^{\gamma}/E = 0.15/\sqrt{E} \oplus 0.01$
  - Isolated lepton: $E_{\text{cone}} \leq \sqrt{6(E_{\text{lep}} - 15)}$ with $\cos\theta_{\text{cone}} = 0.98$
  - Jet clustering: (using particles except neutrinos and Iso-lep)

    Durham algorithm with $Y_{cut}=5 \cdot 10^{-4}$

Simulation:

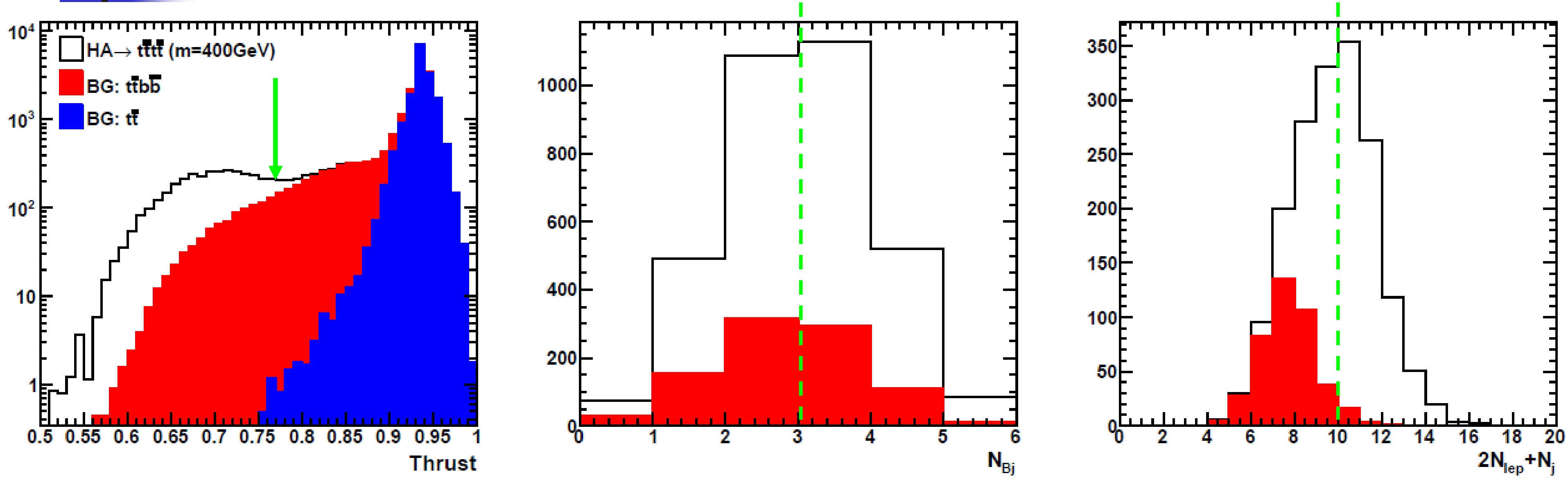
- Jet flavor tagging
  - photon-tag: a jet with only photons
  - (pseudo)B-tag: 65% for a jet with B-hadrons
    (tight) 1% for a jet with D-hadrons
    0.1% for a jet w/o B,D-hadrons
  - Tau-tag: 1 or 3 tracks, $E_{cone}/E > 0.95$ [R_{cone}=0.15]

- Count the “Event Divergence”

$$N = 2N_\ell + N_j \quad \text{with} \quad \begin{cases} N_\ell = N_e^{\text{Iso}} + N_\mu^{\text{Iso}} + N_{\tau_j} \\ N_j = N_{Bj} + N_{Lj} \end{cases}$$

- Selections Cuts: No separation of events by N_l, N_j, etc., but we just impose
  - ① Thrust: T<0.77
  - ② $N_{Bj} \geqq 3$
  - ③ $2N_l+N_j \geqq 10$

Results (Preliminary):



	$\sigma_{\rm tot}$ [fb]	$T \leq 0.77$	$N_{b_j} \geq 3$	$2N_\ell + N_j \geq 10$
$e^+e^- \to HA \to t\bar{t}t\bar{t}$				
$m_{H,A} = 360$ GeV	$\sim 4.2 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	78%	43%	25%
400 GeV	$\sim 2.7 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	92%	49%	29%
440 GeV	$\sim 1.4 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	96%	51%	30%
480 GeV	$\sim 0.28 \times \mathcal{B}^H_{t\bar{t}}\mathcal{B}^A_{t\bar{t}}$	96%	50%	30%
500 GeV		94%	51%	30%
520 GeV		95%	51%	30%
560 GeV		93%	50%	30%
$e^+e^- \to t\bar{t}$	166.	1.7×10^{-4}	0.	0.
$e^+e^- \to t\bar{t}b\bar{b}$	5.0	18%	8.4%	0.43%
$e^+e^- \to t\bar{t}t\bar{t}$ (SM)	2.2×10^{-3}	-	-	-

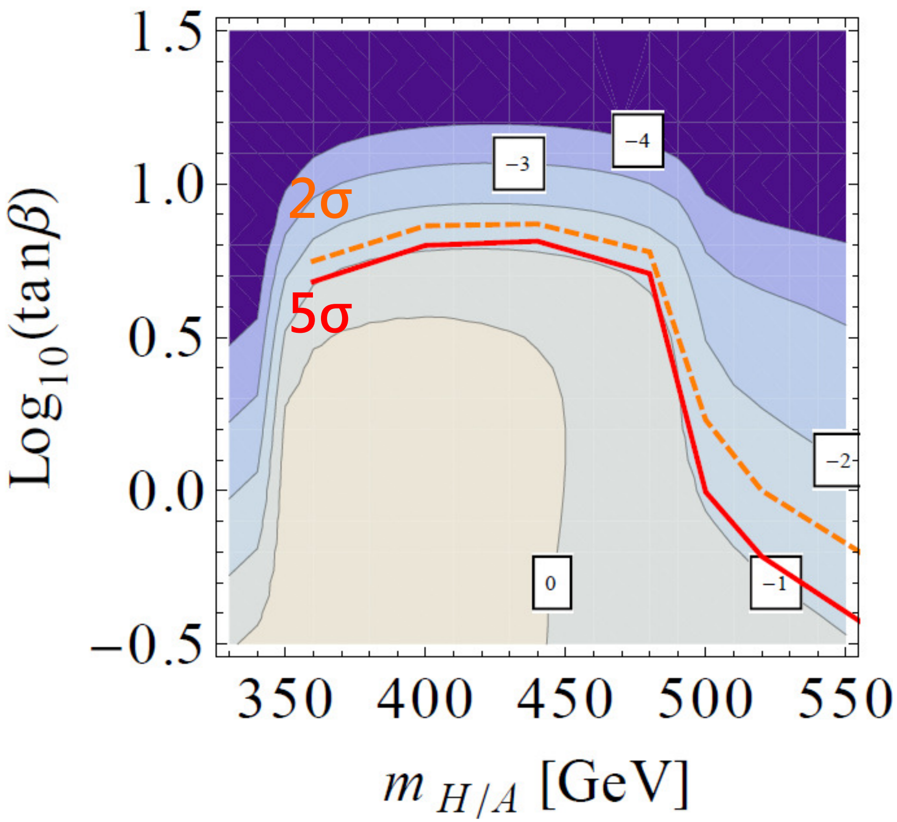
- Signal efficiency: 25~30%
- BG rejection: 0.4% [ttbb]
  $<10^{-6}$ [tt]

$\Rightarrow$ Only ~20 BG for $1ab^{-1}$

Discovery Reach

- Upper limit of cross-section for each mass
  → upper limit in tanβ for discovery/exclusion
- Discovery potential contours in the (mH/A, tanβ) plane

Contours of $\log_{10}[\sigma_{4t}]$



(Type-II(Y) Yukawa, $\sin(\beta-\alpha)=1$)

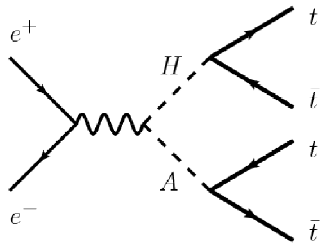
σ_{4t} of about ~0.08(0.03) [fb] can be probed at 5σ(2σ) C.L.

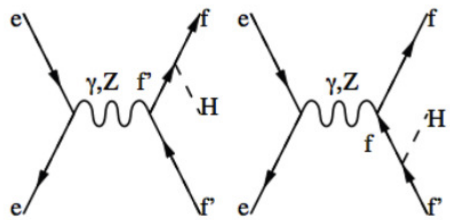
Summary

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

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

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





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

- Simulation study for this process

  Selection cuts with BG → discovery reach in ($m_{H/A}$, tanβ)

  Next : How to reconstruct the mass? (Endpoint method, Weight function method,,,)