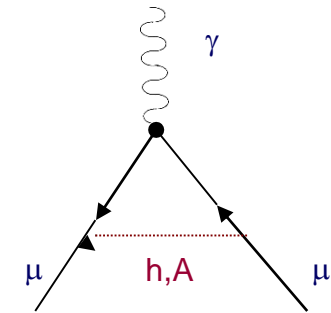
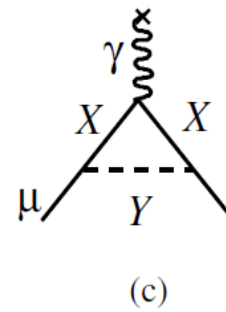
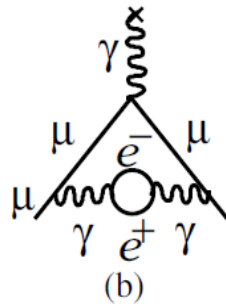
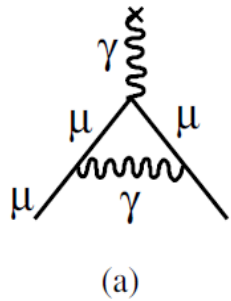


Two Higgs Doublets Model

g-2 muon anomaly in a 2HDM(II)

$$\vec{\mu}_\ell = g_\ell \frac{Qe}{2m_\ell} \vec{s}, \quad \underbrace{g_\ell = 2(1 + a_\ell)}_{\text{Dirac}}, \quad a_\ell = \frac{g_\ell - 2}{2}$$

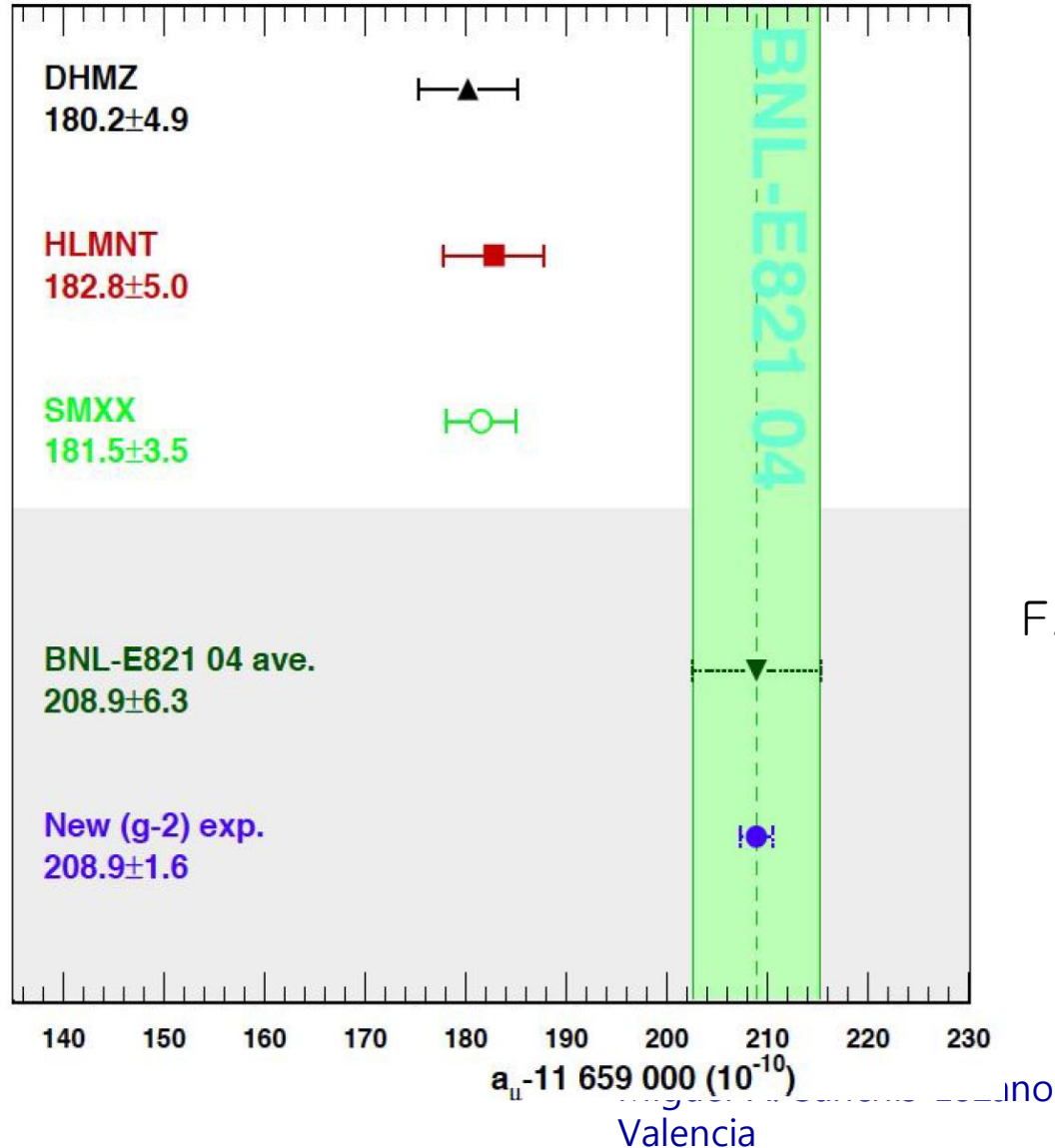
- loop vertex corrections



- Kinoshita et al. : 5-loops => 12000 diagrams!!

$$a^{SM} = a^{QED} + a^{Had} + a^{Weak}.$$

Discrepancy between SM and EXP.



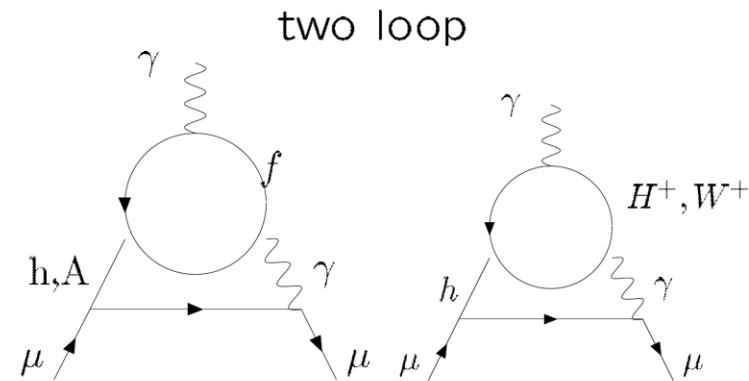
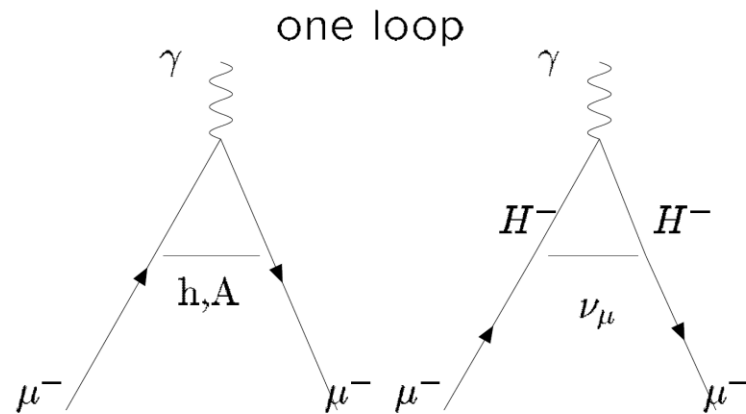
$$a_\mu^{\text{exp}} = 1\,165\,920\,89(63) \times 10^{-11}$$

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (287 \pm 80) \times 10^{-11}$$

F. Jegerlehner and A. Nyeler, Phys. Rept. 477, 1 (2009)

2HDM contribution to a_μ : $a_\mu^{2\text{HDM}} = a_\mu^h + a_\mu^A + a_\mu^H + a_\mu^{H^\pm}$

- **light h scenario** : $a_\mu^{2\text{HDM}} \approx a_\mu^h$
- **light A scenario** : $a_\mu^{2\text{HDM}} \approx a_\mu^A$



Zochowski, MK'96, MK'01; Dedes, Haber'01

Chang at al., Cheung at al, Wu, Zhou, MK'01, '02..

Two loop contributions larger than one-loop for mass \sim few GeV!

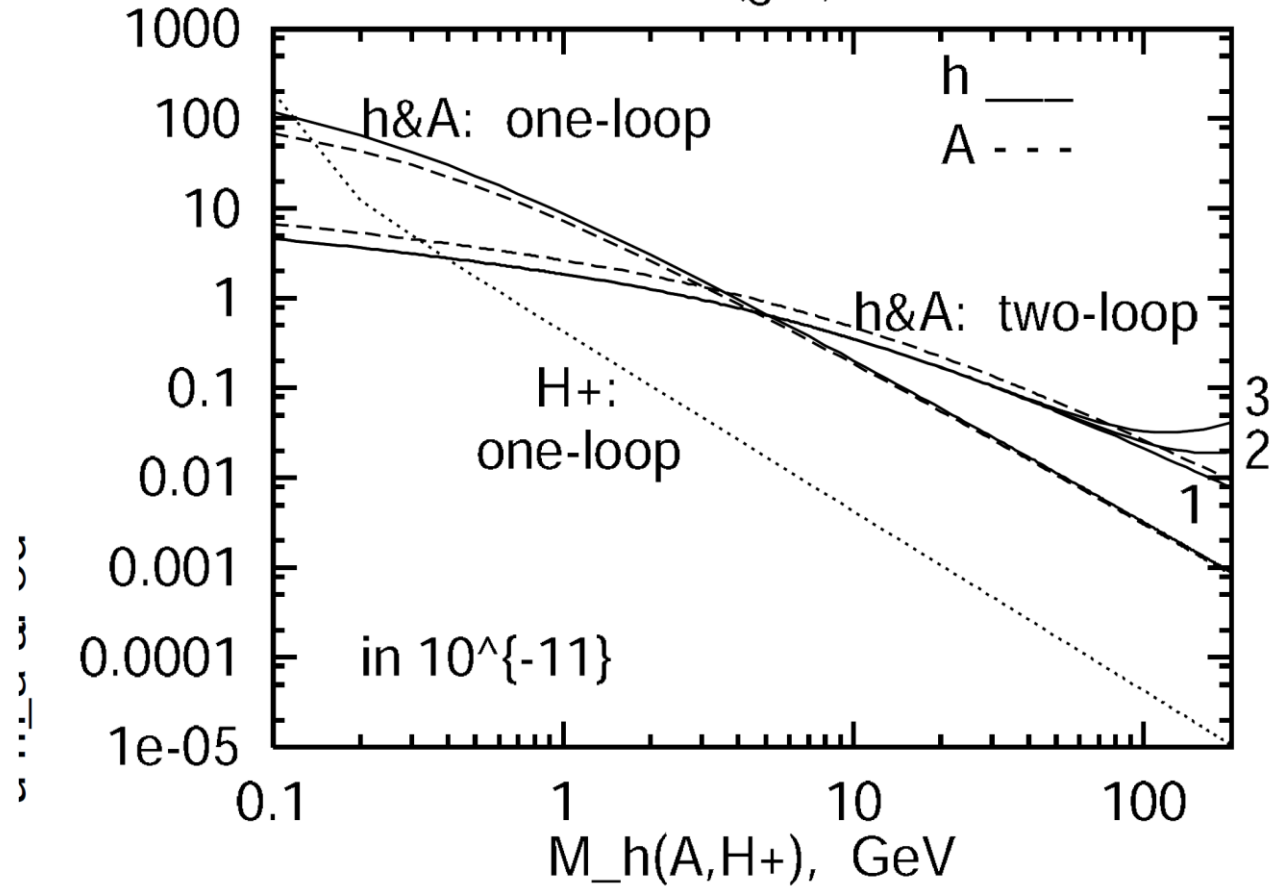
MK, hep-ph/0103223v3

MK, hep-ph/0112112 Snowmass proc

MK, Acta Phys. Pol. B 33 (2002) 2621

(hep-ph/020807)

contribution to $(g-2)/2$ for muon



1-

no H^+

2-

$M_{H^\pm} = 800 \text{ GeV}$

3-

$M_{H^\pm} = 400 \text{ GeV}$

Maria Krawczyk, hep-ph/0410248

Search for 2HDM through Collider

- **Productions** of charged Higgs and/or neutral Higgs at Collider
- **Decays** of charged Higgs and/ or neutral Higgs at Collider

Productions of Charged Higgs (type-II)

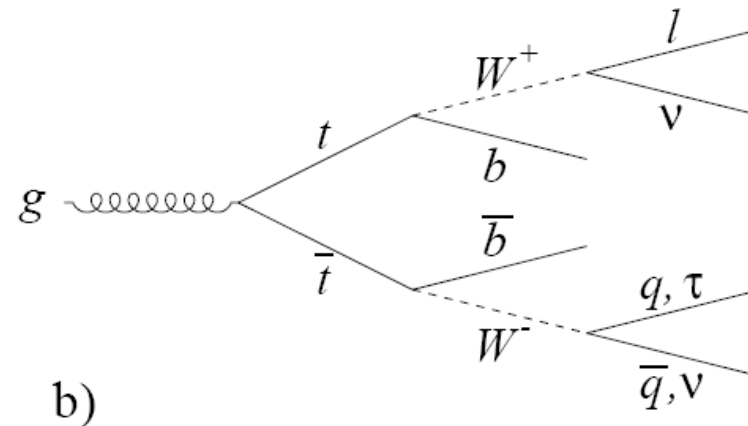
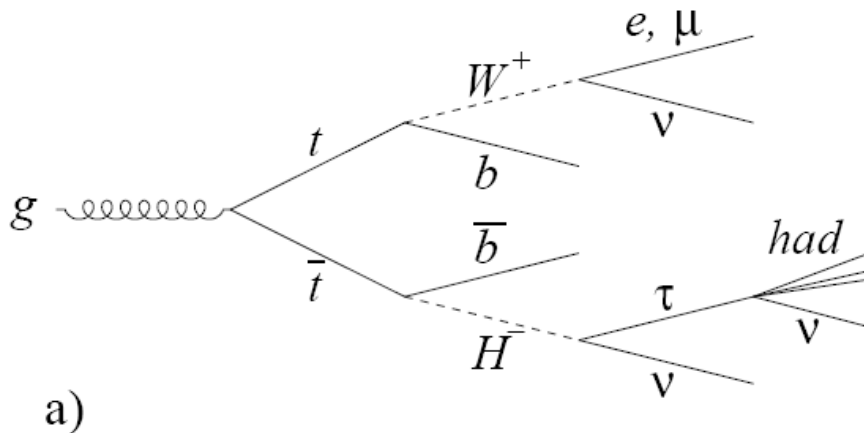
- Light charged Higgs : $m_{H^\pm} < m_t - m_b$

Top decay can produce light charged Higgs : $t \rightarrow H^\pm b$

Constrained by $\text{Br}(t \rightarrow Wb) = 0.94^{+0.31}_{-0.24}$ (Tevatron)

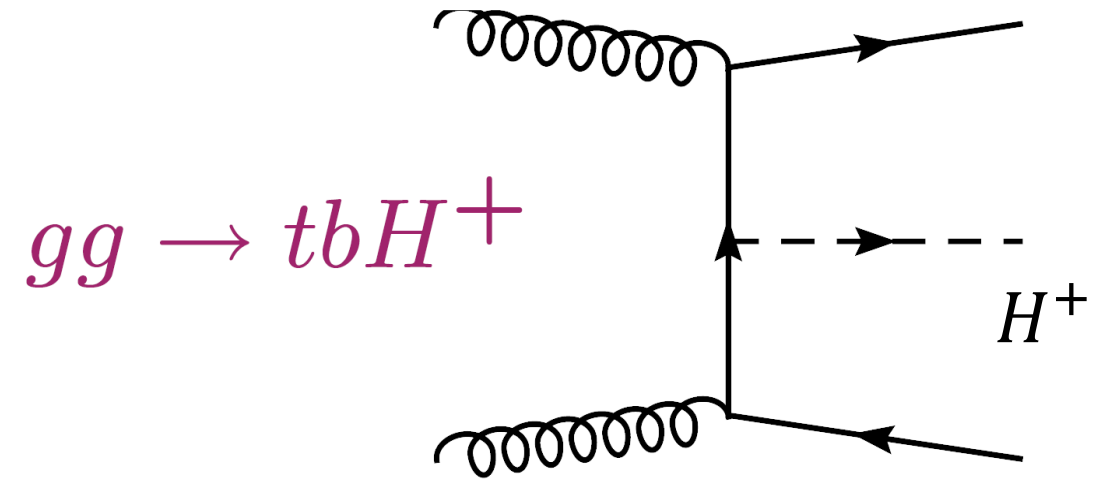
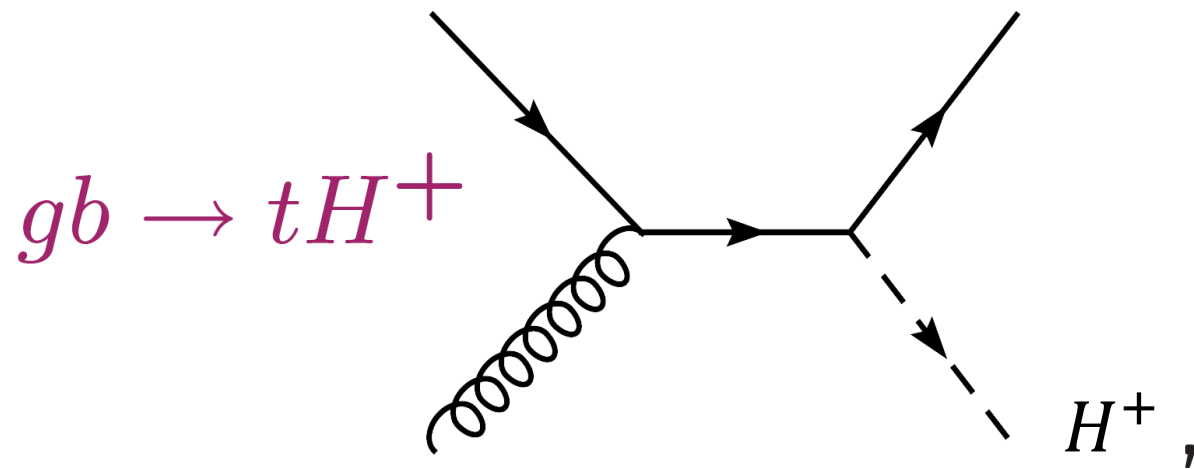
$$\text{BR}(t \rightarrow H^\pm b) \sim m_t^2 \cot^2 \beta + m_b^2 \tan^2 \beta$$

- Production of light charged Higgs at the LHC :

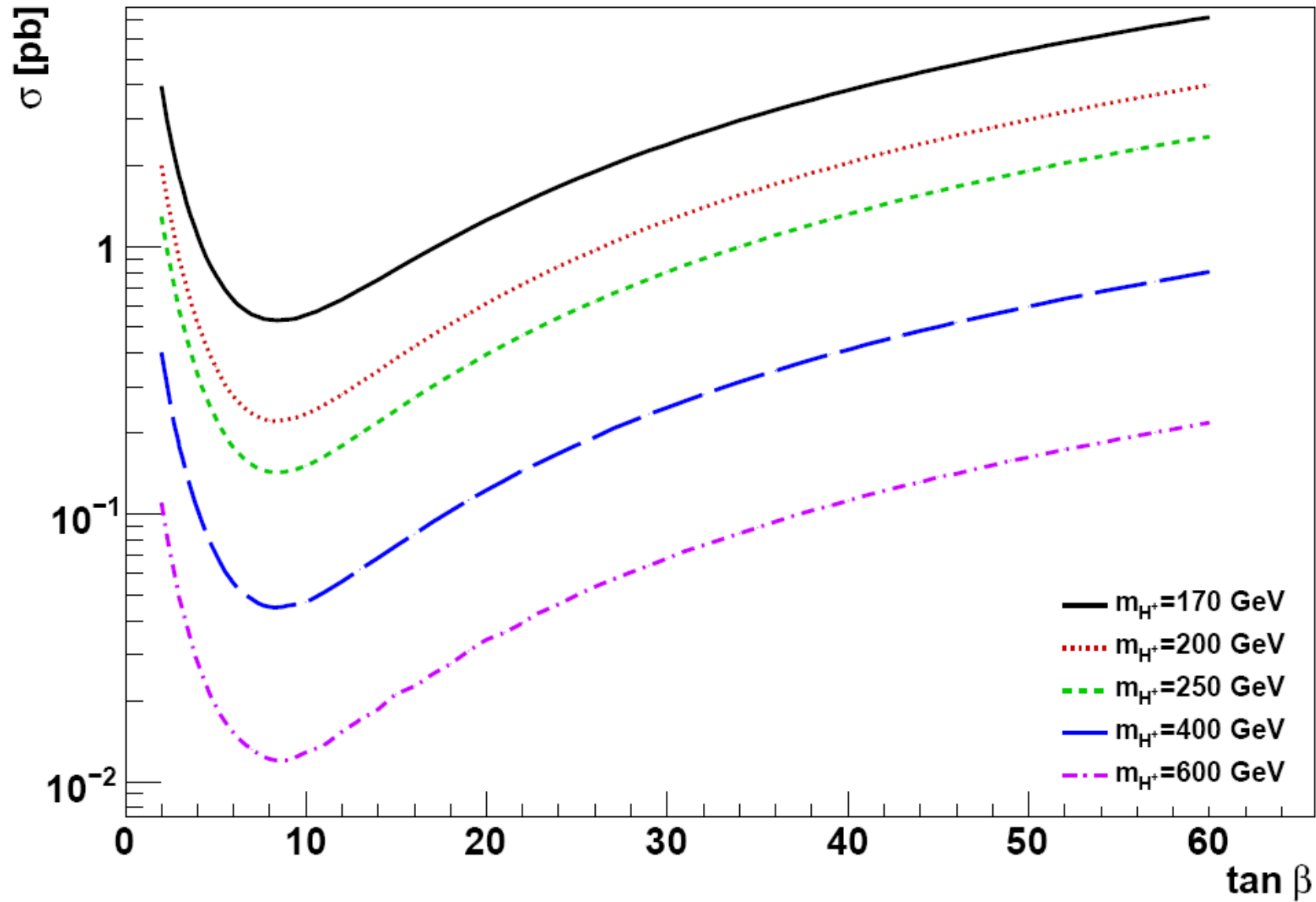


- Production of Heavy charged Higgs at the LHC

- dominant channel : $pp \rightarrow gb \rightarrow \bar{t}H^+$ process



- via gluon fusion, $pp \rightarrow gg \rightarrow tbH^+$



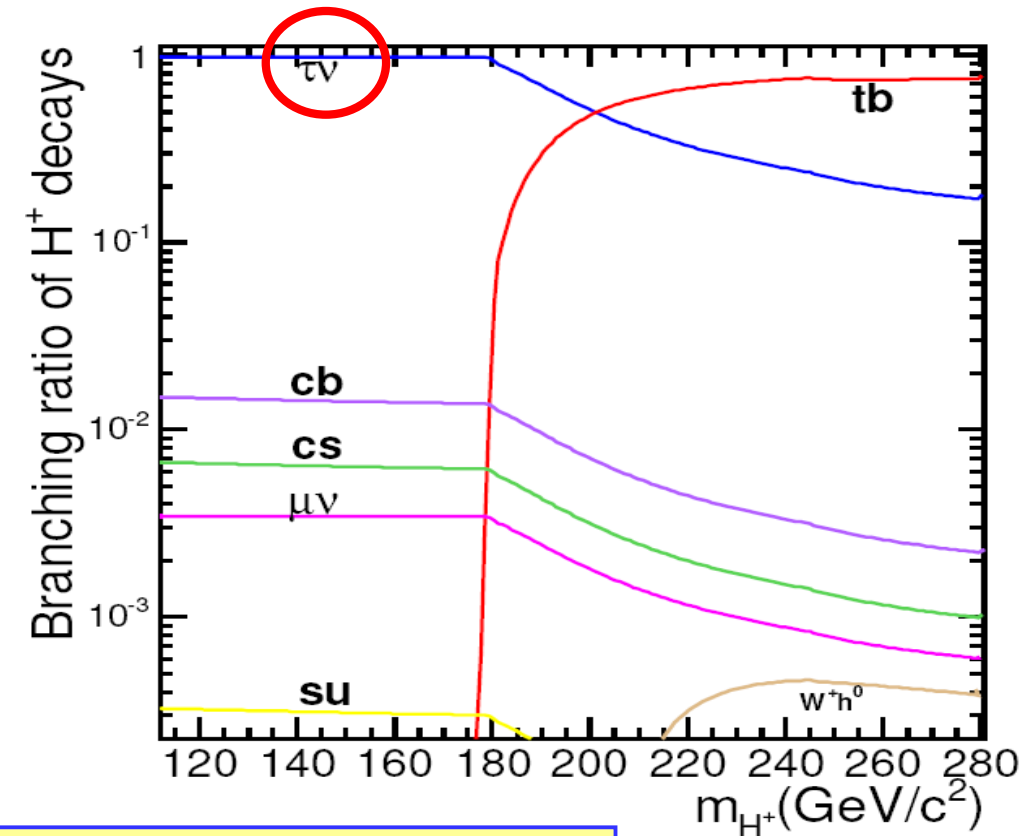
M. Flechl., ATLAS Collaboration, presented at Prospects for Charged Higgs Discovery at Hadron Collider, Uppsala, Sweden (2008)

Search for light charged Higgs at the LHC

- Via **decay channels**
 - for light charged Higgs below top mass

$$H^\pm \rightarrow \tau\nu$$

H^+ Decay	W Decay
$\tau\nu, \tau \rightarrow \text{had}$	qq
$\tau\nu, \tau \rightarrow \text{had}$	$l\nu$
$\tau\nu, \tau \rightarrow \text{lep}$	qq

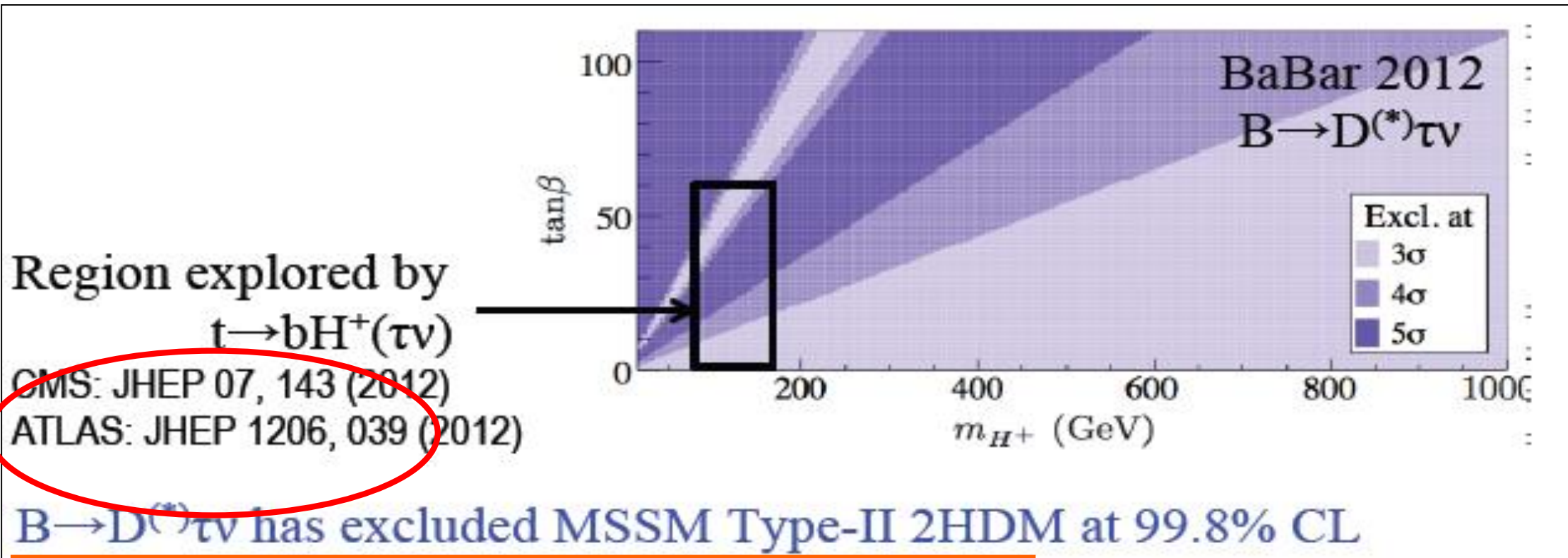


H^\pm decay BR. into different final states for $\tan \beta = 20$

2HDM H^+ Search at LHC

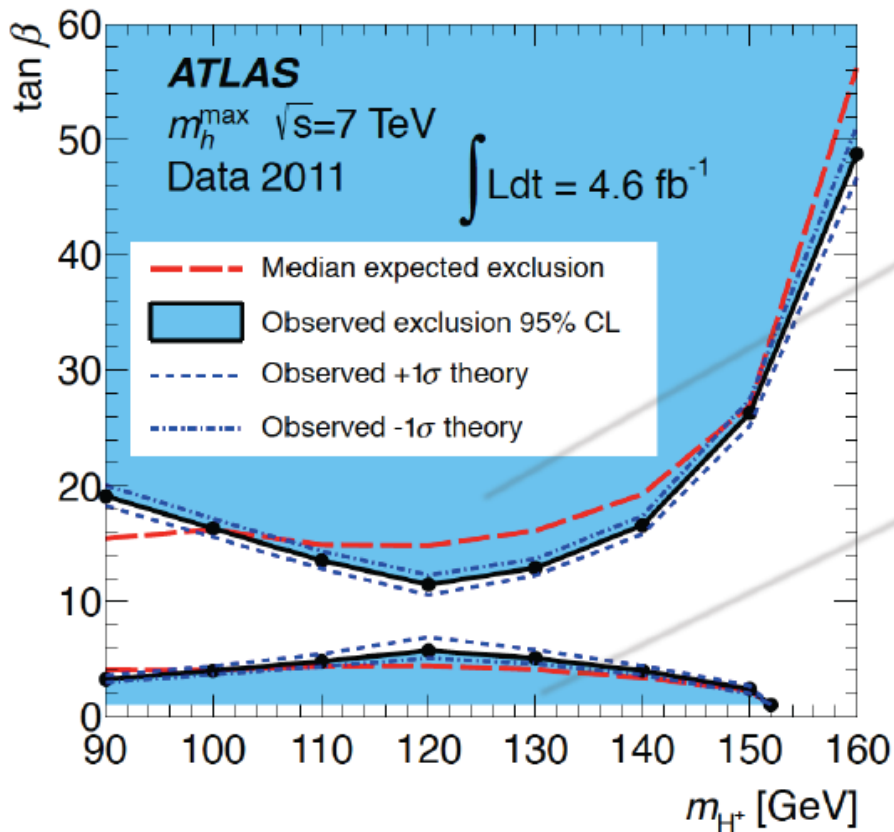
LHC Search has Started !

a BaBar-centric View

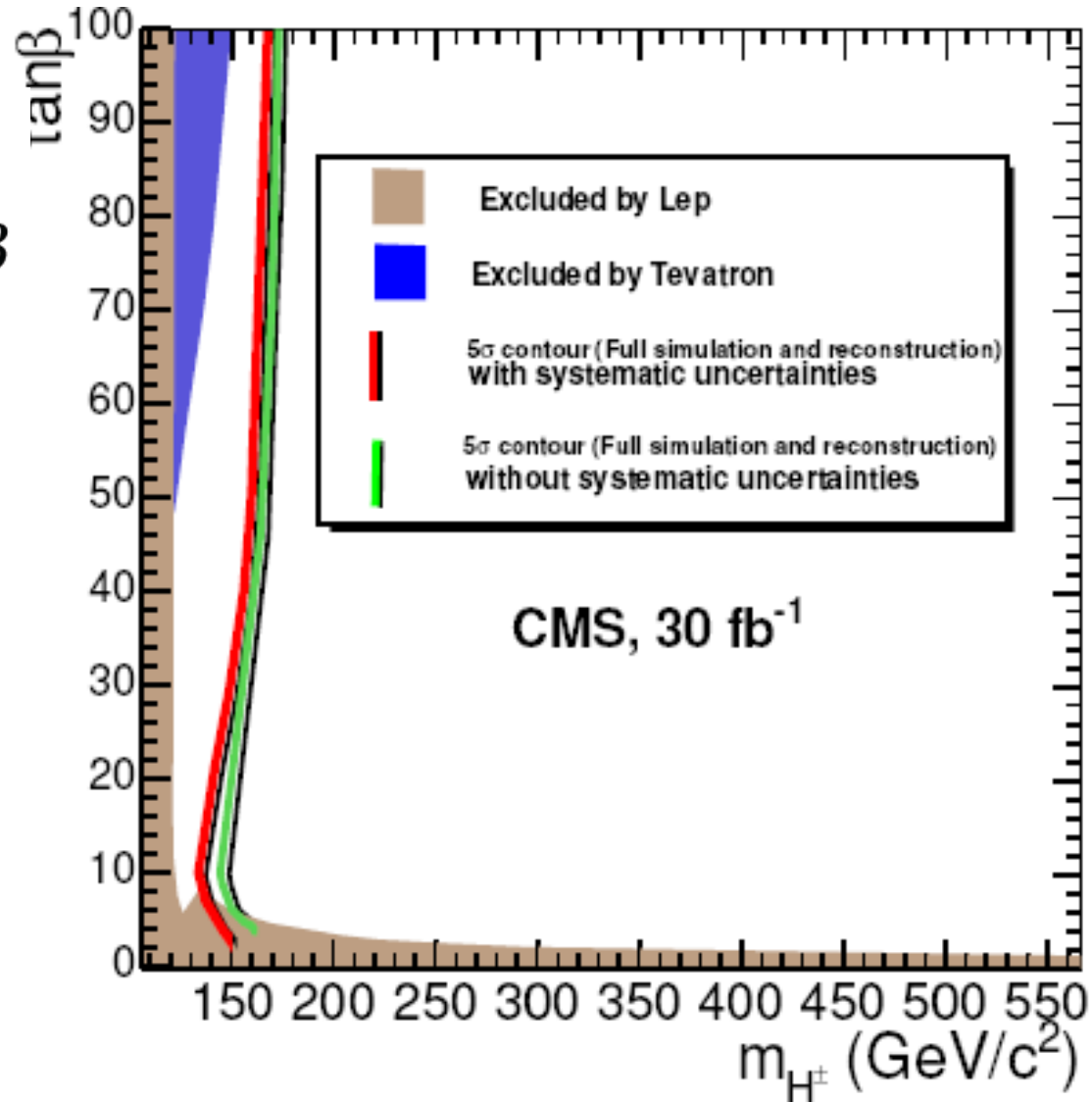


Discovery potential

CMS Note 2006/056



ATLAS JHEP'12
 CMS JHEP'12

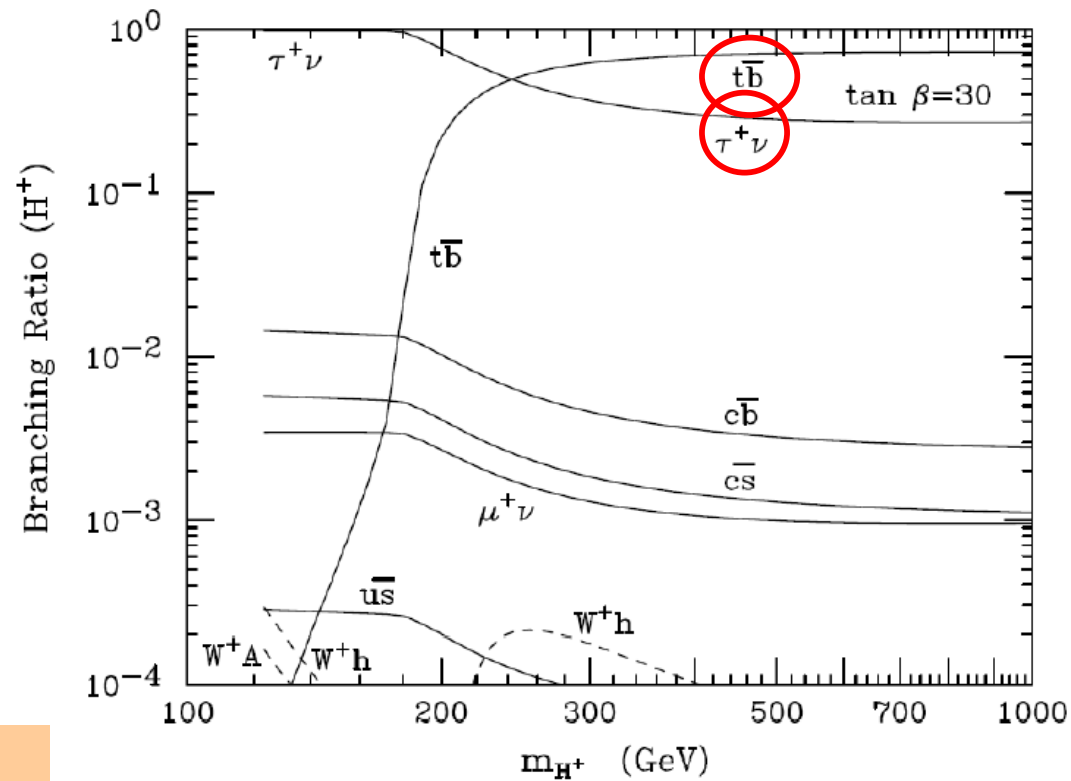


Search for heavy charged Higgs at the LHC

- Above top mass:
 - $BR(H^+ \rightarrow tb) \sim 0.8-1$
 - $H^+ \rightarrow tb$ results in complex final states : 3 or 4 b jets
- Crucial to suppress very large kinematically similar $t\bar{t} + \text{jets}$ background

Channels of interest:

H^+ Decay	W Decay
$\tau\nu, \tau \rightarrow \text{had}$	qq
tb	$l\nu$ & qq

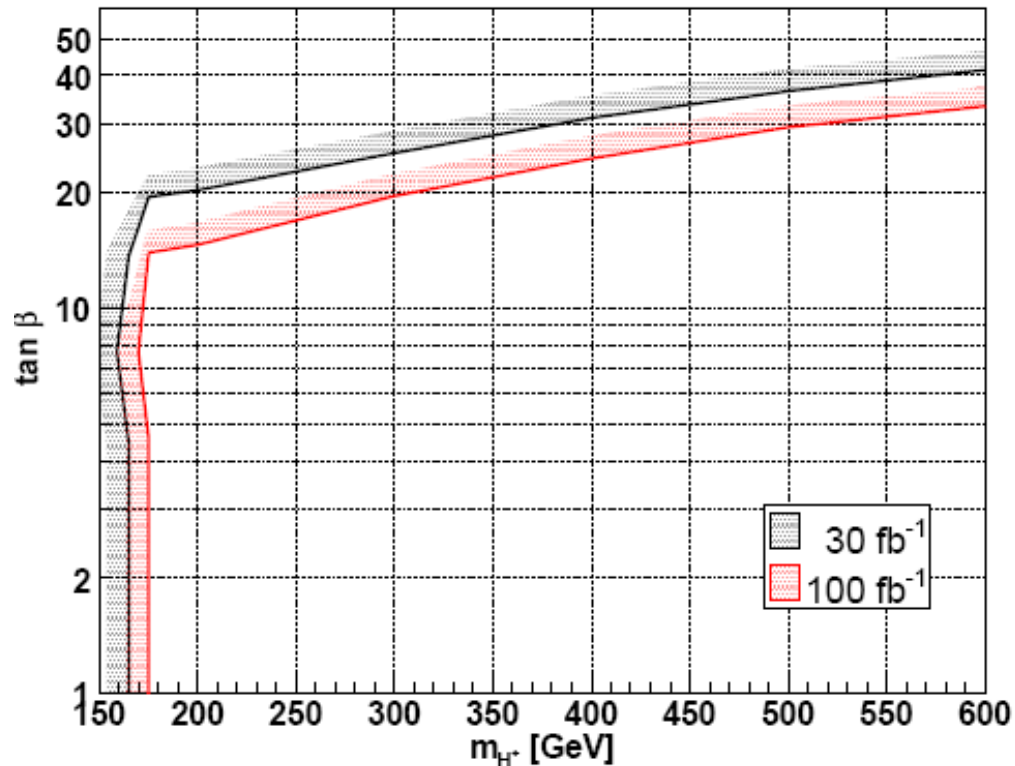


$\sigma \times BR$ (pb)

Process	m_{H^\pm} (GeV/ c^2)	$\tan \beta = 1.5$	$\tan \beta = 10$	$\tan \beta = 30$
$bg \rightarrow H^\pm t \rightarrow l\nu bj\bar{j}bb$	200	3.4	0.4	1.6
	250	2.0	0.18	1.2
	300	1.2	0.14	1.0
	400	0.54	0.08	0.4
	500	0.3	0.04	0.2

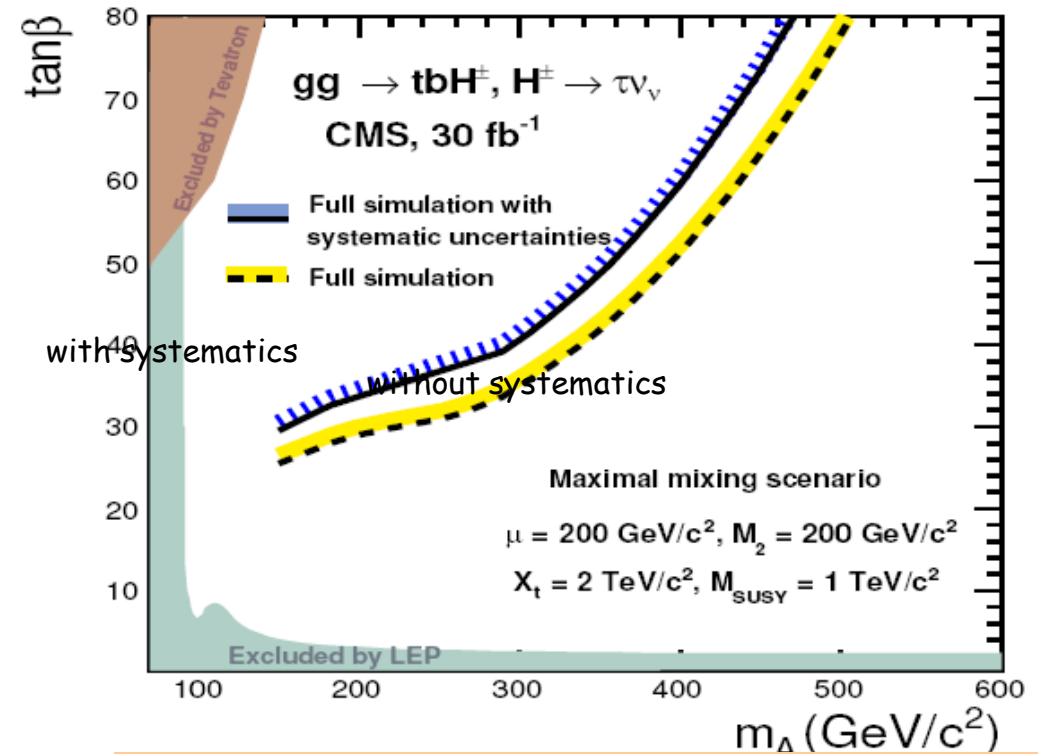
Discovery potential

ATLAS



- without systematics
- Background: FAST simul.

CMS



- systematics included
- Background: Full simul.

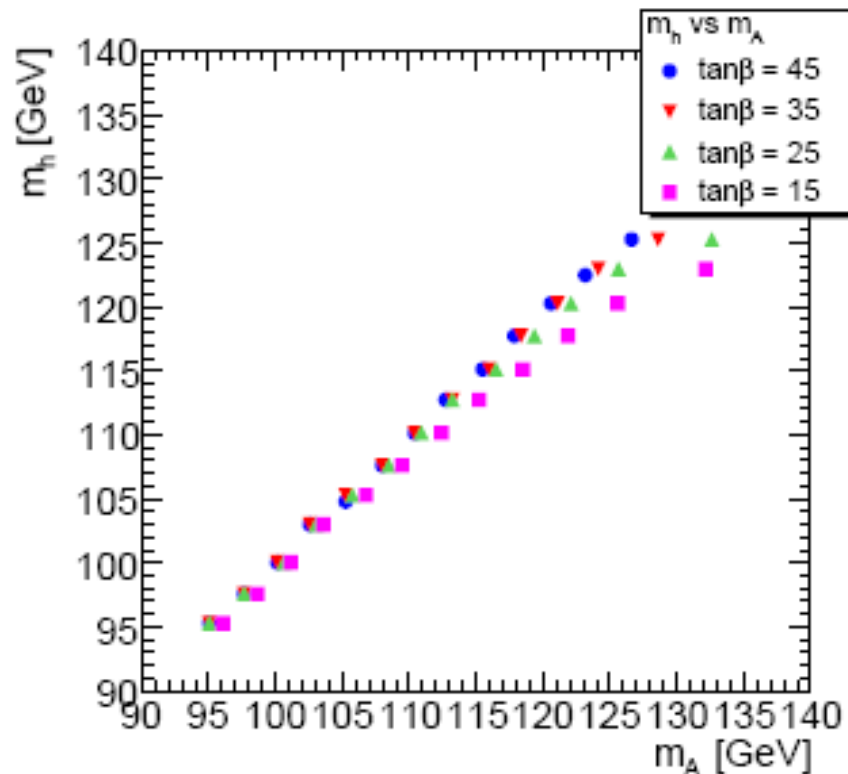
- promising channel for heavy charged Higgs

Search for neutral Higgs

Mass spectrums

- ✦ For $M_A < 135 \text{ GeV}$ (M_h^{max} scenario)
- ✦ The light Higgs is SM-like

$$M_A \approx M_h$$

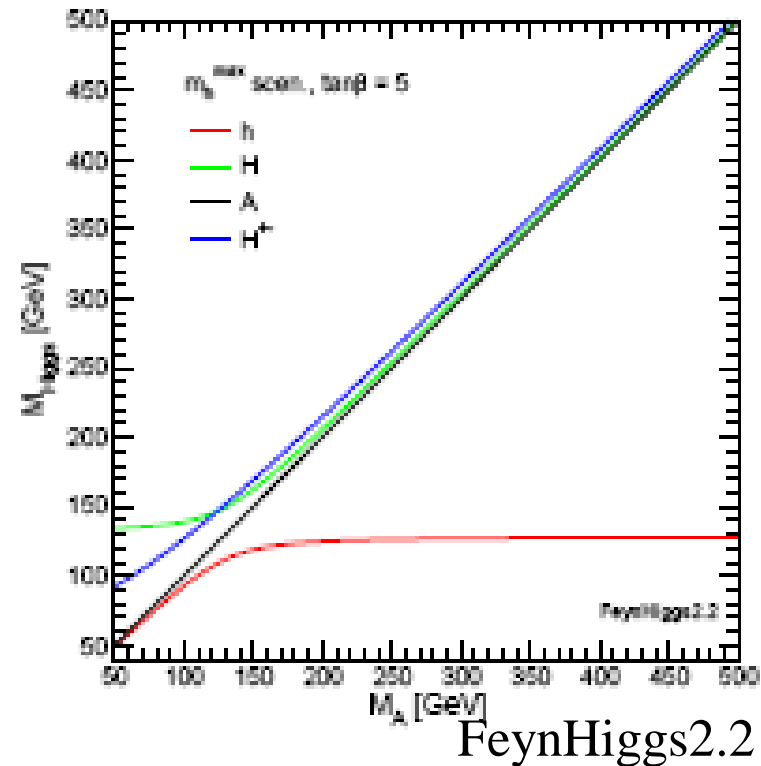


S.G, H.Bilokon, V.Chiarella, G.Nicoletti
ATL-PHYS-PUB-2007-001

Pythia 6.226

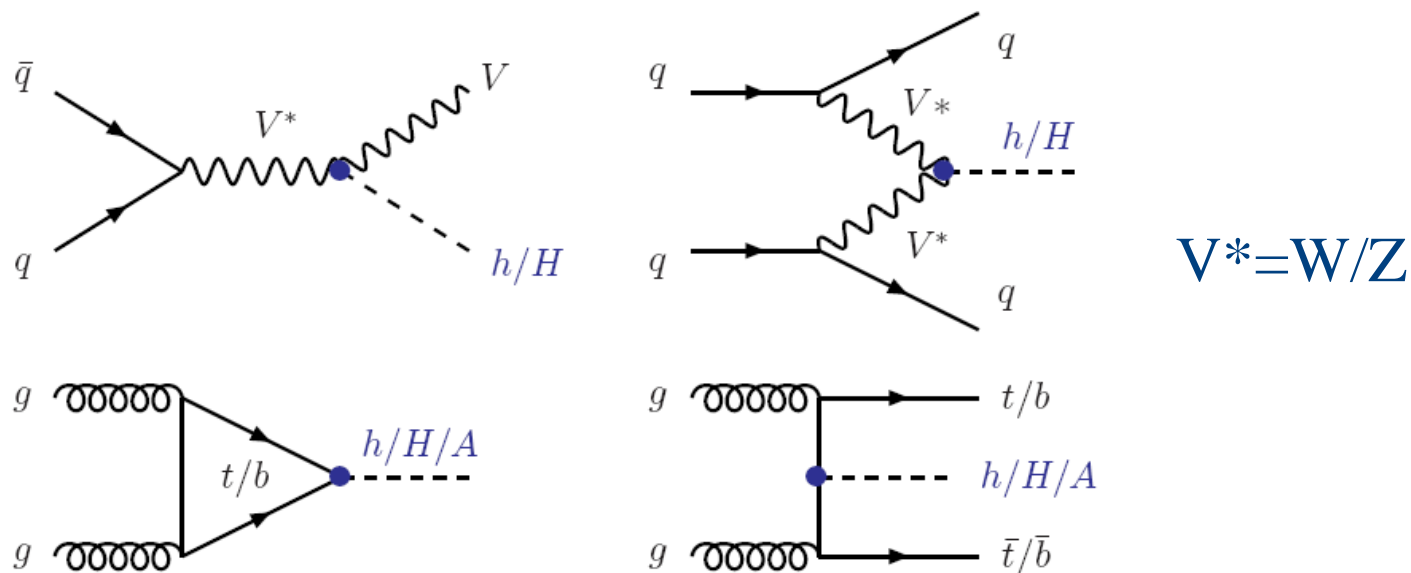
- ✦ For $M_A > 150 \text{ GeV}$ (decoupling limit)
- The heavy Higgs:

$$M_A \approx M_H \approx M_{H^\pm}$$



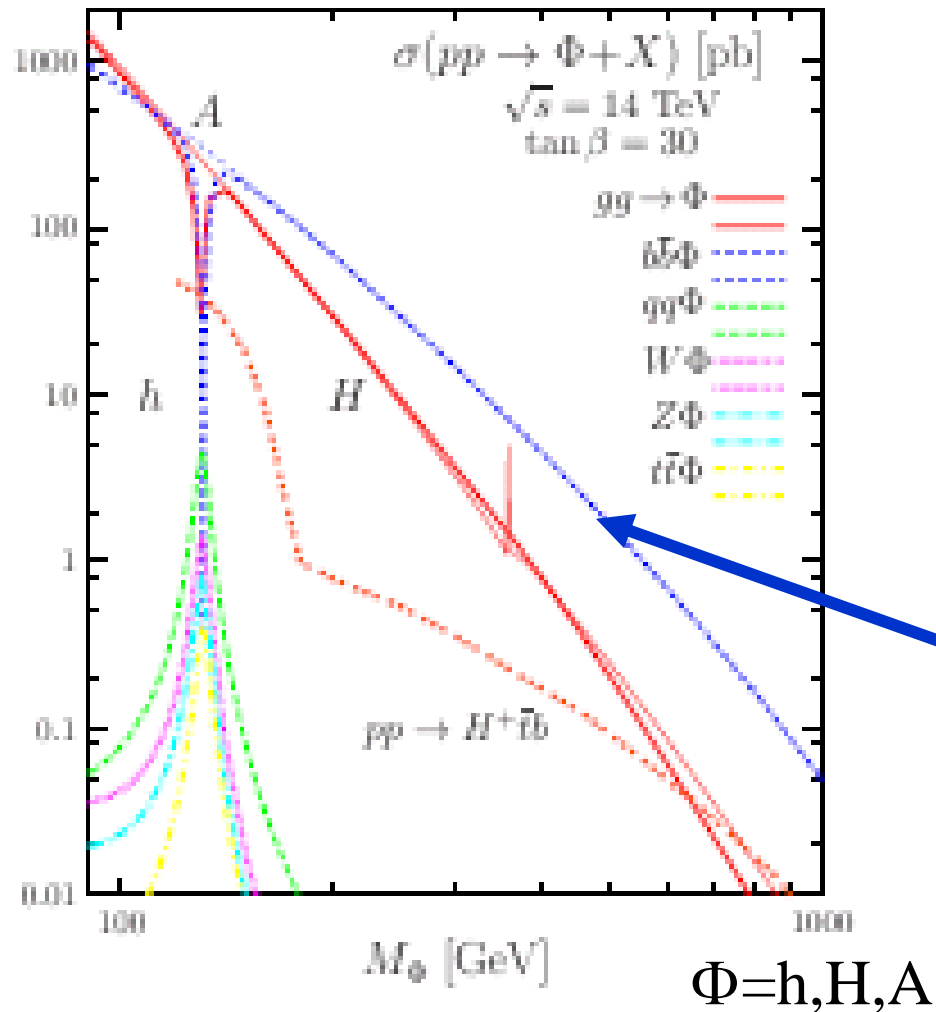
Sven Heinemeyer
Atlas meeting 29.01.2008

Production of neutral Higgses



- Main production mechanism \sim SM
- For high and moderate $\tan\beta$ the production with b quarks is enhanced
- For $m_A \gg m_Z$ A/H behave very similar \rightarrow decoupling region
- A, H, H^\pm cross section $\sim \tan\beta^2$

Production Cross Section

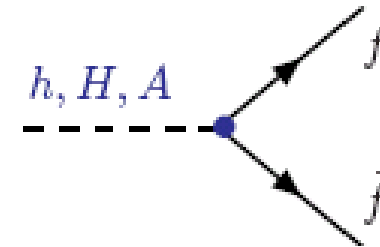


- At small $\tan\beta$
 - $gg \rightarrow h, H, A$ dominant
 - Vector boson fusion process
 $pp \rightarrow qq \rightarrow qq + WW/ZZ \rightarrow qq + h/H$
 important
 - Higgsstrahlung negligible

- At high $\tan\beta$
 - associated b quarks production dominates
 $pp \rightarrow b\bar{b} \rightarrow h/H/A + b\bar{b}$

Branching Ratio for Neutral Higgs Decays

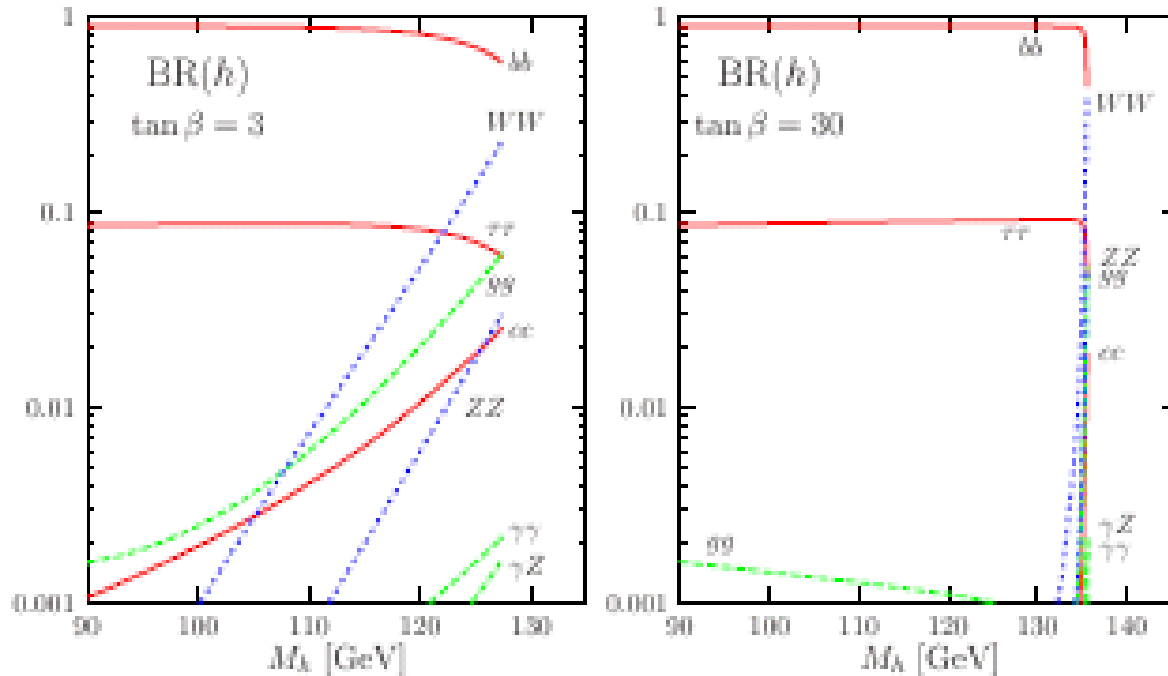
$M_A \geq 150 \text{ GeV}$ $\tan\beta \approx 30$
 or $M_A \geq 400\text{-}500 \text{ GeV}$ $\tan\beta = 3$



Production rate

$$\Gamma(h, H, A) \propto m_f^2$$

- Decay bb dominates

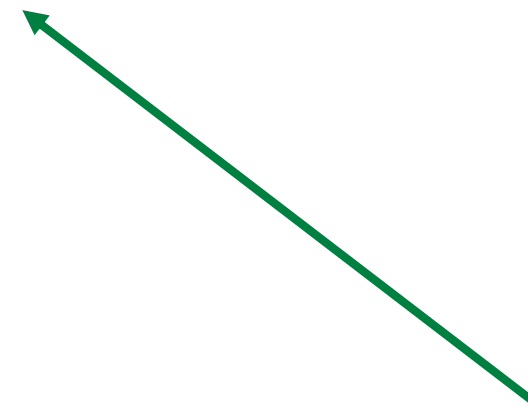
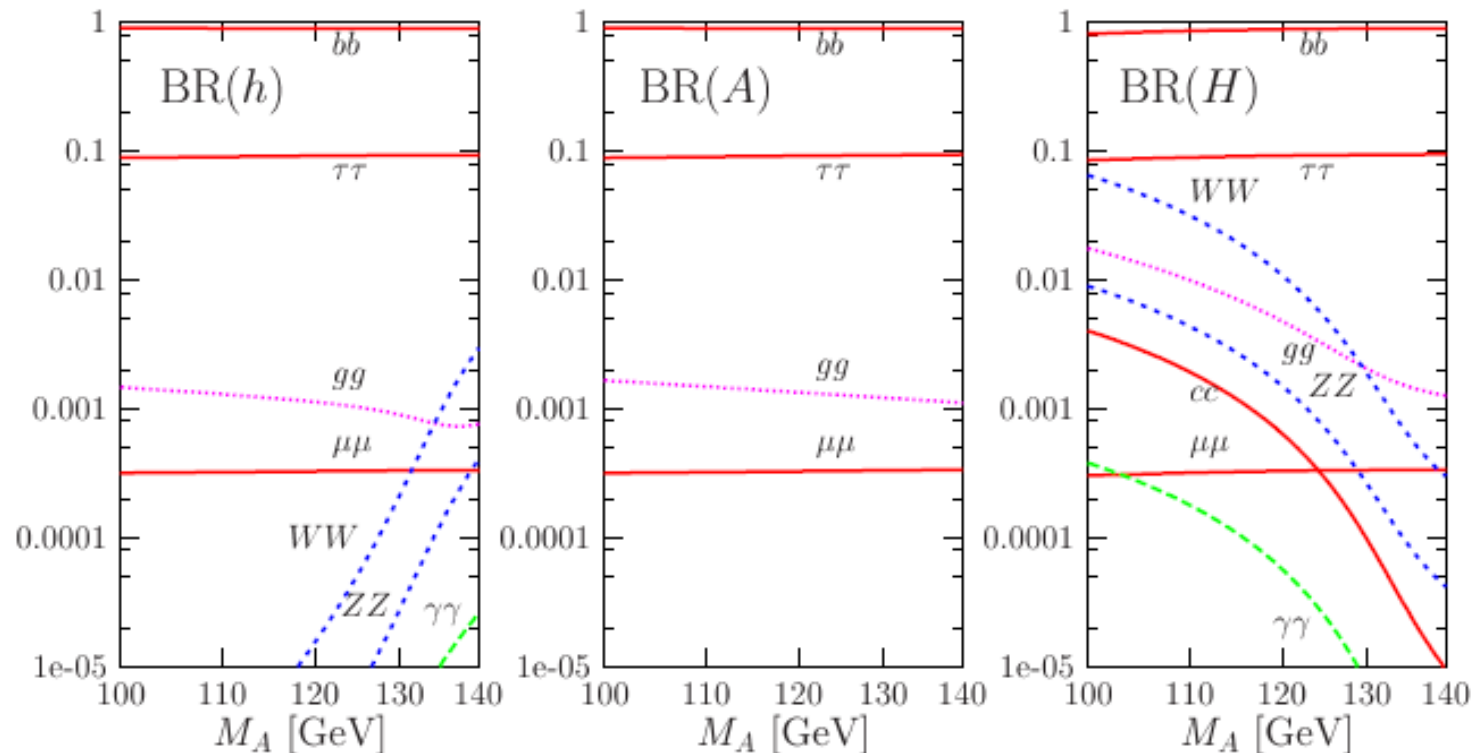


Branching Ratio for Neutral Higgs Decays

• **Intense coupling region** $\tan\beta \approx 30$ $M_A \sim 120-140$ GeV

Coupling to W,Z up quarks suppressed

Coupling down quark (b) and τ enhanced



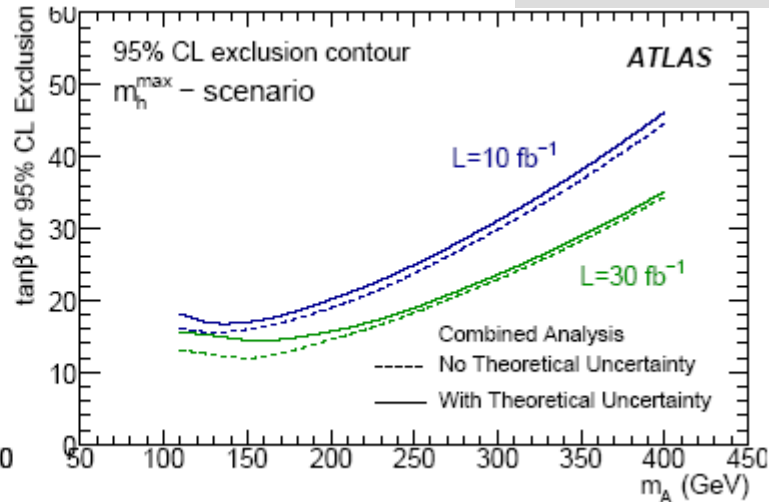
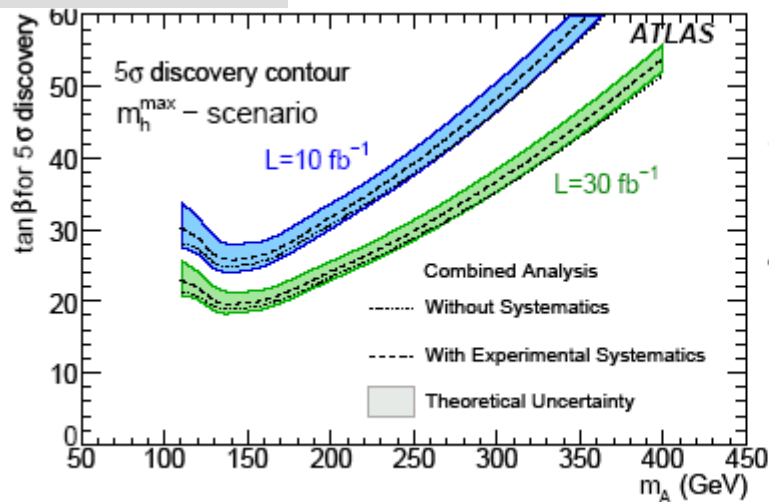
- Decay $bb, \tau\tau$ dominates
- Decay $\mu\mu$ possible

Discovery Potential

- Signal cross section uncertainties 17%
- Systematic experimental uncertainties based on detector expected performances: e.g. muon efficiency, muon PT scale, muon resolution, Jet energy scale, Jet energy resolution, btag efficiency, b-tagging fake rate. Based on detector expected performance 10-20%

Large systematic uncertainties demand for data-driven method background estimation

preliminary Combined 0-b-jet and ≥ 1 b-jet analysis preliminary

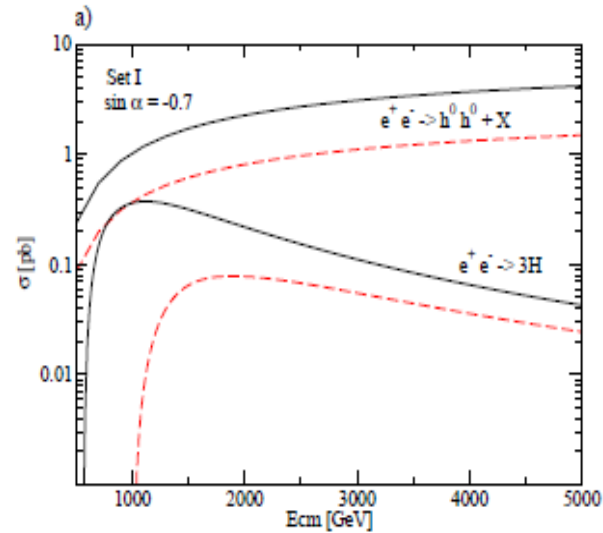
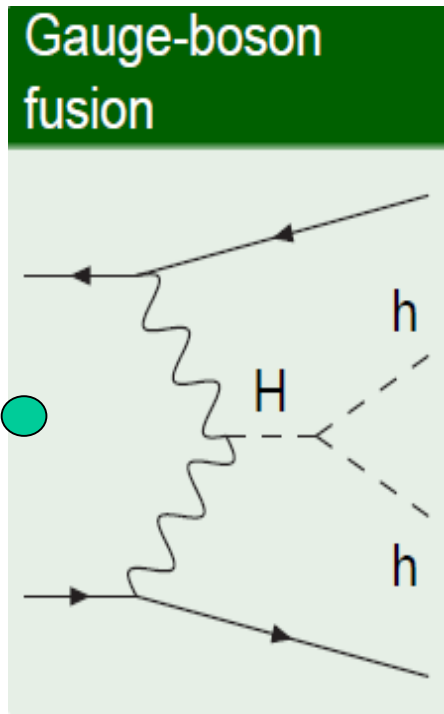


Pair Productions

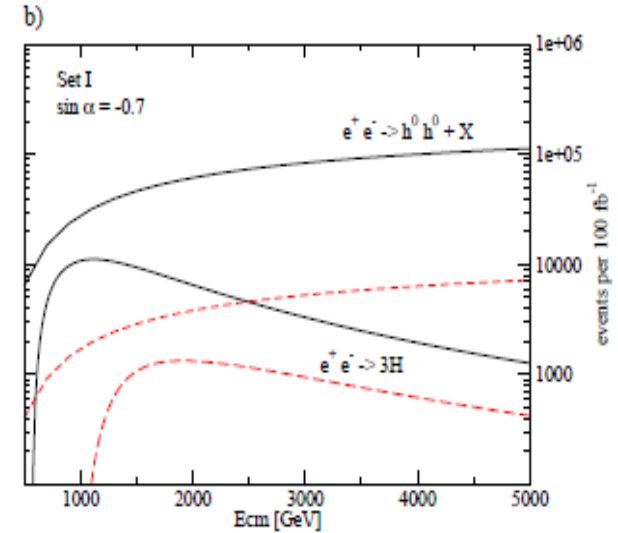
$$\lambda_{HHH} = \frac{3}{2} \frac{eM_H^2}{s_W M_W}$$

Trilinear coupling can be large for Heavy Higgs

(Robert N. Hodgkinson)



$\tan \beta \simeq 25(4)$



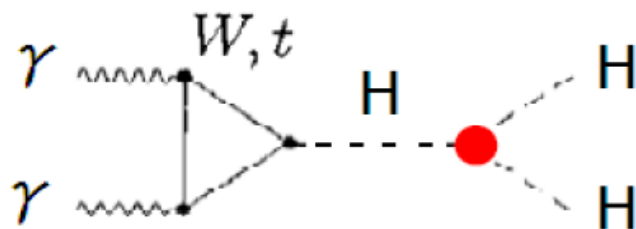
$\tan \beta \simeq 14(2)$

	M_{H^0} [GeV]	M_{A^0} [GeV]	M_{H^\pm} [GeV]
Set I (solid)	100	360	350
Set I' (dash)	100	800	800

Pair Productions

“Feasibility study of Higgs pair creation in gamma-gamma collider”
(Norizumi Maeda)

For measuring Higgs self coupling

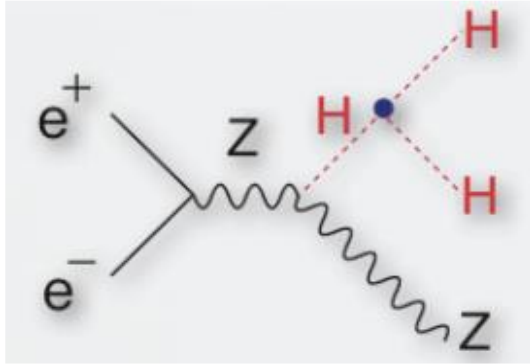


Low Higgs mass regions

$$H H \rightarrow b \bar{b} b \bar{b}$$

Studies on **Higgs self coupling & top Yukawa coupling** measurements
 at **ILC with 500 GeV** $m_h = 120 \text{ GeV}$

“Analysis of 6-jet mode in ZHH” (Yosuke Takubo)



Analysis mode: ZHH \rightarrow qqHH

- › Higgs mass: 120 GeV
 - ✓ Higgs mainly decays into bb with $\sim 70\%$ branching ratio.
- › Integrated luminosity: 2 ab^{-1}

	qqHH	tt	tbtb
• No cut	: 270	1167290	2154
• $\chi^2 < 20$: 219	615456	1810
• $90 < M_{H1,2} < 140 \text{ GeV}$: 196	529501	1607
• $60 < M_Z < 110 \text{ GeV}$			
• $N_{\text{lepton}}=0$: 178	411467	1102
• missing E < 70 GeV	: 156	302953	816
• $N(\text{HH})_{\text{b-tag}}=4$: 20.1	475	38.7
• $N(\text{Z})_{\text{b-tag}}=2$: 4.3	0	0.6

Significance : ~ 3

Near confident obs.

Next step

\rightarrow Full simulation

Fit of 2HDM to the LHC data

- What has the LHC observed to look for Higgs ?
- Is the LHC data compatible with 2HDM ?

(S. Chang, SK, J. Lee, K. Lee, S. Park, J. Song to appear in JHEP)

Current status of LHC data for Higgs

- How both ATLAS and CMS look for Higgs ?
 - in several decay channels : $\gamma\gamma$, WW^* , ZZ^* , $\bar{b}b$, $\bar{\tau}\tau$
- Recently, they have updated the Higgs search results using the full data recorded in 2011 and 2012 with the integrated luminosity up to $5 fb^{-1}$ at 7 TeV and $21 fb^{-1}$ at 8 TeV.
- The new data support the SM Higgs boson interpretation further, even though each individual channel is still fluctuating.
- The excess in the diphoton channel decreased in the updated CMS data, but retained in the ATLAS data

$\mu_{\gamma\gamma} = 1.65_{-0.30}^{+0.34}$ (ATLAS),	$0.78_{-0.26}^{+0.28}$ (CMS-MVA mass-fact.)
	$1.11_{-0.30}^{+0.32}$ (CMS-cut-based)

Current status of LHC data for Higgs

- Even though the data seem to indicate very SM-like Higgs boson, other scalar candidates in various new physics models are not excluded yet.
- The aim of the work :
 - how much parameter space of 2HDM still survives especially outside the decoupling region ?
 - whether 2HDM can explain the current data better than the SM ?
 - whether there is any chance to miss the light Higgs boson h^0 with H^0 being the observed one ?

Two scenarios for probing 2HDM

- I. h^0 is the 125 GeV Higgs observed at the LHC
- II. H^0 is the 125 GeV Higgs observed at the LHC while h^0 has been missed.
- We constrain $1 \leq \tan \beta \leq 50$
- Effective Lagrangian :

$$L = c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{2m_Z^2}{v} h Z_\mu Z_\mu - c_b \frac{m_b}{v} h \bar{b}b - c_\tau \frac{m_\tau}{v} h \bar{\tau}\tau - c_c \frac{m_c}{v} h \bar{c}c - c_t \frac{m_t}{v} h \bar{t}t + c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^a G^{a\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h A_{\mu\nu} A^{\mu\nu}$$

($h = h^0$ for scenario-I, $h = H^0$ for scenario-II)

- SM values for the coefficients :

$$c_{V,SM} = c_{f,SM} = 1, \quad c_{g,SM} \approx 1, \quad c_{\gamma,SM} \approx -0.81$$

- Useful parameterization for the observed signal in the Higgs search at the LHC : ratio of the observed event rate to SM prediction which is identified with signal strength : $\hat{\mu} = \sigma/\sigma_{SM}$

$$R_{\text{decay}}^{\text{production}} \equiv \frac{\sum_j \sigma(pp \rightarrow j \rightarrow h) \times \text{B}(h \rightarrow \text{decay})|_{\text{observed}}}{\sum_j \sigma(pp \rightarrow j \rightarrow h) \times \text{B}(h \rightarrow \text{decay})|_{\text{SM}}},$$

(production : $ggF, VBF, Vh, t\bar{t}h$, decay : $\gamma\gamma, WW^*, ZZ^*, \bar{b}b, \bar{\tau}\tau$)

- In terms of effective couplings :

$$R_{\gamma\gamma}^{ggF} = \left| \frac{c_g c_\gamma}{c_{\gamma,SM} C_{tot}^h} \right|^2, \quad R_{ii}^{ggF} = \left| \frac{c_g c_i}{C_{tot}^h} \right|^2,$$

$$R_{ii}^{VBF} = R_{ii}^{Vh} = R_{ii}^{VBF+Vh} = \left| \frac{c_V c_i}{C_{tot}^h} \right|^2,$$

$$R_{\gamma\gamma}^{VBF} = R_{\gamma\gamma}^{Vh} = R_{\gamma\gamma}^{VBF+Vh} = \left| \frac{c_\gamma c_V}{c_{\gamma,SM} C_{tot}^h} \right|^2,$$

where $C_{tot}^h = \sqrt{\Gamma_{tot}^h / \Gamma_{tot}^{hSM}}$, and $i = W, Z, \tau, b$.

- LHC data

Table 1. Summary of the LHC Higgs signals at 7 and 8 TeV.

Production	ATLAS	CMS
$ggF + t\bar{t}h$	$\tilde{R}_{\gamma\gamma}^{ggF+t\bar{t}h} = 1.47^{+0.66}_{-0.52}$ [46] $\tilde{R}_{WW}^{ggF} = 0.82 \pm 0.36$ [48] $\tilde{R}_{ZZ}^{ggF+t\bar{t}h} = 1.8^{+0.8}_{-0.5}$ [49] $\tilde{R}_{\tau\tau}^{ggF} = 1.0^{+2.1}_{-1.4}$ [50]	$\tilde{R}_{\gamma\gamma}^{ggF+t\bar{t}h} = 0.52 \pm 0.5$ [47] $\tilde{R}_{WW}^{ggF} = 0.73^{+0.22}_{-0.20}$ [5] $\tilde{R}_{ZZ}^{ggF+t\bar{t}h} = 0.9^{+0.5}_{-0.4}$ [35] $\tilde{R}_{\tau\tau}^{ggF} = 0.93 \pm 0.42$ [51]
$VBF + Vh$	$\tilde{R}_{\gamma\gamma}^{VBF+Vh} = 1.73^{+1.27}_{-1.11}$ [46] $\tilde{R}_{WW}^{VBF} = 1.66 \pm 0.79$ [48] $\tilde{R}_{ZZ}^{VBF+Vh} = 1.2^{+3.8}_{-1.4}$ [49] $\tilde{R}_{\tau\tau}^{VBF+Vh} = 1.5^{+1.1}_{-1.0}$ [50] $\tilde{R}_{b\bar{b}}^{VBF+Vh} = 0.20 \pm 0.64$ [52]	$\tilde{R}_{\gamma\gamma}^{VBF+Vh} = 1.48^{+1.5}_{-1.1}$ [47] $\tilde{R}_{WW}^{VBF} = -0.05^{+0.75}_{-0.56}$, $\tilde{R}_{WW}^{Vh} = 0.51^{+1.26}_{-0.94}$ [5] $\tilde{R}_{ZZ}^{VBF+Vh} = 1.0^{+2.4}_{-2.3}$ [35] $\tilde{R}_{\tau\tau}^{VBF} = 0.94 \pm 0.41$, $\tilde{R}_{\tau\tau}^{Vh} = -0.33 \pm 1.02$ [51] $\tilde{R}_{b\bar{b}}^{VBF+Vh} = 0.96 \pm 0.47$ [53]

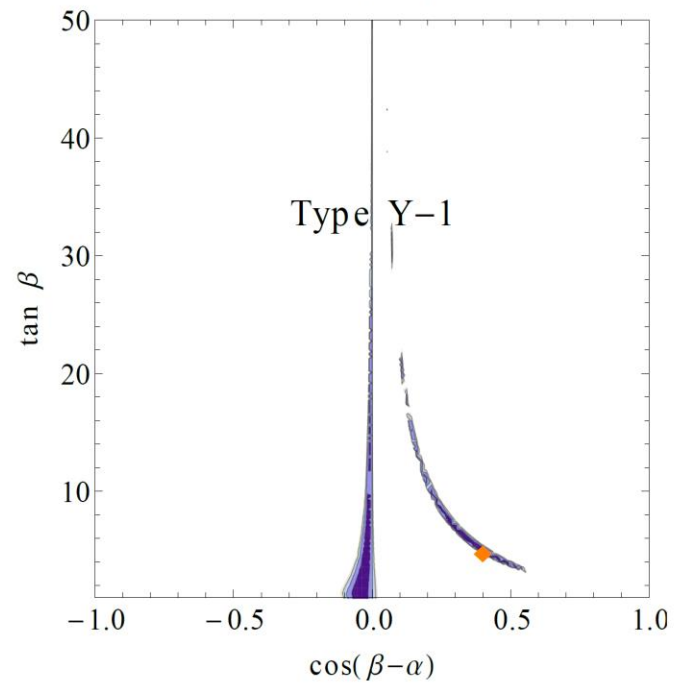
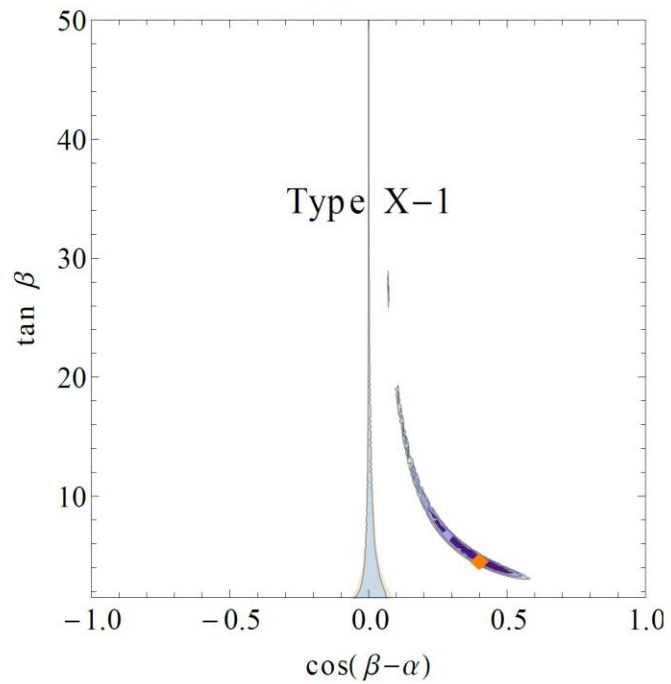
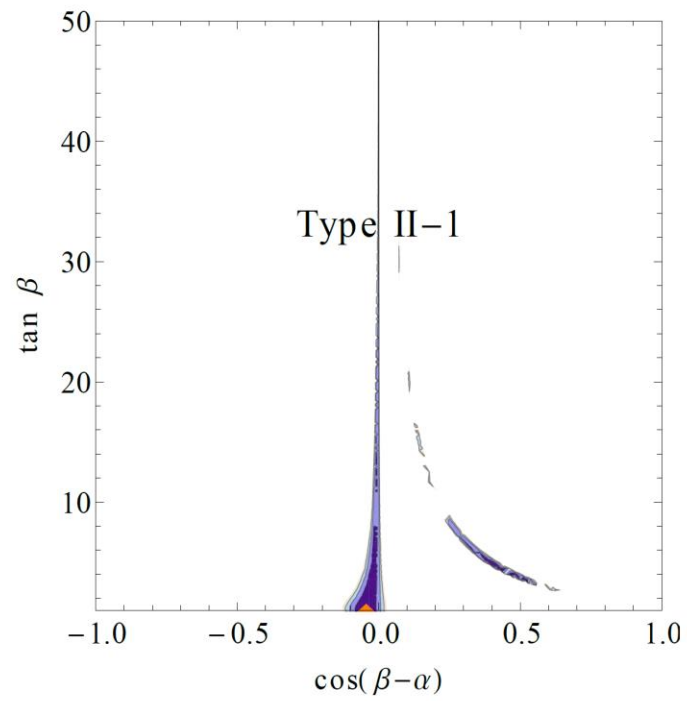
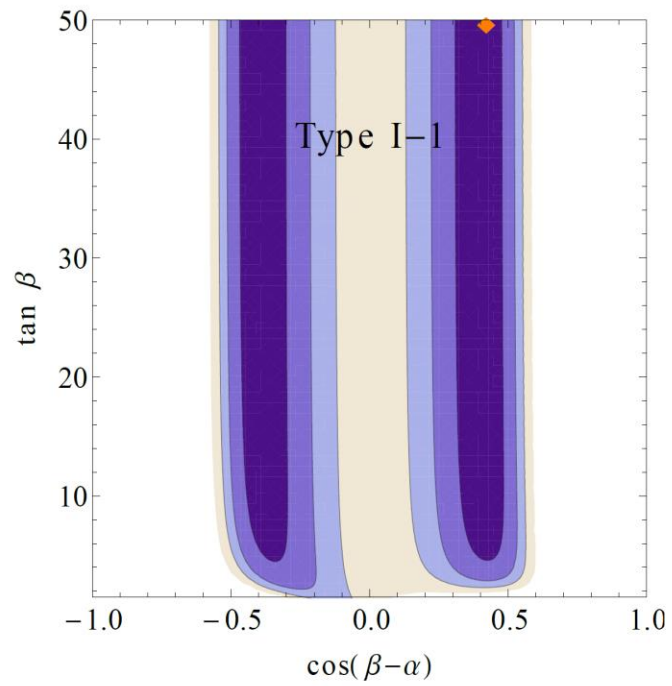
- Performing global fit to the LHC data

$$\chi^2 = \sum_{i=1}^{20} \frac{(R_i - \tilde{R}_i)^2}{\sigma_i^2}, \quad \chi_{\text{SM}}^2|_{\text{d.o.f.}=20} = 12.40.$$

- In Scenario-I : $c_V = \sin(\beta - \alpha)$, $c_b = \xi_d^h$, $c_\tau = \xi_l^h$, $c_t = \xi_u^h$
-2HDM with 2 free parameters has 18 d.o.f.

Table 2. The best-fit points and the corresponding couplings in Scenario-1. Note that $\chi_{\text{SM}}^2/\text{d.o.f} = 0.62$.

Type	$\chi_{\text{min}}^2/\text{d.o.f}$	$\tan \beta$	$\cos(\beta - \alpha)$	c_V	c_b	c_τ	c_t
I-1	0.58	49.83	0.42	0.92	0.92	0.92	0.92
II-1	0.64	1.00	-0.047	1.00	1.05	1.05	0.95
X-1	0.60	4.71	0.40	0.92	1.00	-0.97	1.00
Y-1	0.62	4.94	0.40	0.92	-1.06	1.00	1.00



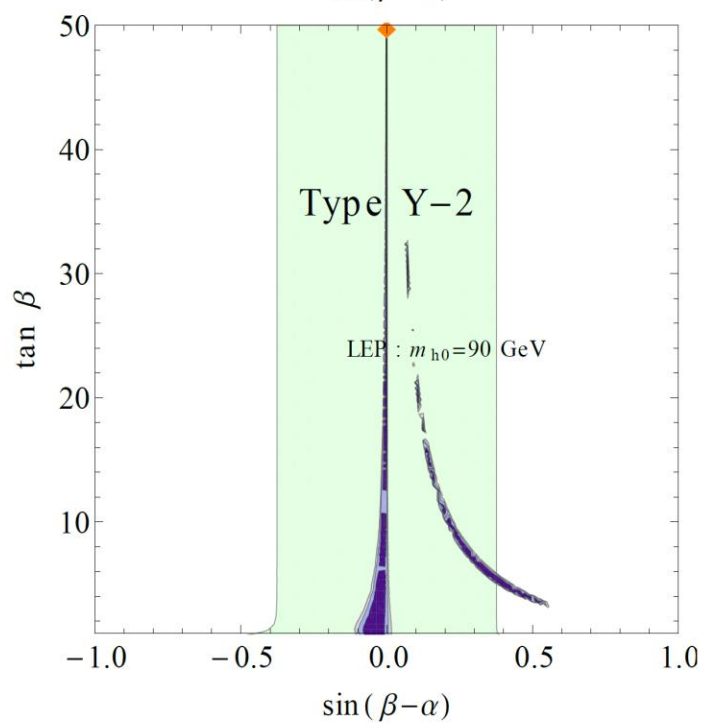
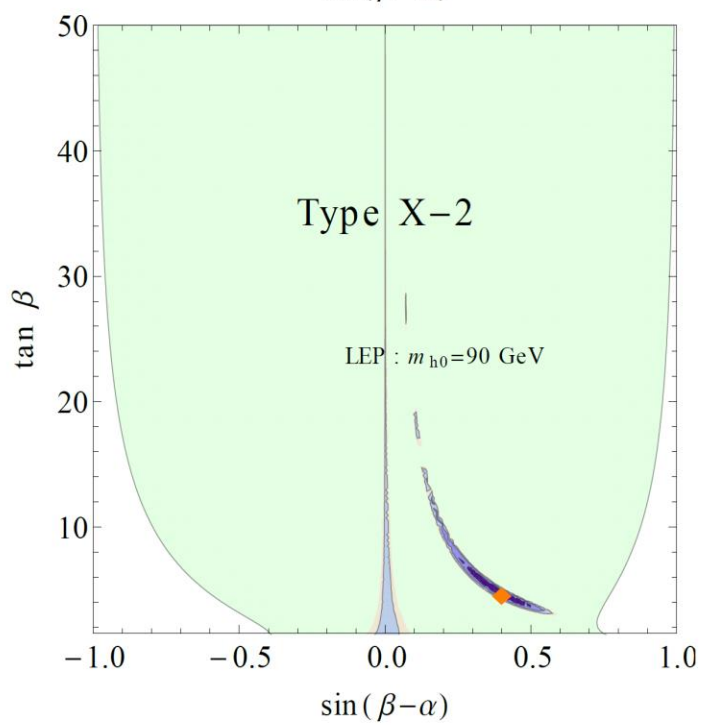
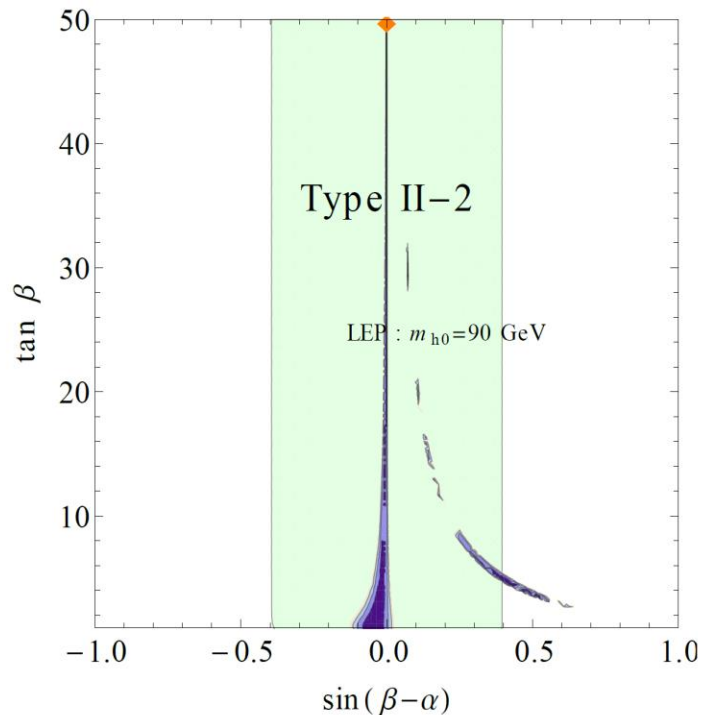
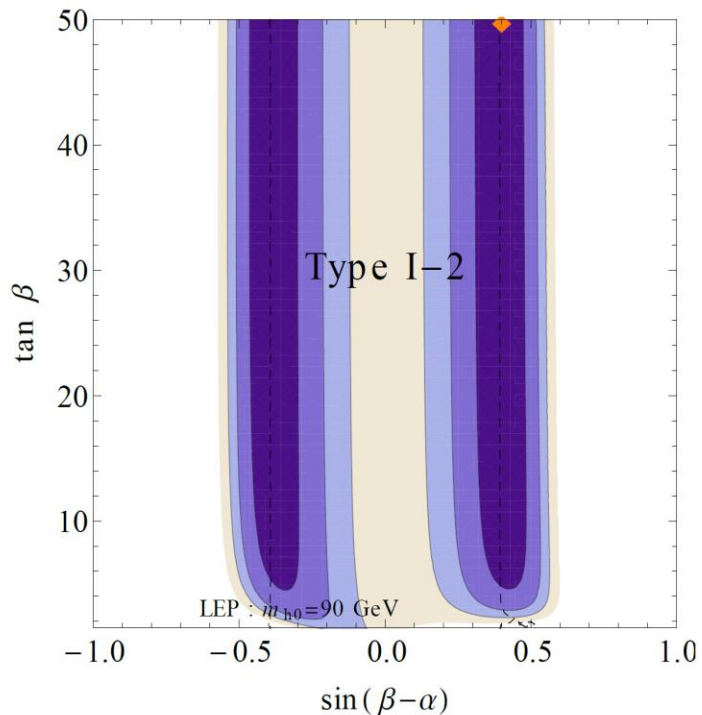
- In Scenario-II : $c_V = \sin(\beta - \alpha)$, $c_b = \xi_d^H$, $c_\tau = \xi_l^H$, $c_t = \xi_u^H$
- We demand that the event rate of flavor-independent jet decay of light higgs boson h^0 be smaller than the exp. Limit.

$$|\xi|^2 = |c_V|^2 \cdot \frac{\mathcal{B}(h^0 \rightarrow jj)}{\mathcal{B}(h_{\text{SM}} \rightarrow jj)} \quad \longrightarrow \quad \text{Constrained by LEP result}$$

(By taking $m_{h_0} = 90 \text{ GeV}$, $|\xi|^2 < 0.155$)

Table 3. The best-fit points and the corresponding couplings in Scenario-2.

Type	$\chi_{\text{min}}^2/\text{d.o.f}$	$\tan \beta$	$\sin(\beta - \alpha)$	c_V^H	c_b^H	c_τ^H	c_t^H
I-2	0.58	50.0	0.40	-0.92	-0.93	-0.93	-0.93
II-2	0.59	50.0	3×10^{-4}	1.00	1.01	1.01	1.00
X-2	0.60	4.72	0.40	-0.92	-1.00	0.97	-1.00
Y-2	0.59	50.0	3×10^{-4}	1.00	1.01	1.00	1.00



- Green regions: LEP allowed for $m_{h^0} = 90$ GeV
- Scenario-II (type-II & Y) has slightly better χ^2 due to that the process, $H^0 \rightarrow h^0 h^{0*} \rightarrow 4b$, possibly occurs for large $\tan \beta$.

Summary

- What we have learnt in this lecture
 - brief history of the Higgs mechanism and standard model.
 - how to extend the SM to model with two Higgs doublets
 - how to derive higgs masses and couplings in 2HDM
 - how 2HDM can be constrained
 - how signals of 2HDM can be probed at colliders
 - how 2HDM is compatible with recent LHC data.