Multi-top events in the 2HDM at the LHC and ILC

Hiroshi Yokoya (QUC,KIAS / KEK)

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

NPB886(2014)524, arXiv:1505.01089

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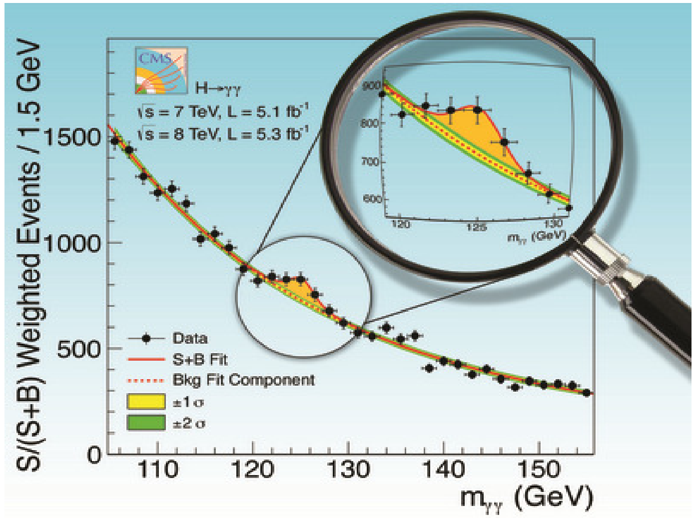
Introduction : Discovery of Higgs Boson

- 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.

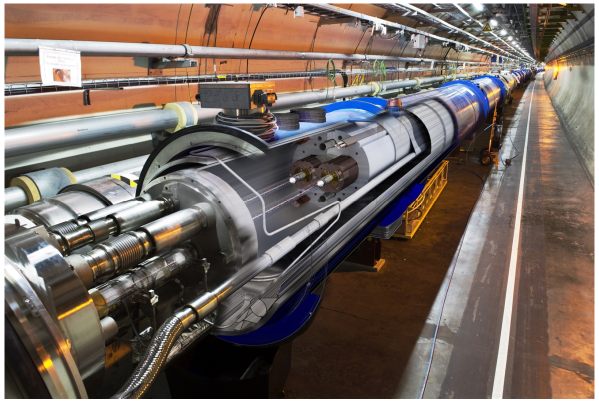
- **Direct Searches** — find second Higgs at colliders; clear evidence; need sufficient energy to produce
- **Indirect Searches** — find deviations in Higgs couplings (hVV,hff) from the SM; need precision; distinguish models by fingerprinting

Direct searches at future colliders

LHC $\sqrt{s}$ = 13-14TeV

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

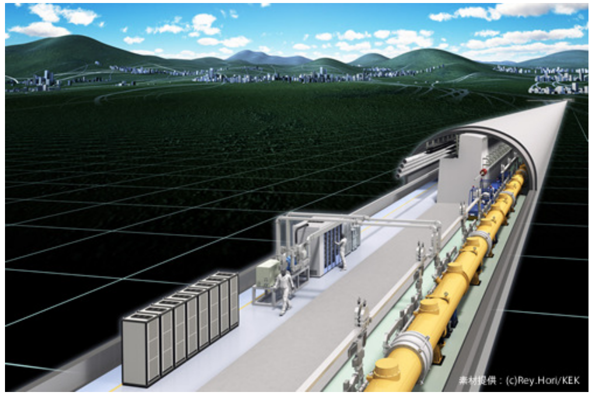
3000fb^{-1} (HL-LHC) 2025(?) ~



ILC

$\sqrt{s}$ = 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.

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, etc.

Glashow,Weinberg ('77)

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

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

Parameters in the model

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

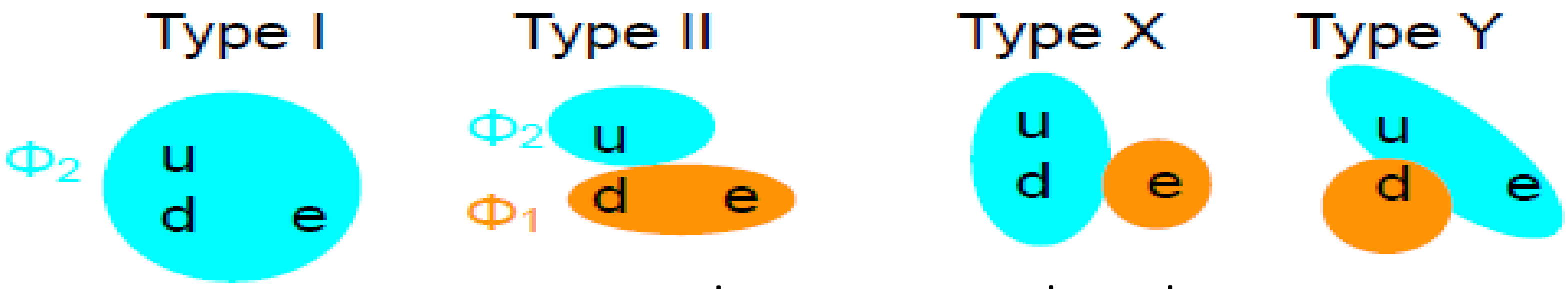
Two Higgs Doublet Model (2HDM):

Z_2-parity of Fermions → 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)



Type I	Type II	Type X	Type Y
all fermion couples to one Higgs boson	up v.s. down (MSSM)	quark v.s. lepton	flipped

We consider the SM-like limit (alignment)

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

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

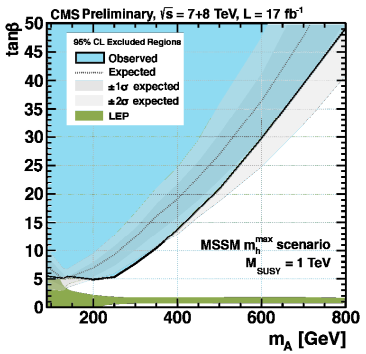
→ Indirect method is difficult, but the direct method is still available

LHC Run-I, Flavor, Theoretical constraints

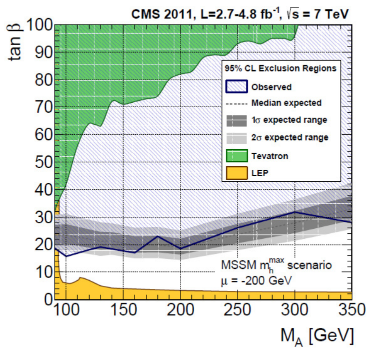
LHC Run-I constraints on the model parameter space.

- Neutral Higgs: $H/A \to \tau^+\tau^-, b\bar{b}$

CMS-HIG-12-033, 050



type-II

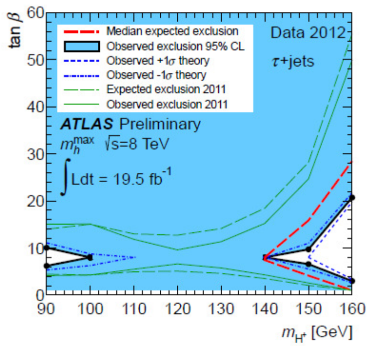


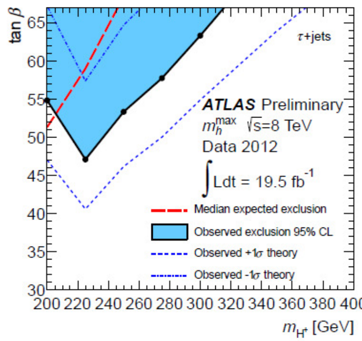
type-II,Y

- Charged Higgs ($m_{H^+} < m_t$):

$t \to bH^+ \to b\tau^+\nu$ ATLAS-CONF-2013-090

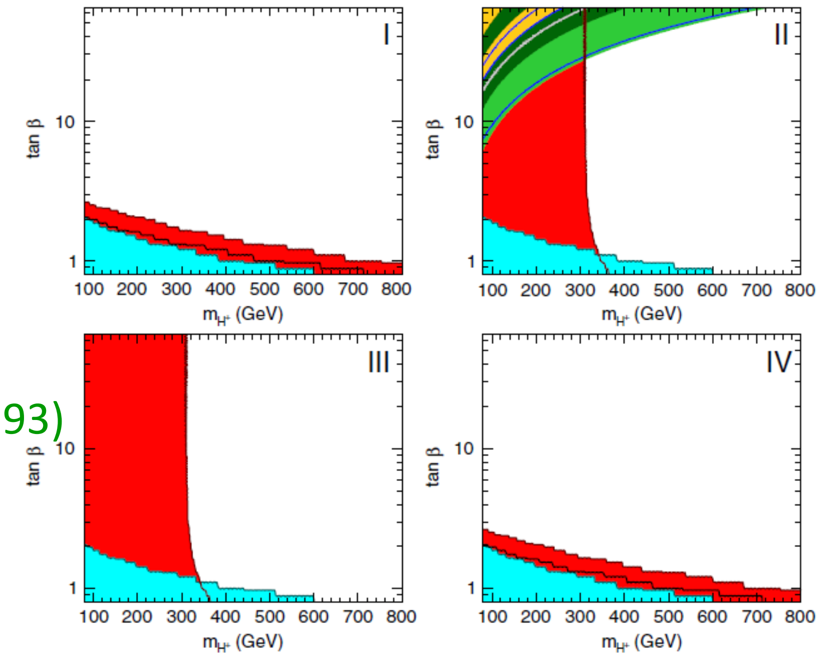
type-II





Flavor Constraints: Mahmoudi, Stal (10)

b->sγ, B-meson mixing, D_s->τν



Theoretical Constraints: Kanemura,Kubota,Takasugi(93) Akeroyd,Arhrib,Naimi(00),,,

Perturbative unitarity, vacuum stability,,,

Future prospects at the LHC

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

Discovery reaches of additional Higgs boson interpreted from the MSSM Higgs boson searches prospects (ATLAS TDR).

Kanemura,HY,Zheng (14)

Processes included:

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

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

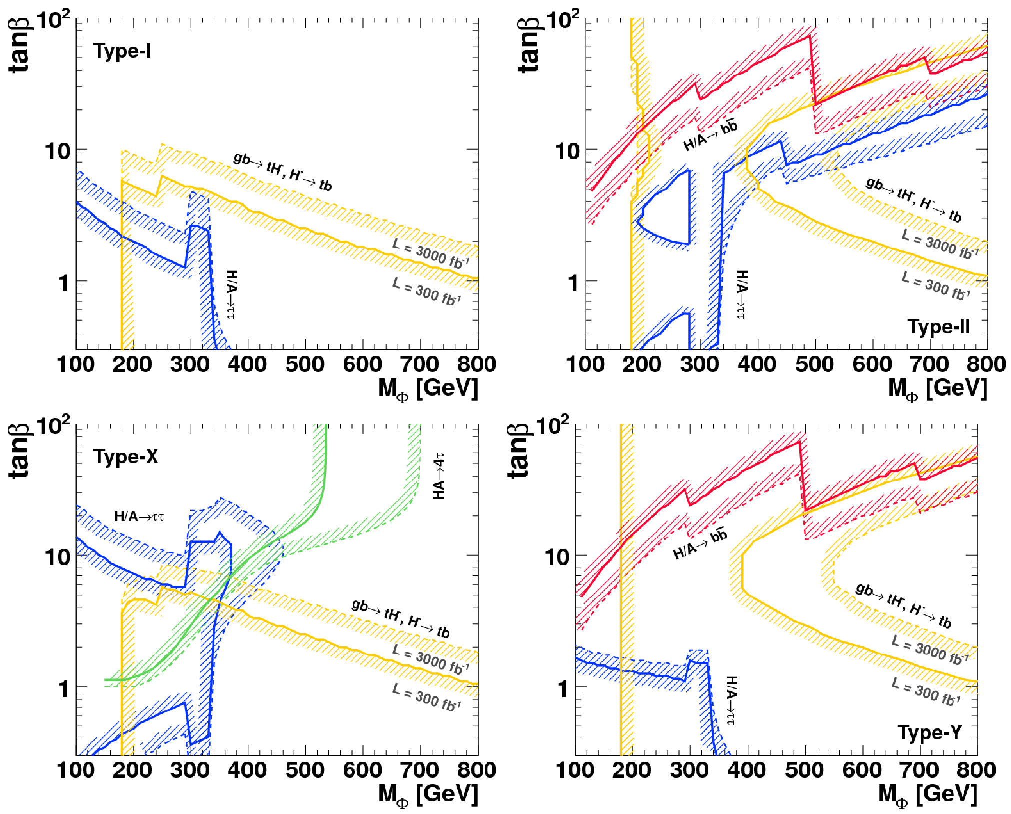
$gb \to tH^-;\, H^- \to \bar{t}b$

QCD, Top Yukawa

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

EW

Contour plots (95% C.L.) Solid:300fb^{-1}, dashed:3000fb^{-1}



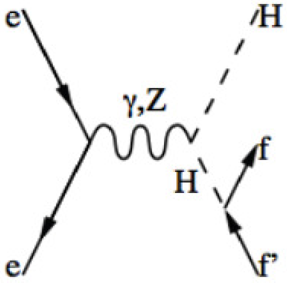
Direct searches at the ILC

Kanemura,Moretti,Odagiri(01), Morreti (04), Kiyoura et al. (06),,, Kanemura,HY,Zheng ('14)

Pair and Single production processes

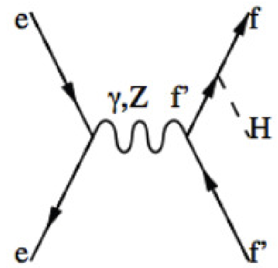
- $/s > m_H + m_A$ or $2m_{H+}$

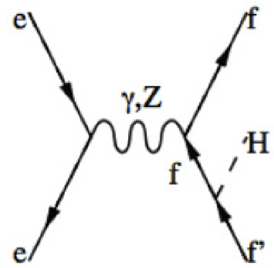
$$e^+e^- \to HA$$
$$e^+e^- \to H^+H^-$$



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

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

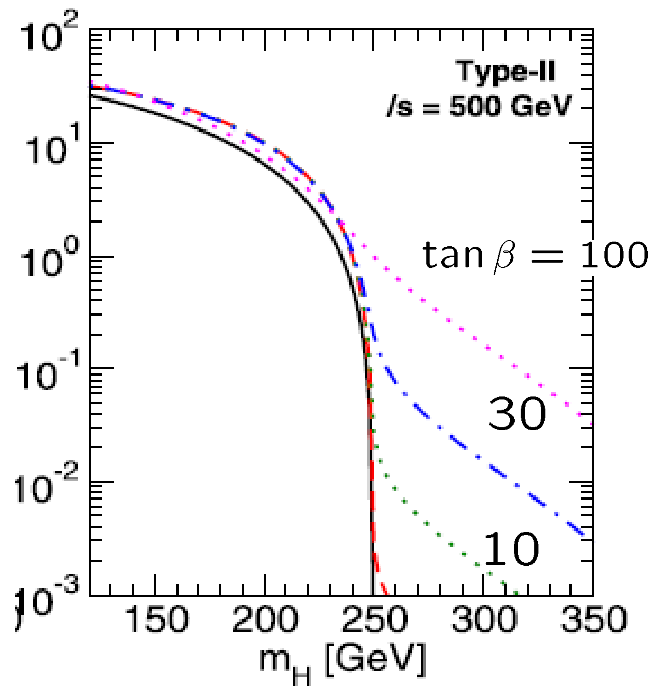




- Pair production process has large cross section, but is limited for $M \lesssim \sqrt{s}/2$

$$\sqrt{s} = 250\ \text{GeV} \to M \lesssim 125\ \text{GeV}$$
$$\sqrt{s} = 500\ \text{GeV} \to M \lesssim 250\ \text{GeV}$$
$$\sqrt{s} = 1\ \text{TeV} \to M \lesssim 500\ \text{GeV}$$

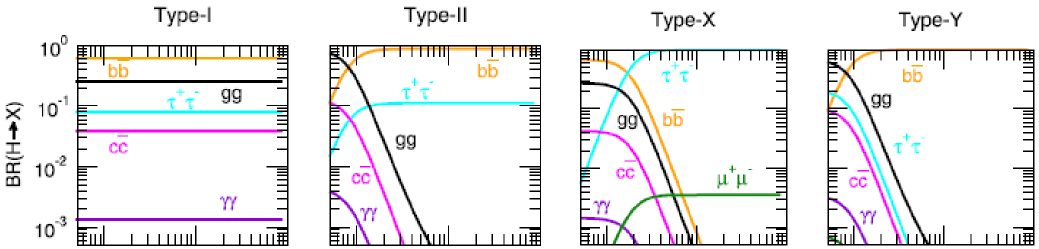
- Single production cross section is proportional to Yukawa coupling squared. → tanβ dependent



Direct searches at the ILC

- Various collider signatures according to the branching ratio of Higgs bosons.

Br(H) [m=250GeV]

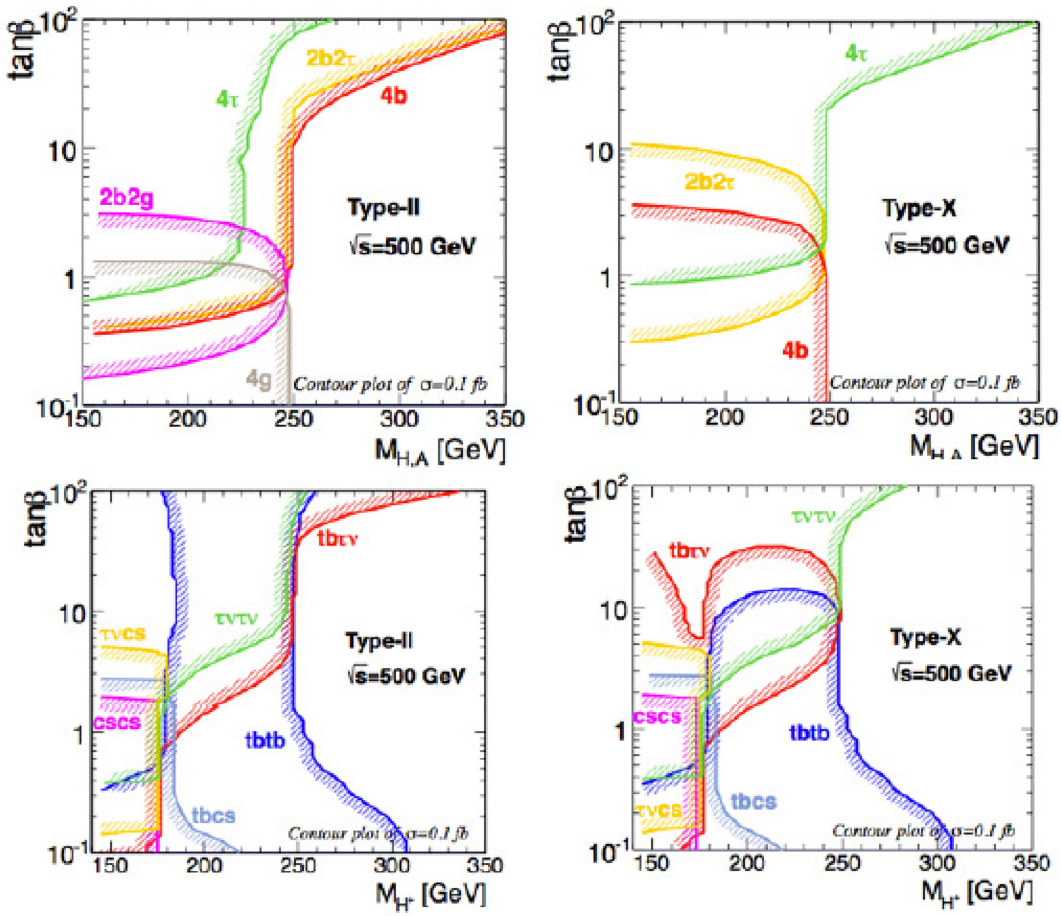


- At lepton colliders, thanks to clean BG, various signals can be detected as long as the signal events are large enough.
- Type of Yukawa models can be discriminated from the combination of the signals.
- Single production process can be useful in very large or small tanβ regions.

<u>Contours at σ = 0.1 fb</u>

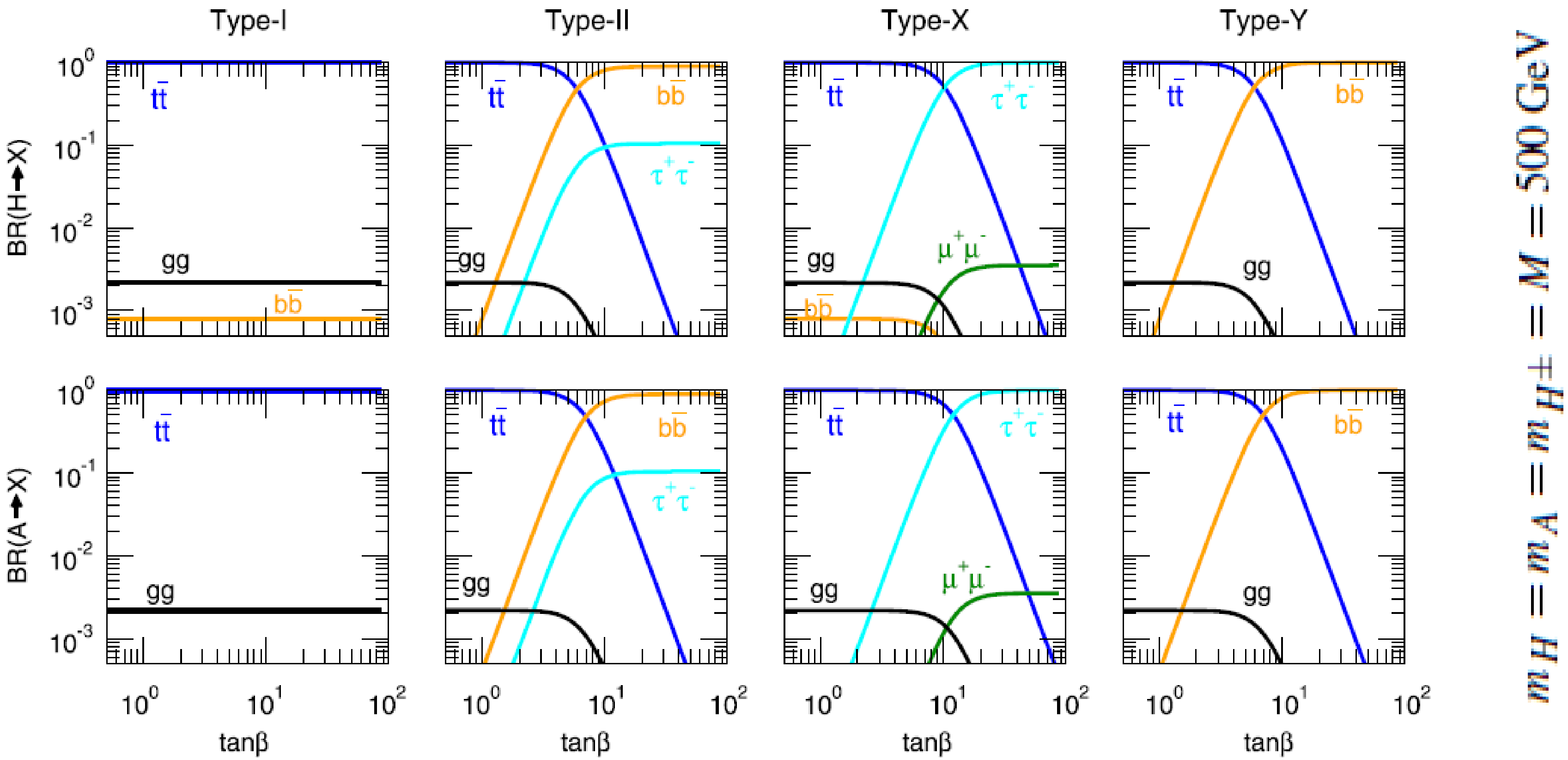
(no detection efficiency included)

$\sqrt{s}$ = 500 GeV Type-II & X



Searches for heavier H and A

- For H and A with $m_{H,A}$>350 GeV, ttbar decay mode dominates in wide regions in tanβ in any type of Yukawa.
- Collider signatures of heavier Higgs bosons are, then, multi-top events.
- (charged Higgs with m>180 GeV decays into tb.)

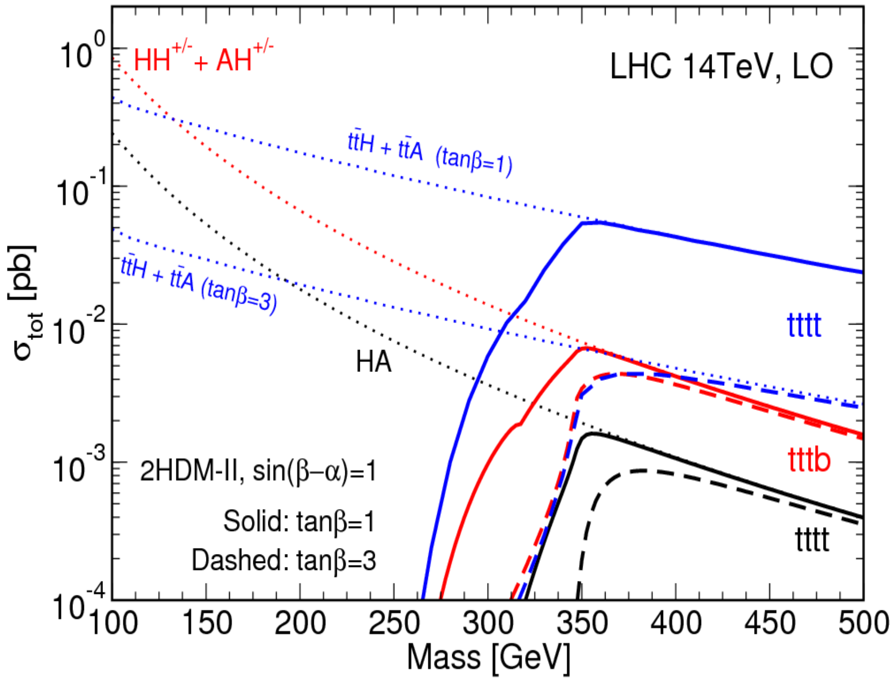


Multi-Top events at the LHC

Craig,D'Eramo,Draper,Thomas,Zhang (15),
Hajer,Li,Liu,Shiu (15), Kanemura,HY,Zheng (15)

Production processes:

$$\begin{cases} pp \to t\bar{t}H/t\bar{t}A \to t\bar{t}t\bar{t}, & \text{QCD} \\ pp \to HA \to t\bar{t}t\bar{t}, & \\ pp \to HH^\pm/AH^\pm \to t\bar{t}t\bar{b} & \text{EW} \end{cases}$$



- Studies on the same final-state but different models:

Cheung; Barger, Keung, Yencho; Jung, Wells; Cacciapaglia et al.,,,,
Greiner, Kong, Park, Park, Winter(14)

- Upper limit on the cross section at 8 TeV; σ_{4t}<32 fb.

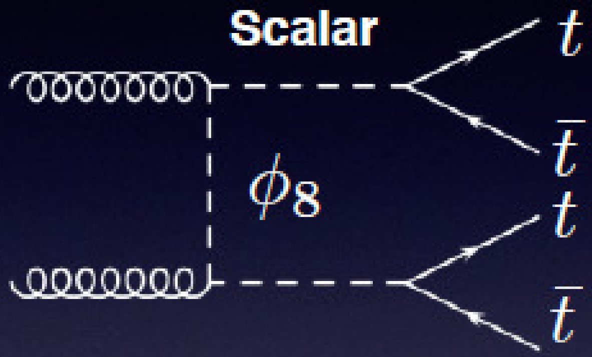
CMS 1409.7339

- SM prediction for 14 TeV at NLO; $\sigma_{\rm SM} = 15$ fb, $\delta\sigma_{\rm SM} = 4$ fb Bevilacqua, Worek (12)

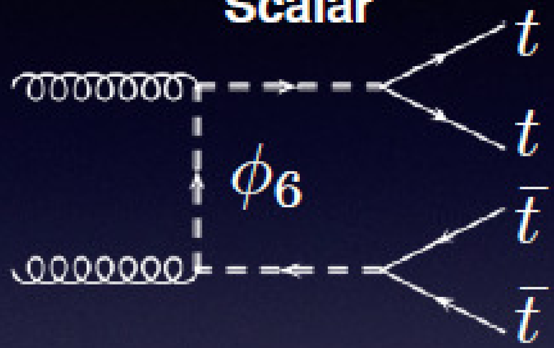
Four Top Production and New Physics

Axigluon
KK Gluon

Color Octet Scalar

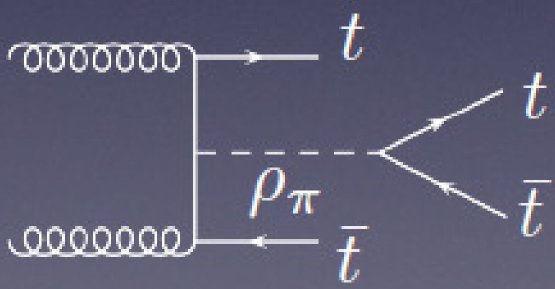


Color Sextet Scalar



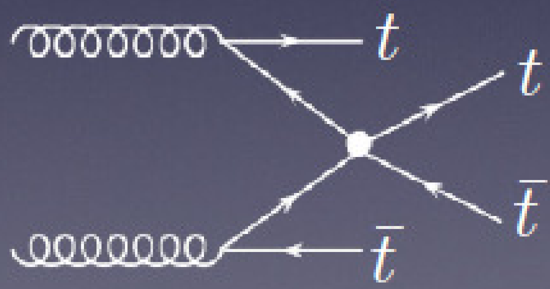
Chen, Klemm, Rentala, Wang (2008)

TC2



Han, Liu, Wu, Yang (2012)

Top Compositeness



Lillie, Shu, Tait (2007)
Kumar, Tait, Veg-Morale (2009)

Qing-Hong Cao

Multi-Top events at the LHC

Kanemura,HY,Zheng (15)

- Analysis of signal-to-background ratio:

Lillie, Shu, Tait (08)

signal efficiency of ~3% with the BG cross-section of 7.2 fb can be achieved.

signal detection accuracy: $$\frac{\delta\sigma_S}{\sigma_S} = \sqrt{\frac{(\sigma_S + \sigma_{\mathrm{SM}})\epsilon + B}{\sigma_S^2 \epsilon^2 \mathcal{L}} + \frac{\delta\sigma_{\mathrm{SM}}^2 \epsilon^2 + (\delta B)^2}{\sigma_S^2 \epsilon^2}}$$

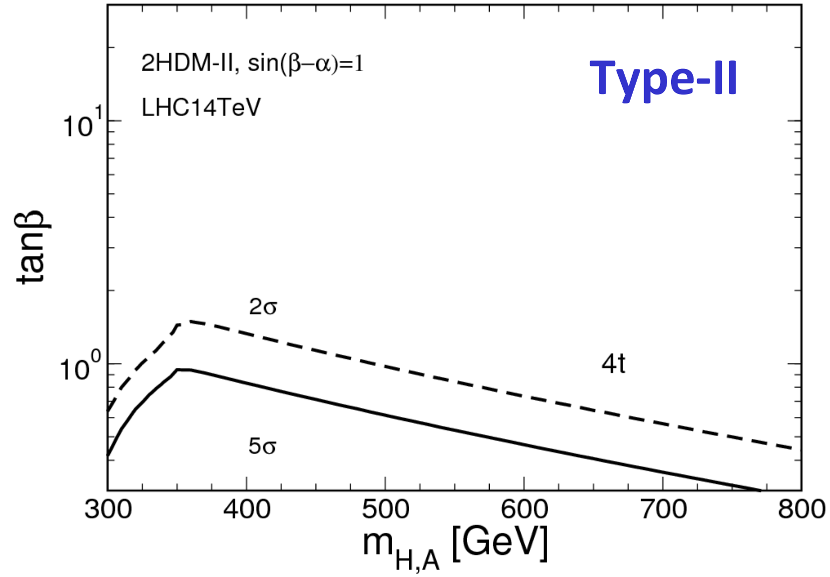
$\rightarrow \sigma_S > 25$ fb [63 fb] @ 2σ [5σ] CL (we assume δB=0.05B)

- Discovery reach in the 2HDM parameter space

only small tanβ regions can be probed;

almost independent of the type of Yukawa;

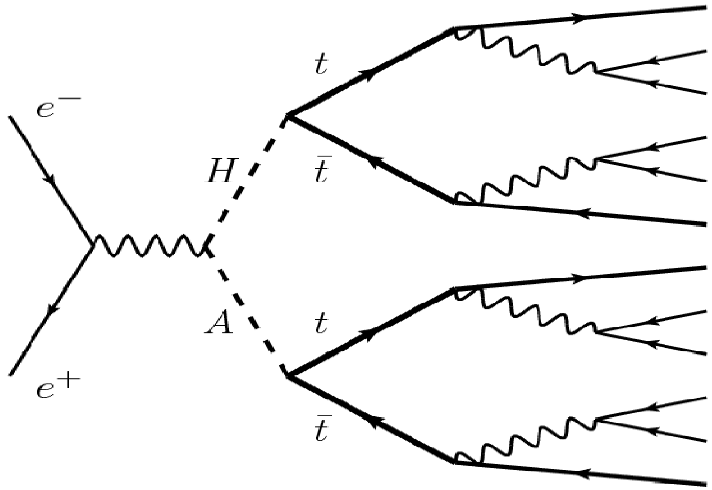
systematic error dominance
→ not improved by increasing luminosity



Multi-Top events at the ILC

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

- Only available if we get 1 TeV collider
- Negligible background, characteristic signals
- No study so far on this final-state at lepton colliders



Event characteristics:

- Many jets (4 of them are b-jet), many leptons, missing energy
- **$2N_{lep} + N_q = 12$** (at parton level)
- Small thrust distribution (because of heavy particle decay)

BG processes:

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

Selection cuts (Our proposal):

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

Simulation analysis

- Event Genearation

MadGraph + Pythia (+ Tauola)

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

BG: $e^+e^- \to t\bar{t}b\bar{b}, t\bar{t}\ell^+\ell^-, t\bar{t}$
$(t\bar{t}b\bar{b} = t\bar{t}g^*, h^*, Z^*, \gamma^*/tbW^*/W^*W^*)$

- Hadron-level simulation with detector effects:

  - Acceptance $|\eta| \leq 1.5$ & $p_T^{\text{chg}} > 0.3$ GeV
  - Momentum smearing according to the expected detector resolution at the ILC
    $$\begin{cases} \sigma_{p_T}^{\text{chg}}/p_T = 10^{-4} p_T \oplus 10^{-3}, \\ \sigma_E^{\text{ntrl}}/E = 0.4/\sqrt{E} \oplus 0.02, \\ \sigma_{pE}^{\gamma}/E = 0.15/\sqrt{E} \oplus 0.01 \end{cases}$$
  - Isolated lepton: $E_{\text{cone}} \leq \sqrt{6(E_{\text{lep}} - 15)}$ with $\cos\theta_{\text{cone}} = 0.98$
  - Jet reconstruction by Durham algorithm with $Y_{cut}=5\cdot 10^{-4}$
    + flavor-tagging (loose b-tag)

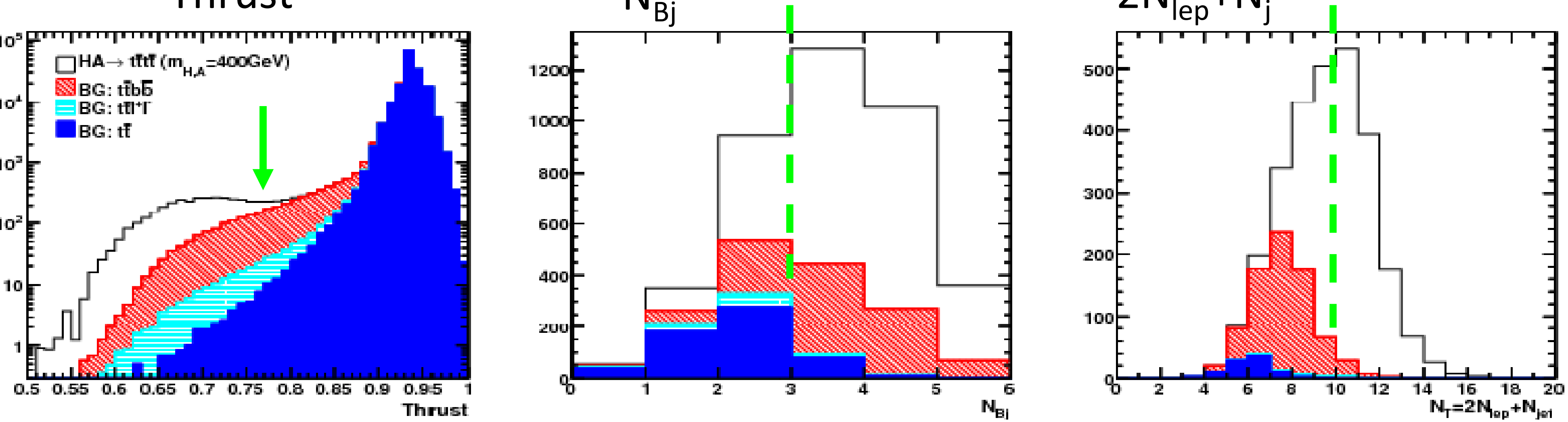
ILC TDR

Results:

Kanemura,HY,Zheng (15)

(tt: 170 fb, ttbb: 5 fb, ttll: 0.8 fb, tttt(SM): 4 ab)

Thrust N_{Bj} $2N_{lep}+N_j$

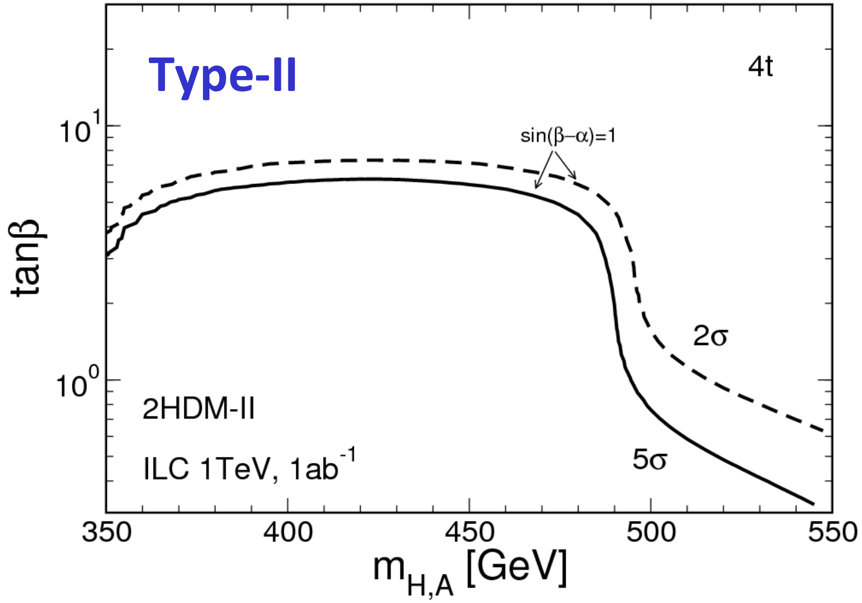


- With **signal efficiency of 40~50%**, BG can be reduced to 0.7% [ttbb], 1.4% [ttll], $\sim 10^{-6}$ [tt]

  ⇒ **BG ~ 50 events for 1 ab^{-1} data**

- Discovery reach in parameter space:

  Accessible up to $\sigma_{HA\to 4t}$ ~ 0.1 fb [0.03 fb] at 5σ [2σ] level at the 1TeV ILC.



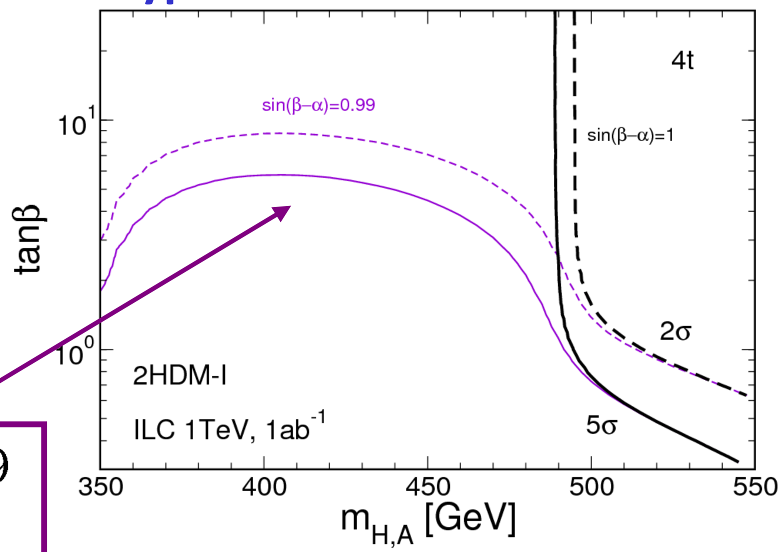
Results:

Kanemura,HY,Zheng (15)

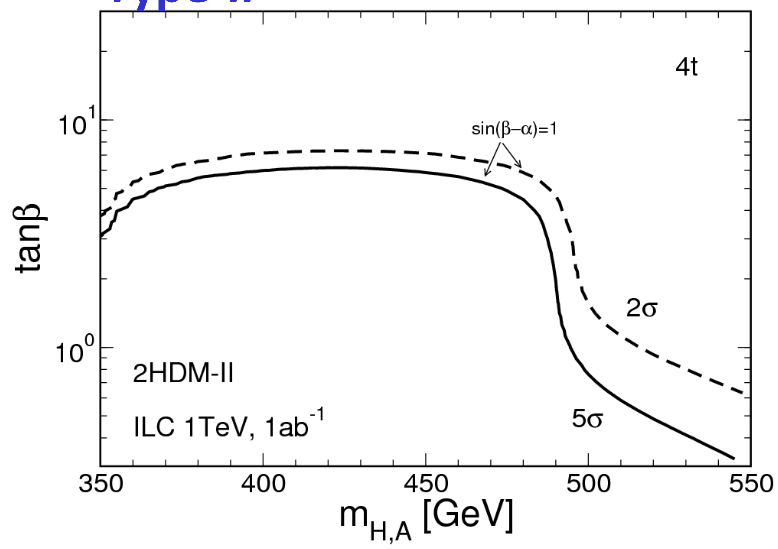
- Other Yukawa types

$$\sin(\beta - \alpha) = 0.99$$
$$H \to WW, ZZ, hh$$
$$A \to Zh$$

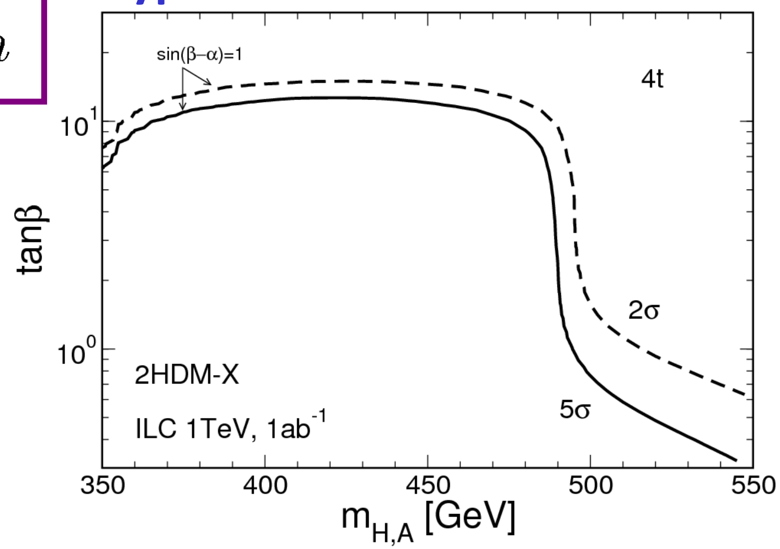
Type-I



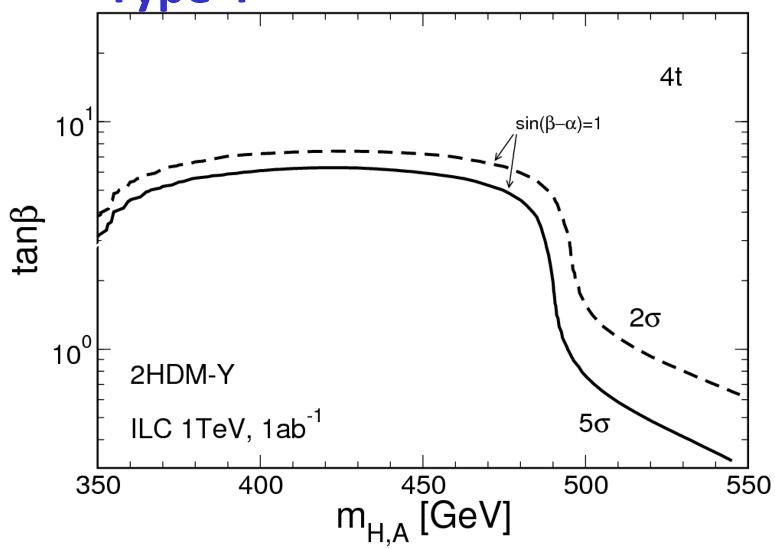
Type-II



Type-X



Type-Y



Summary

We have been studying the direct search potential for the extra Higgs bosons at the future LHC and ILC, in the context of 2HDM with softly-broken Z_2.

- For neutral Higgs bosons with M>350GeV, H/A dominantly decay into ttbar.

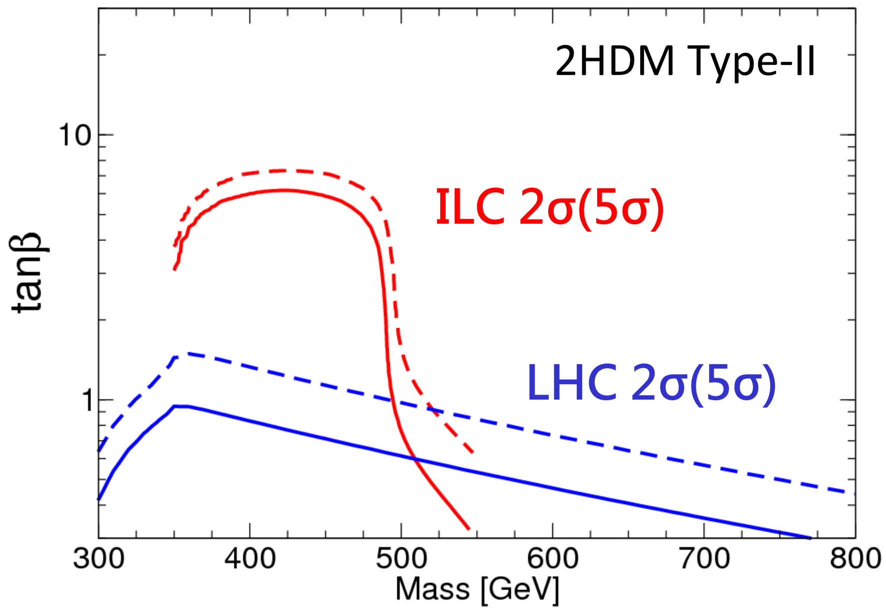
  → **Searches for multi-top events**

- We studied the detectability of multi-top events at the LHC and ILC, and investigated the discovery reach in the parameter space in the 2HDM.

LHC: higher mass, but only small tanβ

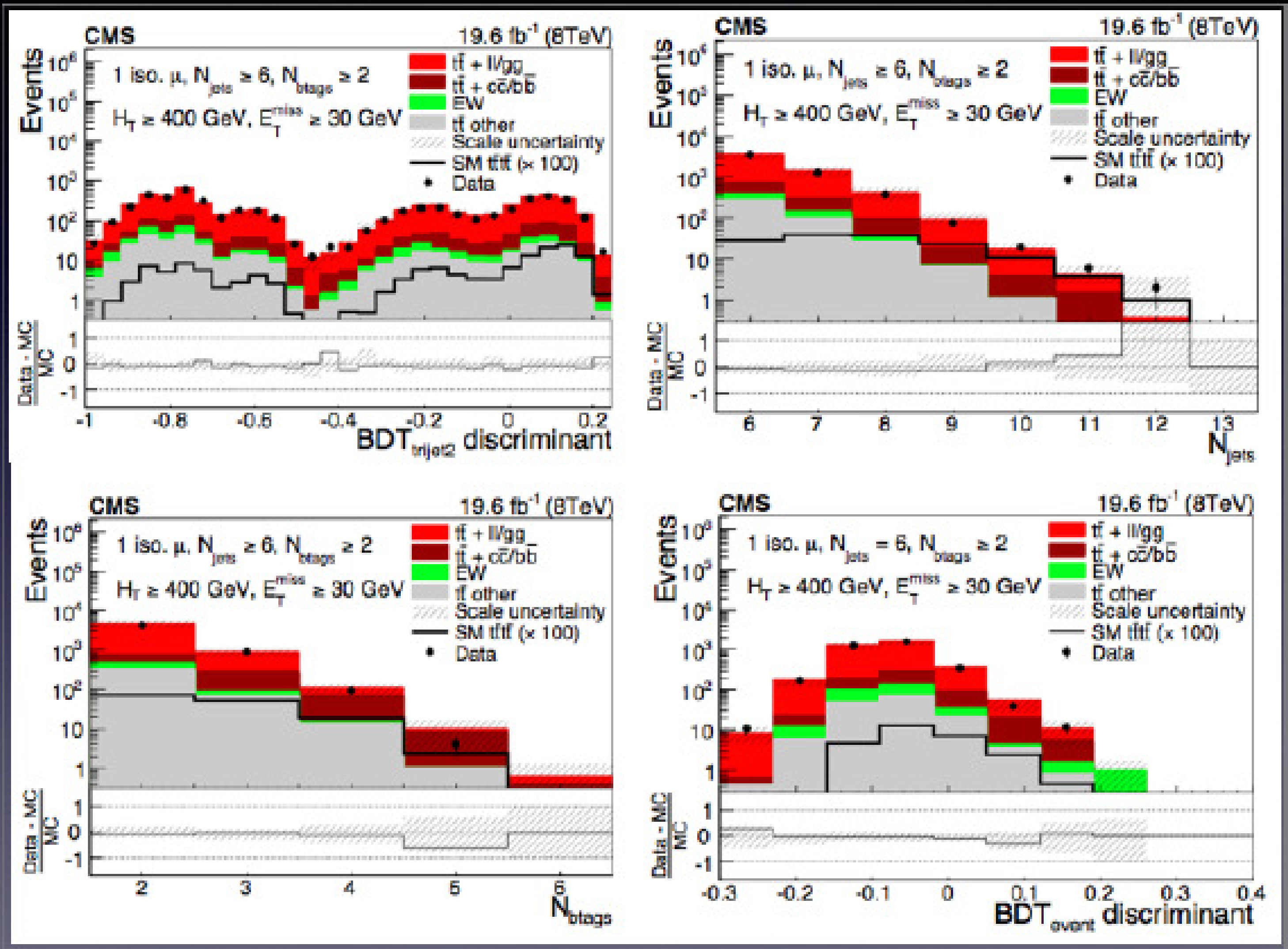
ILC(1TeV): larger tanβ, but m<500 GeV

Type-II



- Furthermore, at the ILC, Yukawa type can be discriminated by detecting various signals, and mass determination may be possible by the threshold scan.

CMS Measurements of $\sigma(tt\bar{t}\bar{t})$



8TeV, 19.6fb^{-1}

arXiv:1409.7339

$\Rightarrow$ $\sigma(tt\bar{t}\bar{t}) \leq 32$ fb

Qing-Hong Cao

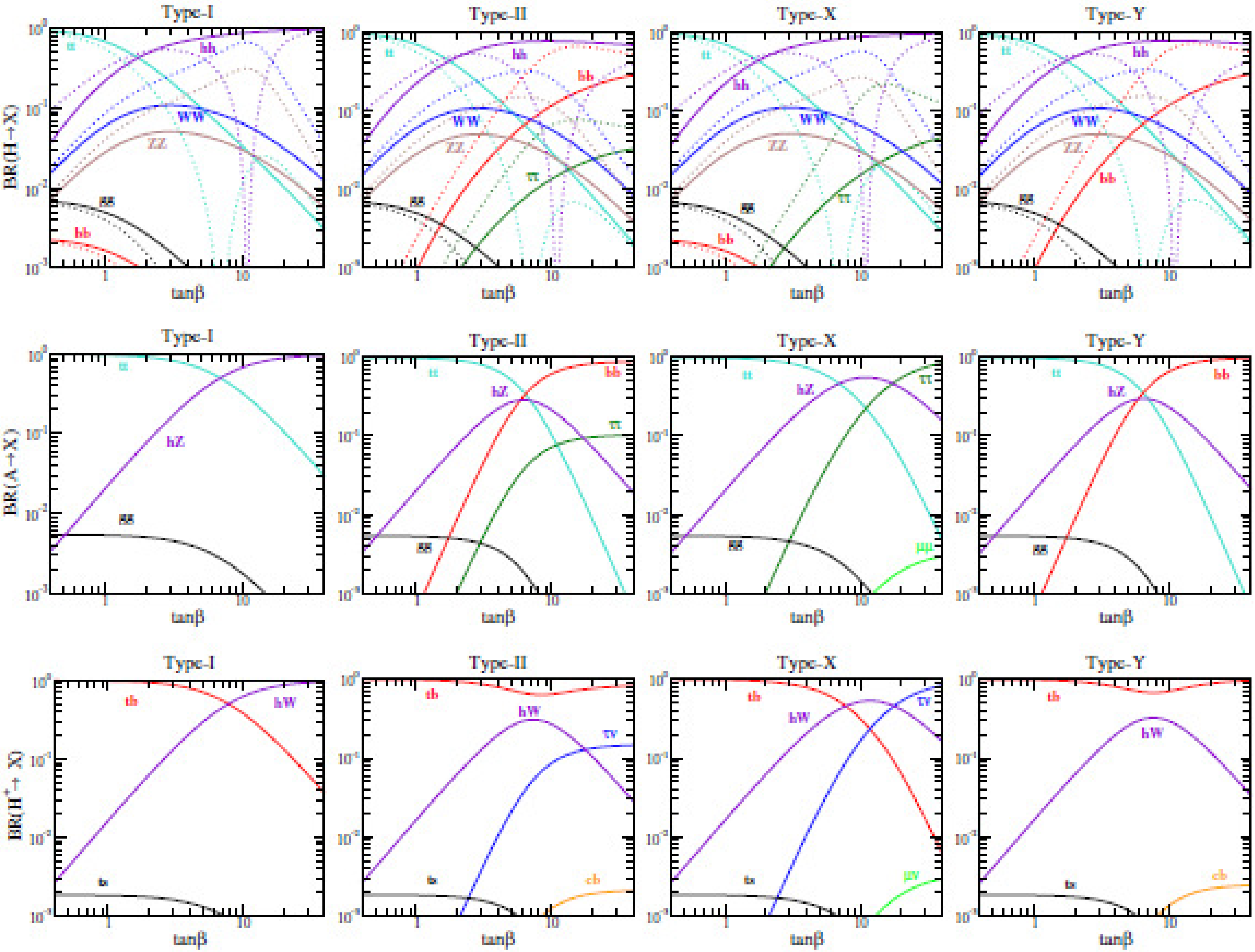
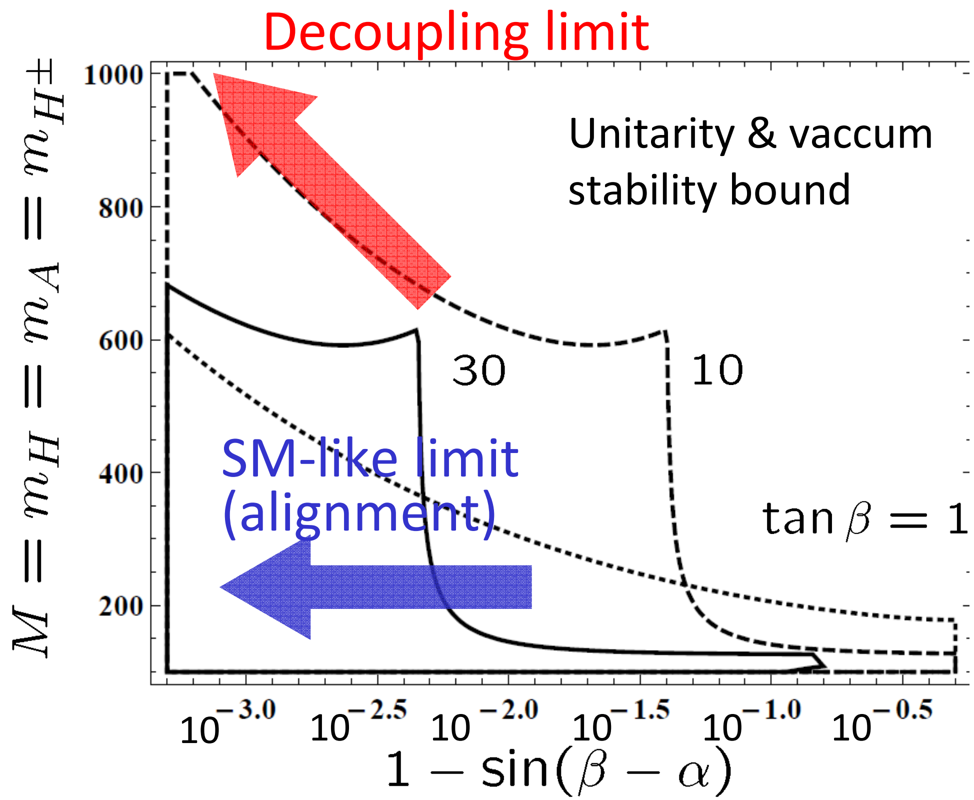


FIG. 8 (color online). Decay branching ratios for H, A, and $H^{\pm}$ as a function of $\tan\beta$ in the case of $m_\Phi = M = 400$ GeV and $\sin(\beta-\alpha) = 0.99$. For the H decay, the solid and dashed curves, respectively, show the cases with $\cos(\beta-\alpha) < 0$ and $\cos(\beta-\alpha) > 0$.

SM-like limit and Decoupling limit

$$\kappa_V^h \to 1,\ \kappa_V^H \to 0$$

In the **SM-like limit** **[sin(β-α)→1]**, all the couplings of h(125GeV) become SM-like.
Extra scalars can still be light.



If extra scalars are all heavy, sin(β-α) has to be close to unity.
The SM remains to be an effective theory at low energy
(Decoupling limit)

LHCスケジュール

->Run1 |　　　|--Run2-------------------->

2012 | 2013-14 | 2015 | 2016 | 2017 | 2018 | 2019

2012:
- √s = 7-8 TeV
- L = 0.7×10^{34} cm^{-2}s^{-1}
- Pile Up < ~35
- 合計: 25 fb^{-1}

2015:
- √s = 13-14 TeV
- L = 1-2×10^{34} cm^{-2}s^{-1}
- Pile Up < ~60
- 合計: ~100fb^{-1}

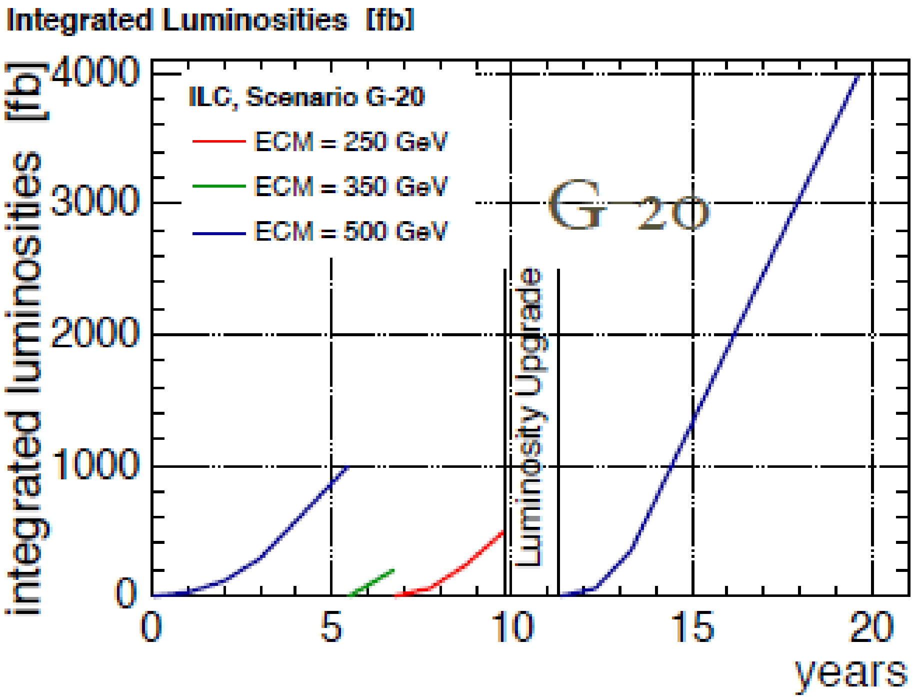
2019:
- √s = 14 TeV
- L > 2-3×10^{34} cm^{-2}s^{-1}
- Pile Up < ~60
- 合計: ~300fb^{-1}

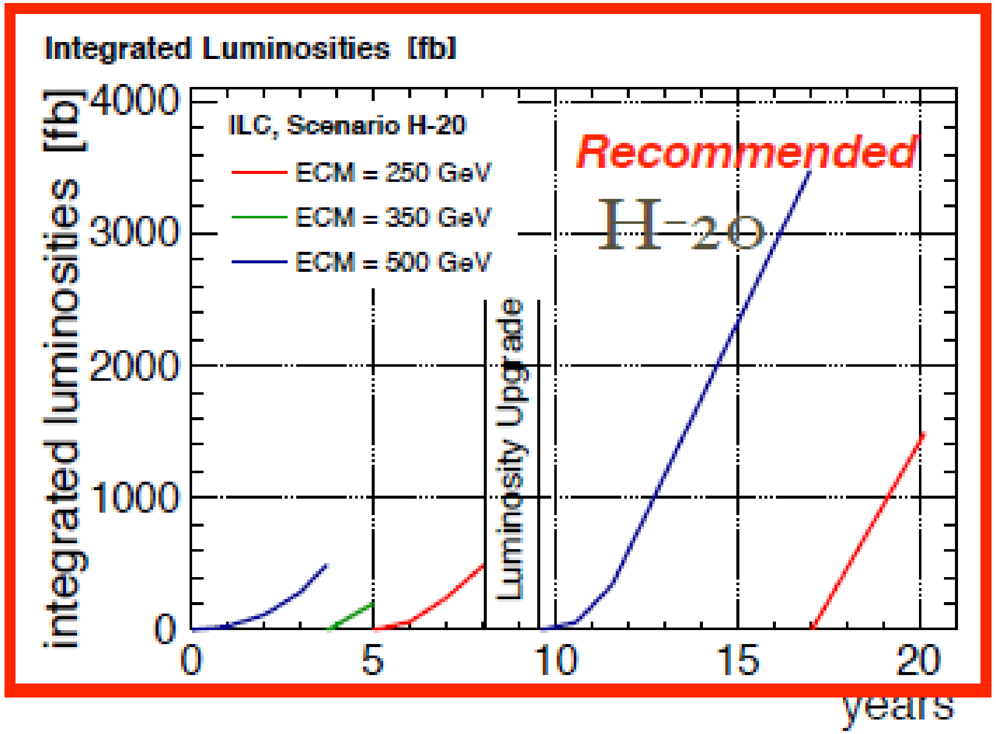
|-Run3------------------->　　　|--High Luminosity LHC--

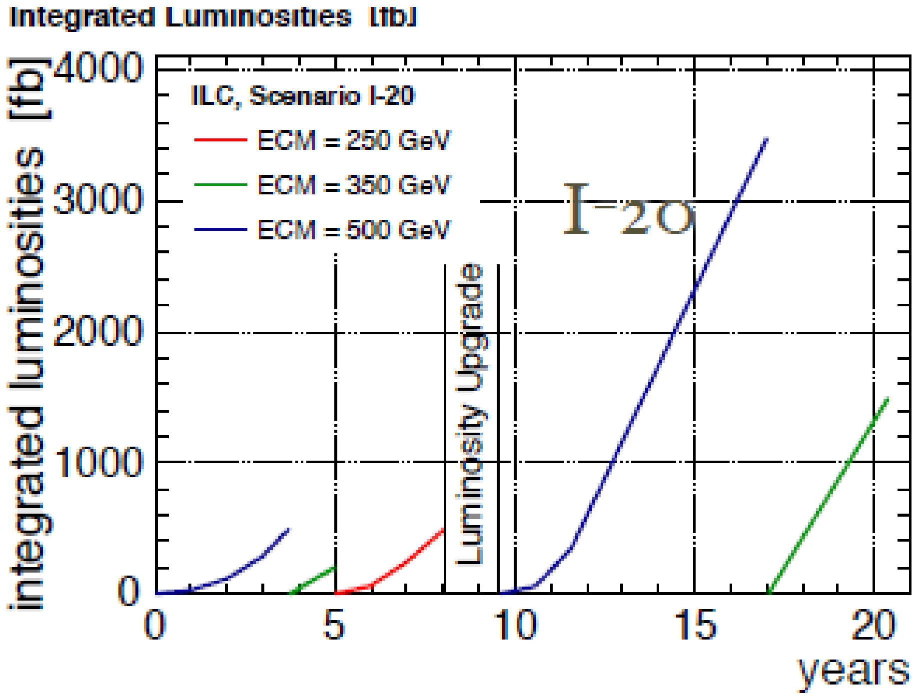
2020 | 2021 | 2022 | 2023-24 | 2025 | …

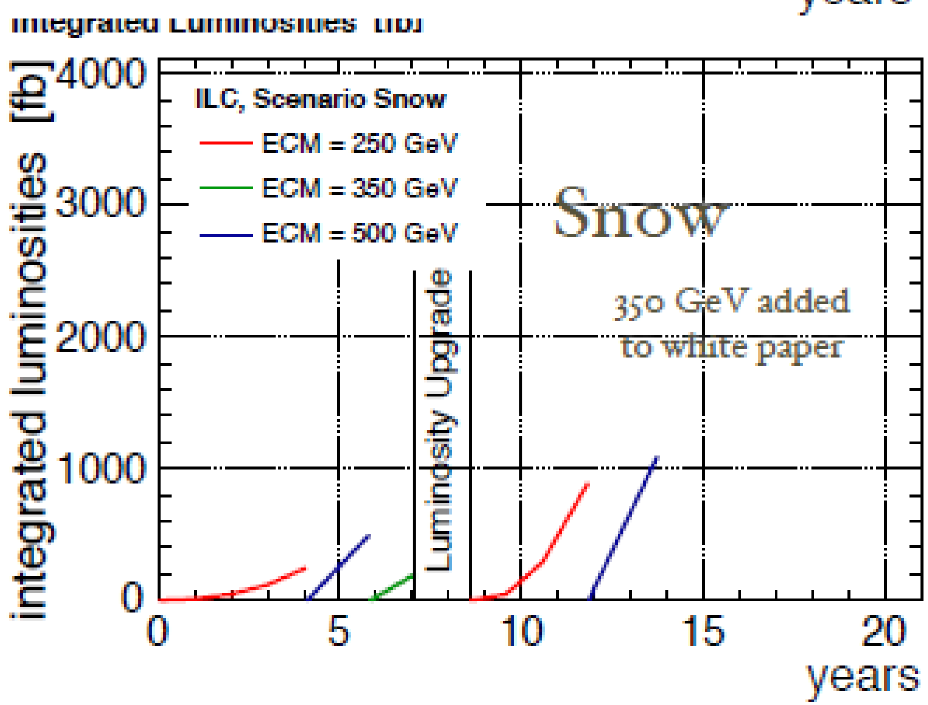
High Luminosity LHC:
- √s = 14 TeV
- L = 5.0×10^{34} cm^{-2}s^{-1}
- Pile Up > ~140
- 合計: ~3000fb^{-1}

- 約2年間のシャットダウンを経て
  2015年5月実験開始(Run2)。
- 衝突エネルギーは13TeV、後に14TeVへ。
- Run2終了時に100fb^{-1}が目標


Integrated Luminosities [fb]
integrated luminosities [fb]
ILC, Scenario G-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
G-20
Luminosity Upgrade
years


Integrated Luminosities [fb]
integrated luminosities [fb]
ILC, Scenario H-20
Recommended
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
H-20
Luminosity Upgrade
years


Integrated Luminosities [fb]
integrated luminosities [fb]
ILC, Scenario I-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
I-20
Luminosity Upgrade
years


Integrated Luminosities [fb]
integrated luminosities [fb]
ILC, Scenario Snow
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
Snow
350 GeV added
to white paper
Luminosity Upgrade
years