2HDMs (Two Higgs doublet models)

PRESENTATION

Koji TSUMUTA (Nagoya U.)

Higgs as a Probe of New Physics 2013
Toyama, Japan

13-16/2/2013

2HDMs (Two Higgs doublet models)

Towards ILC

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- **Extended Higgs sector**
  - ρ parameter and FCNC
- **2HDM (two-Higgs-doublet model)**
  - Model & experimental status
- **Leptophilic 2HDM**
- **tanβ measurement**
- **Summary**

Introduction

Whether

"the" Higgs boson in the SM,

or "a" Higgs boson?

Introduction

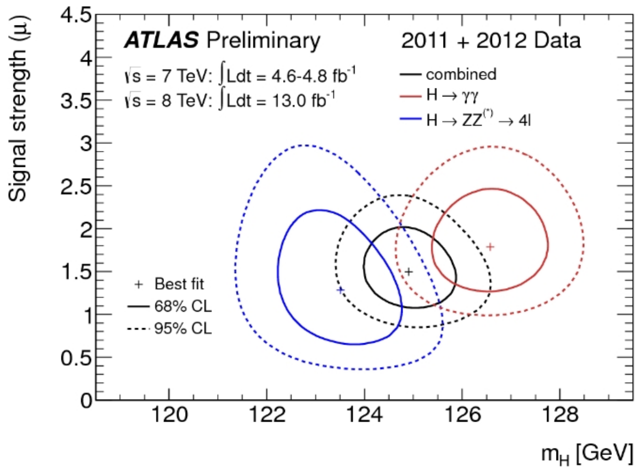
Whether

"the" Higgs boson in the SM,

or "a" Higgs boson,

or Higgs bosons,

or dilaton, etc…



Guideline for Ext. Higgs sector

- **Electroweak ρ parameter:**

$$\rho = \frac{\sum_\alpha (I_\alpha(I_\alpha+1) - Y_\alpha^2) v_\alpha^2}{\sum_\beta 2Y_\beta^2 v_\beta^2}$$

Veltman (1977)

  - Precision data suggests [ρ ~ 1]
  - SM predicts [ρ = 1] @ tree level

- **FCNC** (Flavor Changing Neutral Current)
  - No FCNC @ tree level
  - GIM suppression @ 1-loop

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- **Singlet/Doublet w/ Y=1/2 VEV (or Inert multiplets) preserves ρ=1**

- Minimal extension
- Mix w/ Higgs
- No contrib. to EWSB

- Not Higgs, but scalar
- DM candidate
- No contrib. to EWSB

Septet w/ Y=2
26-plet w/ Y=15/2
97-plet w/ Y=-28
362-plet w/ Y=-209/2
1351-plet w/ Y=-390
...

- (Main) contrib. to EWSB
- Yukawa int.
- (SUSY extension)

- **higher rep.** $(d \geq 3)$ **cannot give large contributions to EWSB**

Triplet, Quadruplet, ···

See next presentation by Dr. Yagyu

- No direct interaction w/ SM fermions

Guideline for Ext. Higgs sector

- **Electroweak ρ parameter:** $$\rho = \frac{\sum_\alpha (I_\alpha(I_\alpha+1) - Y_\alpha^2) v_\alpha^2}{\sum_\beta 2Y_\beta^2 v_\beta^2}$$

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- Yukawa int.
- (SUSY extension)

➡ **2HDM can give viable description of the low energy effective theory**

2HDM (two-Higgs-doublet model)

- 2HDM is an effective theory

$$\Phi_1 = \begin{pmatrix} \omega_1^+ \\ \frac{v_1+h_1+i\,z_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \omega_2^+ \\ \frac{v_2+h_2+i\,z_2}{\sqrt{2}} \end{pmatrix}$$

- Softly Z_2 broken 2HDM

$$V_{\rm 2HDM} = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left(m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{H.c.}\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \mathrm{H.c.}\right]$$

- 5 Physical Higgs bosons (assume CP inv.) $\quad m_3^2, \lambda_5$ real

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathrm{R}(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \mathrm{R}(\beta)\begin{pmatrix} z \\ A \end{pmatrix}, \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \mathrm{R}(\beta)\begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix}, \mathrm{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

2HDM

- Mass spectrum (in the nearly SM-like limit)

$$M^2 \equiv m_3^2/(\sin\beta\cos\beta)$$

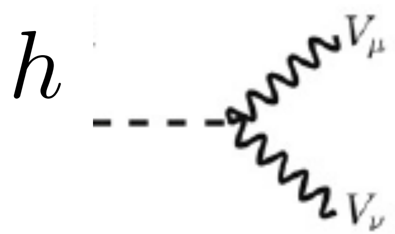
M^2 characterizes non-decoupling effects

(Only important for scalar interactions, eg., hH^+H^- coupling in $h\to\gamma\gamma$)

$$m_h^2 \sim 2\lambda v^2$$ **~ 125 GeV**

$$m_{H,A,H^\pm}^2 \sim M^2 + \frac{\lambda v^2}{2}$$ **~Not yet observed**

- gauge-gauge-Higgs coupling: $\sin(\beta-\alpha)$

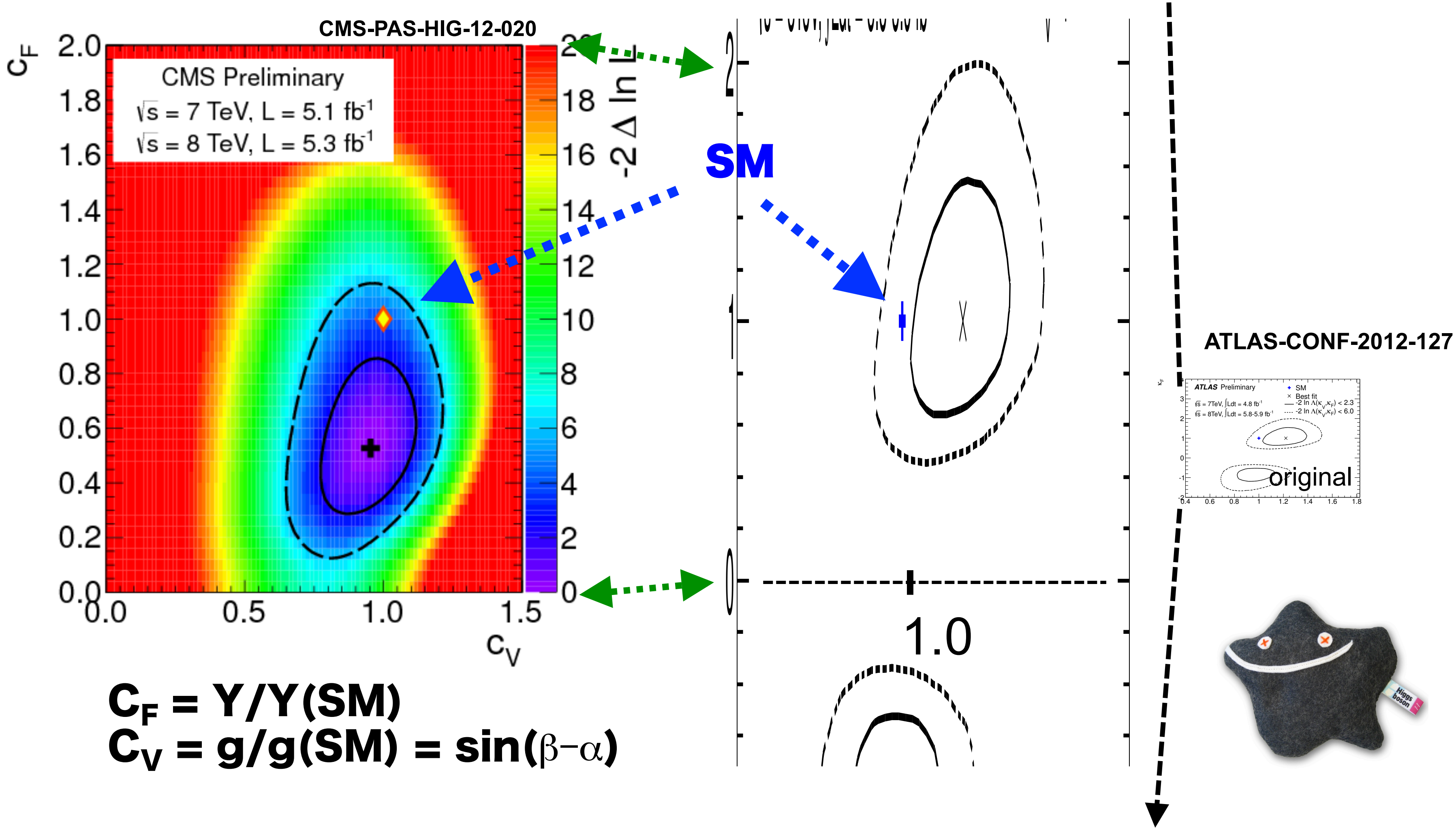


$$i\, g_V M_V \sin(\beta-\alpha) g_{\mu\nu}$$

- $\tan\beta$ ($=v_2/v_1$) is a free parameter

Is it SM-like?

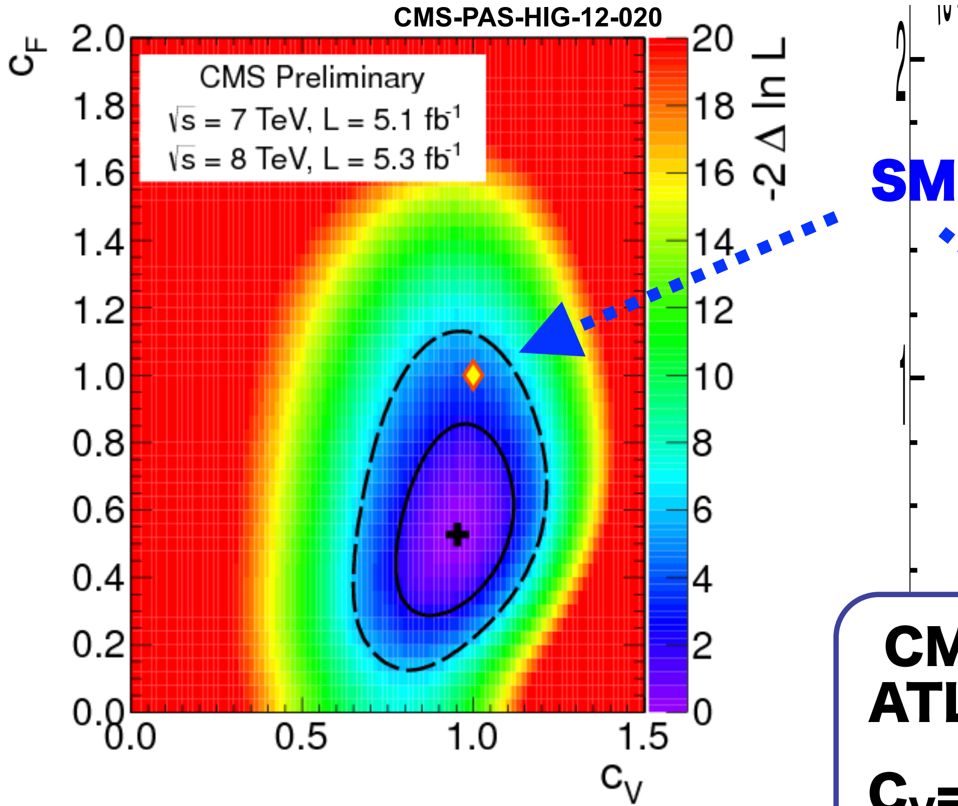
- 125 GeV boson

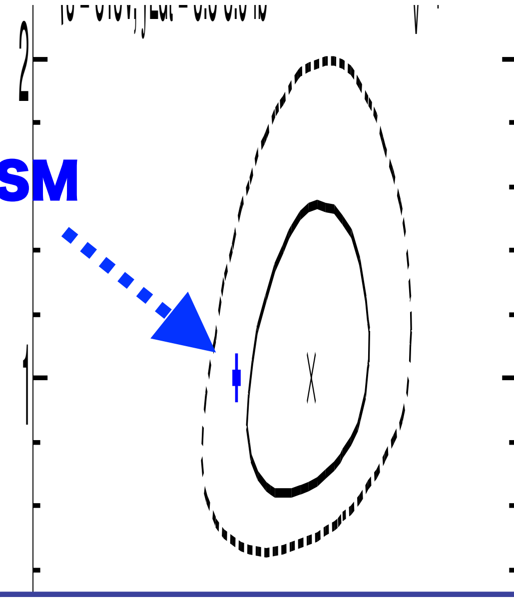


$C_F = Y/Y(SM)$
$C_V = g/g(SM) = \sin(\beta-\alpha)$

Is it SM-like?

- 125 GeV boson





CMS: $C_F < 1$, $C_V \sim 1$
ATLAS: $C_F \sim 1$, $C_V > 1$

$C_V = \sin(\beta-\alpha)$ in 2HDM

$\sin(\beta-\alpha)$ can be different from unity

SUSY Higgs search

- SUSY Higgs sector is the most popular 2HDM
  - Type-II Yukawa interaction w/ SUSY relation $\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$

$$\begin{cases} \Phi_u : u, \\ \Phi_d : d, \ell \end{cases}$$

$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \simeq 1 - \frac{2m_Z^2}{m_A^2\tan^2\beta}$$

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \simeq 1 + \frac{2m_Z^2}{m_A^2}$$

$$\frac{g_{Htt}}{g_{htt}^{\rm SM}} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) \simeq -\frac{1}{\tan\beta}$$

$$\frac{g_{Hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{H\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) \simeq \tan\beta$$

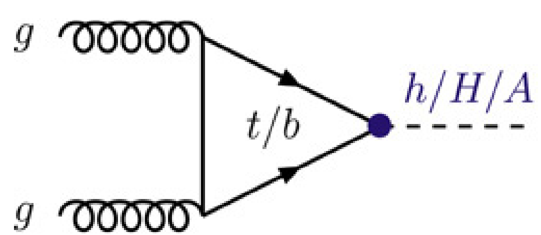
u $\quad$ d, ℓ

Yukawa int. for H, A, H^+ is suppressed/enhanced for large tanβ

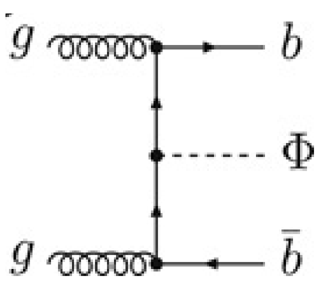
SUSY Higgs production @ LHC

$$\frac{g_{Hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{H\tau\tau}}{g_{h\tau\tau}^{\rm SM}} \simeq \tan\beta$$

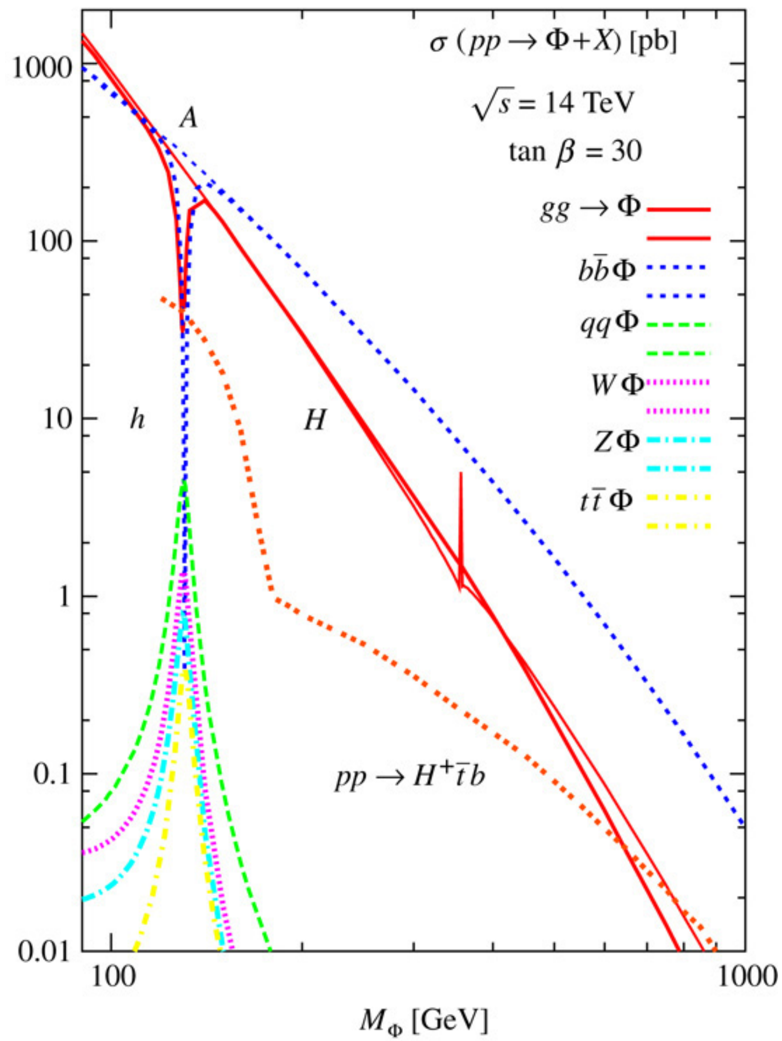
- gg→h/H/A wtith h/H/A→ττ



- bbh/H/A with h/H/A→ττ



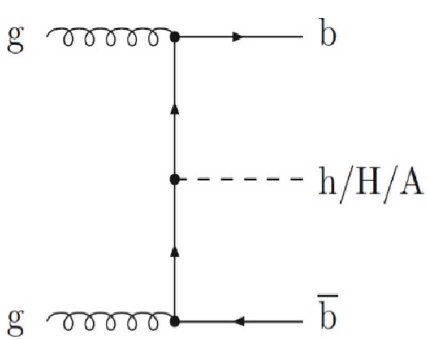
Djouadi (2008)

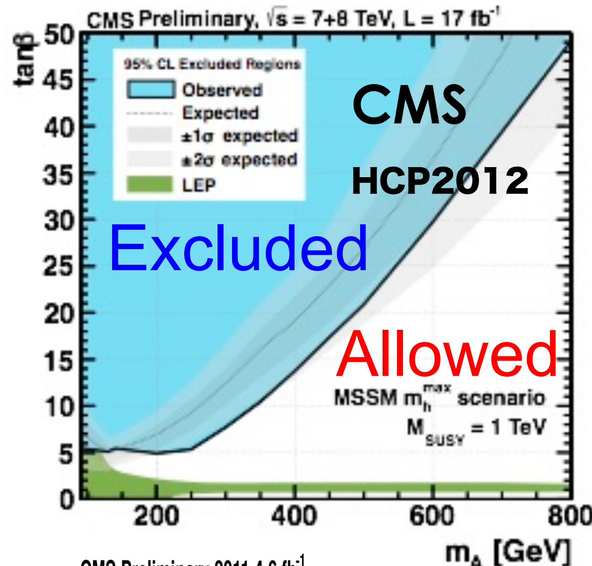


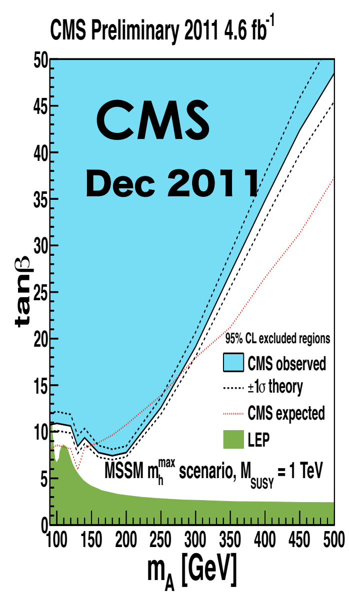
SUSY Higgs search @ LHC

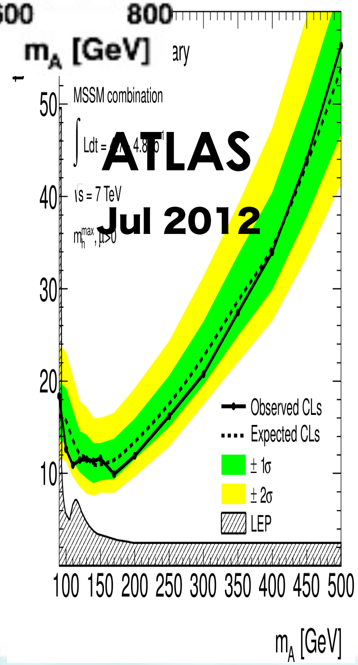
- LHC results

(H/A→ττ)







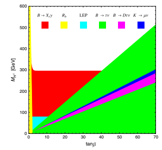


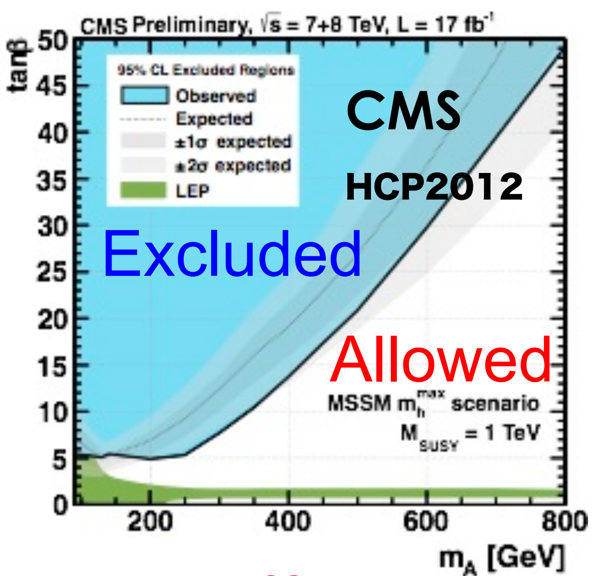
LHC is continuously excluding SUSY Higgs

Other constrains on 2HDM-II

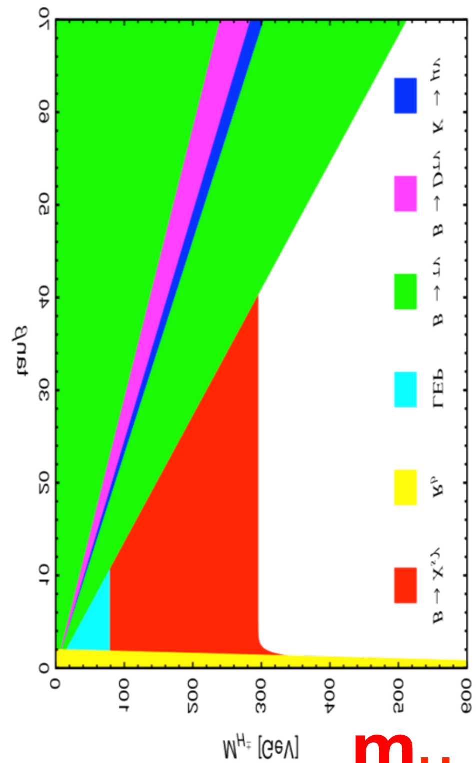
- *2HDM confronts FLAVOR DATA*

Haisch (2008)





m_A



$K \to \mu\nu$

$B \to D\tau\nu$

$B \to \tau\nu$

LEP

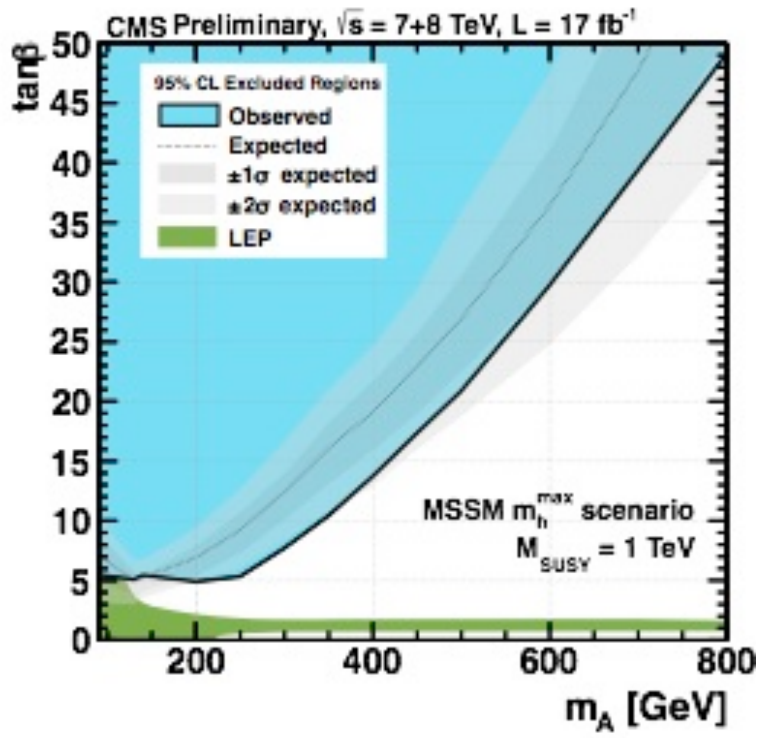
R_b

$B \to X_s\gamma$ [1-loop]

m_{H+}

Direct search exceeds FLAVOR DATA

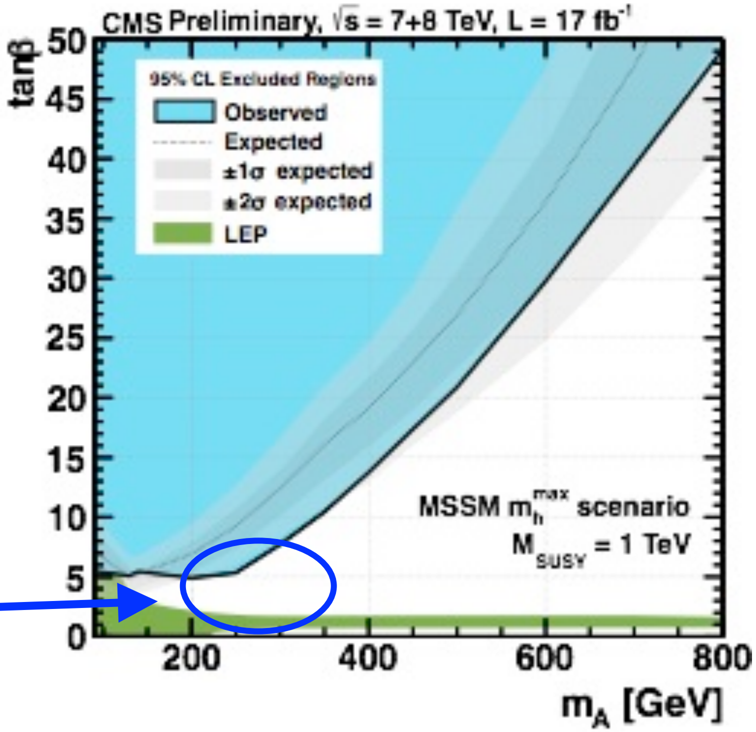
What's Next?

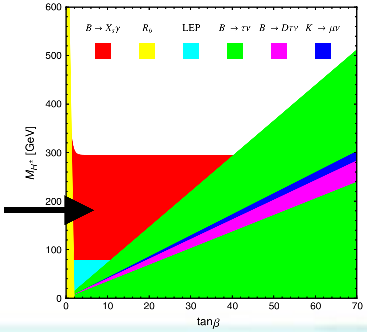


CMS Preliminary, √s = 7+8 TeV, L = 17 fb⁻¹
tanβ
95% CL Excluded Regions
Observed
Expected
±1σ expected
±2σ expected
LEP
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
0
5
10
15
20
25
30
35
40
45
50
200
400
600
800
m_A [GeV]

What's Next?

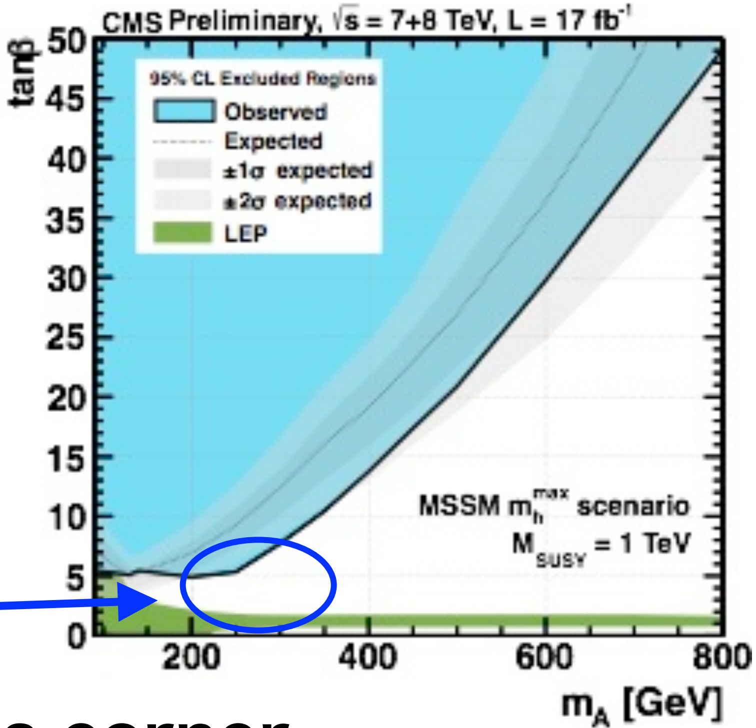
❖ Small m_A w/ small $\tan\beta$





Cancellation mechanism is necessary for $B \to X_s\gamma$

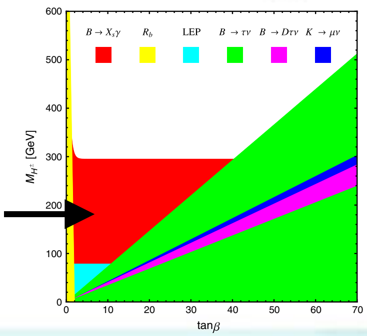
What's Next?



- Small m_A w/ small $\tan\beta$

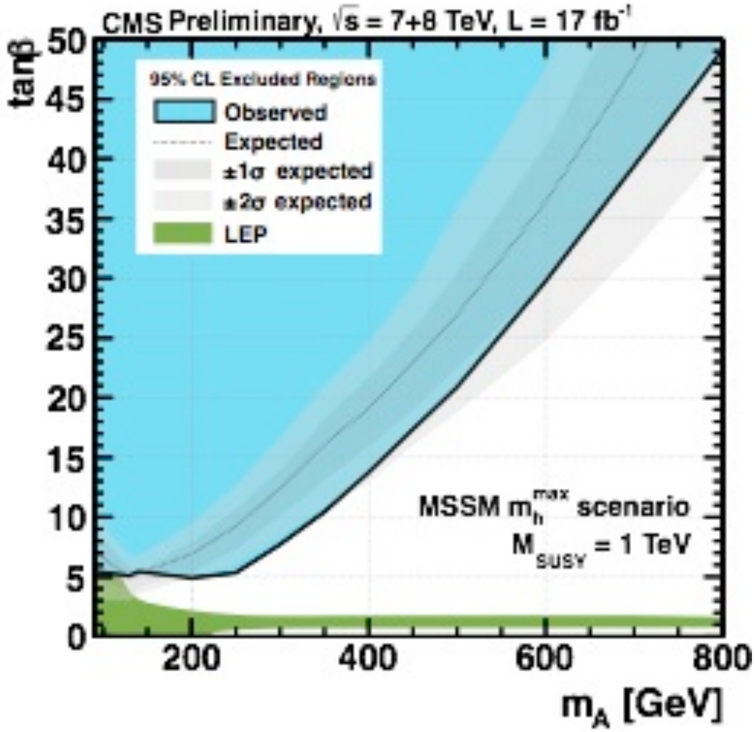
LHC upgrade will answer this corner

Cancellation mechanism is necessary for $B \to X_s\gamma$

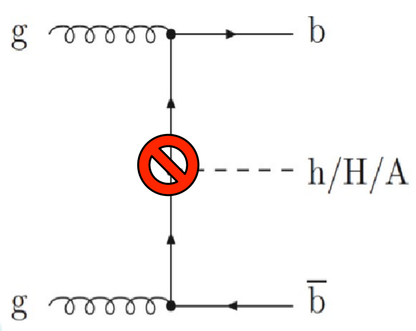


What's Next?

❖ **Leptophilic Higgs bosons**



Beat quark interaction !!
(Less LHC & B phys. Constraints)



Leptophilic 2HDM

Recall

- Electroweak ρ parameter: $$\rho = \frac{\sum_\alpha (I_\alpha(I_\alpha+1) - Y_\alpha^2) v_\alpha^2}{\sum_\beta 2Y_\beta^2 v_\beta^2}$$

Veltman (1977)

  - Precision data suggests [ρ ~ 1]
  - SM predicts [ρ = 1] @ tree level

- FCNC (Flavor Changing Neutral Current)
  - No FCNC @ tree level
  - GIM suppression @ 1-loop

FCNC problem of 2HDM

- Flavor changing neutral current (FCNC)

$$\mathcal{L} = \overline{L}\left(Y_{\ell 1}\Phi_1 + Y_{\ell 2}\Phi_2\right)\ell_R + \mathrm{H.c.}$$

Yukawa int. is not simultaneously diagonalized with mass matrix.

→ Generate tree level FCNC(, highly constrained by data)

- Adding extra Z2 sym. to avoid FCNC

$$\begin{array}{ll} \Phi_1 \to +\Phi_1, & L \to +L \\ \Phi_2 \to -\Phi_2, & \ell_R \to -\ell_R \end{array}$$

$$\mathcal{L} = \overline{L}\left(\times + Y_{\ell 2}\Phi_2\right)\ell_R + \mathrm{H.c.}$$

4 types of Yukawa int.

- 4 independent combinations of Z2 charges

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

- Type-II: 2HDM structure in SUSY

$$\mathcal{L} = +\overline{Q} Y_u u_R H_u + \overline{Q} Y_d d_R H_d + \overline{L} Y_\ell \ell_R H_d + \text{H.c.}$$

4 types of Yukawa int.

- 4 independent combinations of Z2 charges

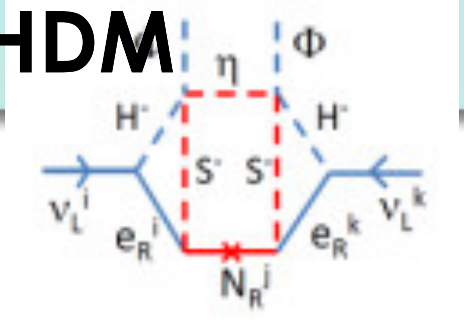
	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

- Type-X: Leptophilic 2HDM for tanβ>1

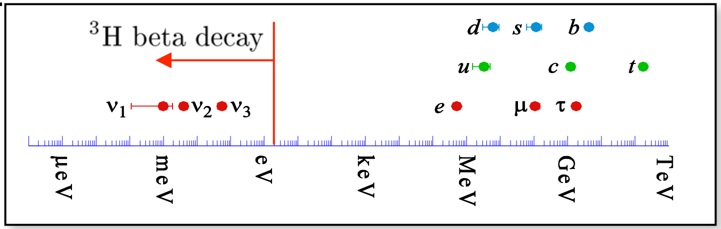
$$\mathcal{L} = +\overline{Q}Y_u u_R H_q + \overline{Q}Y_d d_R H_q + \overline{L}Y_\ell \ell_R H_\ell + \text{H.c.}$$

Higgs doublets distinguish quarks and leptons!!

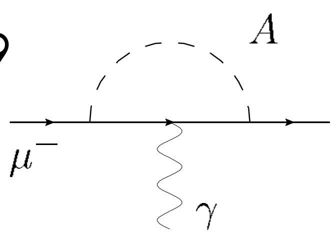
Leptophilic Higgs in 2HDM

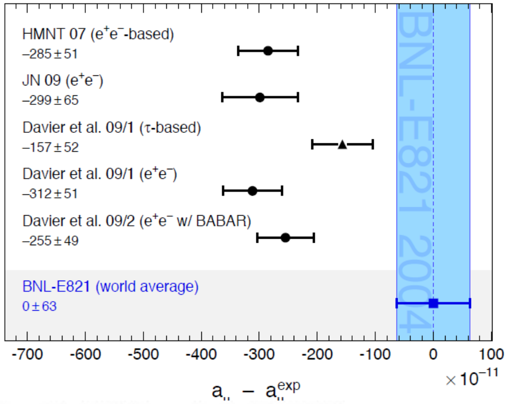


- **Tiny neutrino mass**
  ex. 3-loop radiative seesaw w/ light H+/-
  by Aoki et al. PRL102:051805,2009

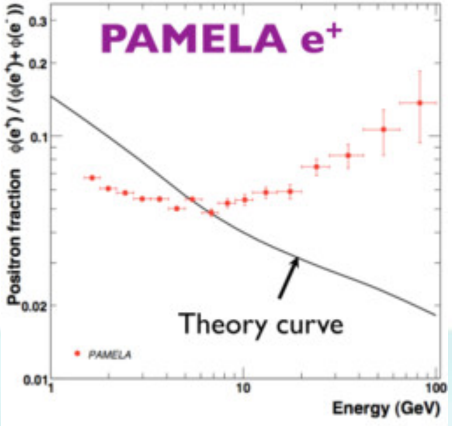


- **μ magnetic moment**
  light A(CP odd) w/ large tanB
  by Cao et al. PRD80:071701,2009





- **e⁺ excess @ PAMELA, FERMI**
  scalars as a messenger to DM
  by Goh et al. JHEP 0905:097,2009

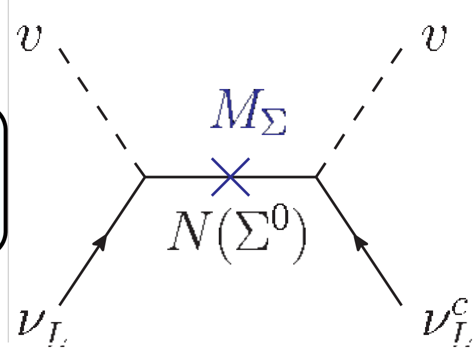


DM DM → Φ' Φ' → ττττ

A model for tiny neutrino masses

◻ Gauged Type-III seesaw

$$\mathcal{L} = +\overline{Q} Y_u u_R \widetilde{H}_q + \overline{Q} Y_d d_R H_q + \overline{L} Y_\ell \ell_R H_\ell + \text{H.c.}$$



[B-L like] U(1) extension [in Type-I seesaw]

◻ Anomaly cancellation requires 2HDM-X

Charge assignment:

$$(u,d)_L \sim (3,2,1/6;n_1), \quad u_R \sim (3,1,2/3;n_2), \quad d_R \sim (3,1,-1/3;n_3),$$

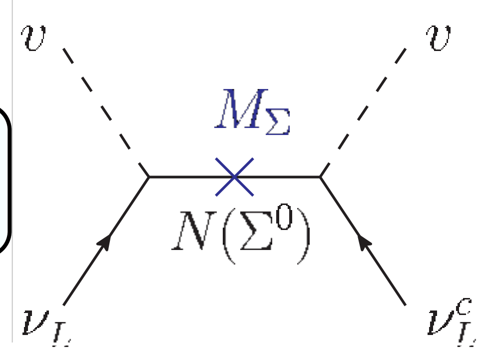
$$(\nu,e)_L \sim (1,2,-1/2;n_4), \quad e_R \sim (1,1,-1;n_5), \quad \Sigma_R \sim (1,3,0;n_6).$$

U(1)x scalar: $\chi^0 \sim (1,1,0;-2n_6)$

A model for tiny neutrino masses

- Gauged Type-III seesaw

$$\mathcal{L} = +\overline{Q}Y_u u_R \widetilde{H}_q + \overline{Q}Y_d d_R H_q + \overline{L}Y_\ell \ell_R H_\ell + \text{H.c.}$$



[B-L like] U(1) extension [in Type-I seesaw]

- **Anomaly cancellation requires 2HDM-X**

Axial-vector anomaly:

$$[SU(3)]^2 U(1)_X : \quad +2n_1 - n_2 - n_3 = 0$$

$$[SU(2)]^2 U(1)_X : \quad +3(\tfrac{1}{2})n_1 + (\tfrac{1}{2})n_4 - (2)n_6 = 0$$

$$[U(1)_Y]^2 U(1)_X : \quad +6(\tfrac{1}{6})^2 n_1 - 3(\tfrac{2}{3})^2 n_2 - 3(-\tfrac{1}{3})^2 n_3 + 2(-\tfrac{1}{2})^2 n_4 - (-1)^2 n_5 = 0$$

$$U(1)_Y [U(1)_X]^2 : \quad +6(\tfrac{1}{6})n_1^2 - 3(\tfrac{2}{3})n_2^2 - 3(-\tfrac{1}{3})n_3^2 + 2(-\tfrac{1}{2})n_4^2 - (-1)n_5^2 = 0$$

$$[U(1)_X]^3 : \quad +6n_1^3 - 3n_2^3 - 3n_3^3 + 2n_4^3 - n_5^3 - 3n_6^3 = 0$$

gravitational anomaly:

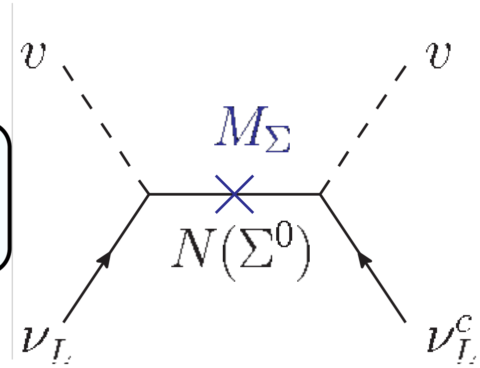
$$+6n_1 - 3n_2 - 3n_3 + 2n_4 - n_5 - 3n_6 = 0$$

Unique solution exists!!

A model for tiny neutrino masses

- Gauged Type-III seesaw

$$\mathcal{L} = +\overline{Q}Y_u u_R \widetilde{H}_q + \overline{Q}Y_d d_R H_q + \overline{L}Y_\ell \ell_R H_\ell + \text{H.c.}$$



[B-L like] U(1) extension [in Type-I seesaw]

- **Anomaly cancellation requires 2HDM-X**

possible Yukawa int:

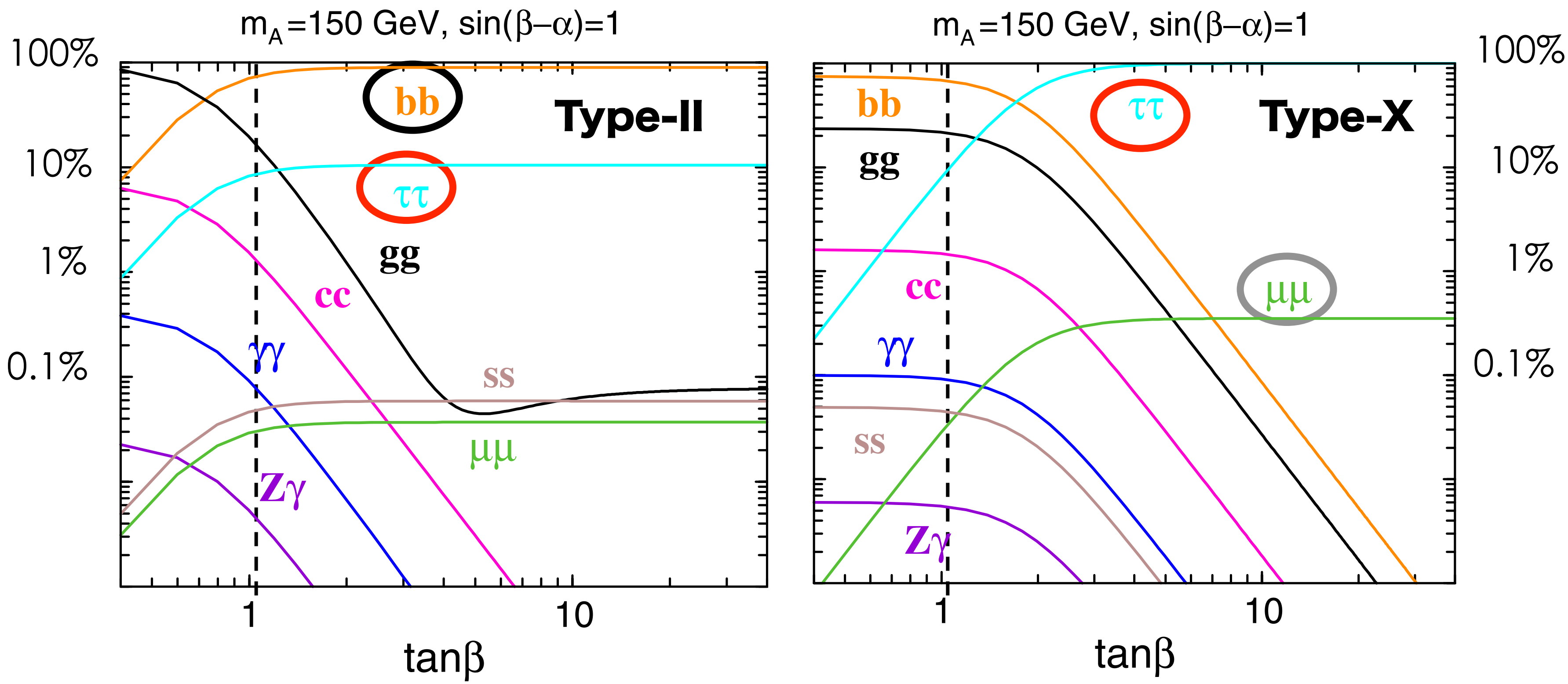
$$n_1 - n_3 = n_2 - n_1 = n_6 - n_4 = \frac{3}{4}(n_1 - n_4), \quad n_4 - n_5 = \frac{1}{4}(9n_1 - n_4),$$

$$H_q \qquad\qquad H_\ell$$

2HDM-X can also be a low energy effective theory

Higgs decays in 2HDMs

Aoki, Kanemura, KT, Yagyu (2009)



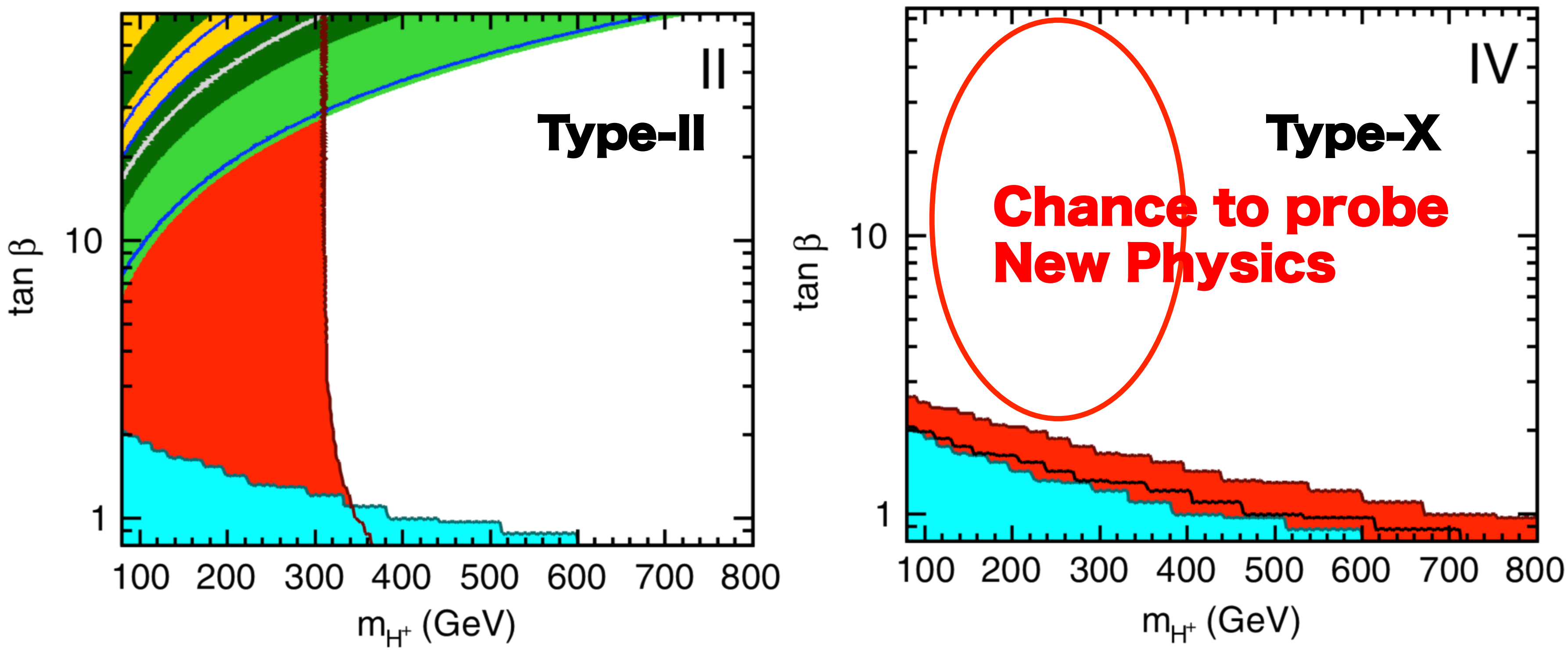
2HDM-X： Enhance leptonic Yukawa int. by tanβ

- More than 99% of H/A decay into ττ
- Sizable μμ [$(m_\mu/m_\tau)^2$=1/300] mode

Flavor constraint on 2HDM-X

- No LHC results, and weaker flavor constraints

Mahmoudi, Stal (2009)

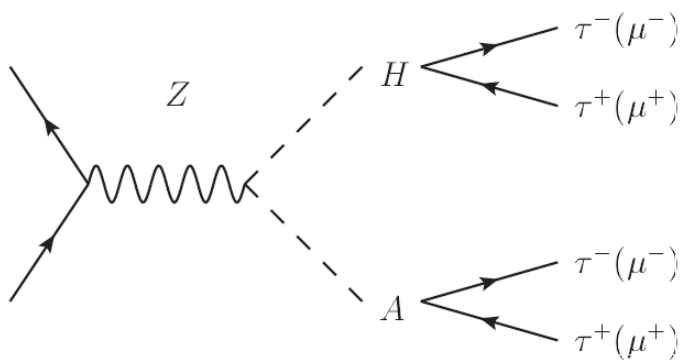


small m_{H+} and
very large tanβ are allowed

2HDM-X @ colliders

Kanemura, KT, Yokoya (2012)

- DY production with leptonic decay modes

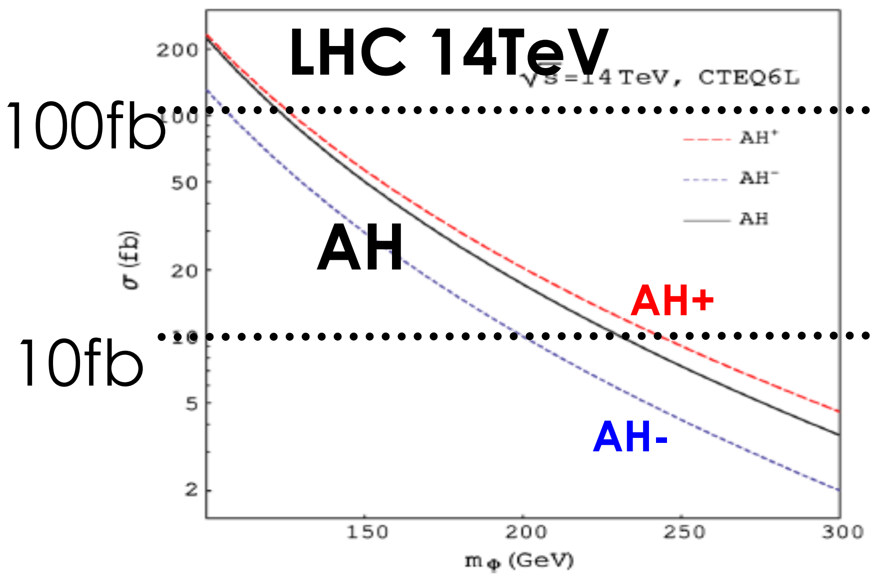


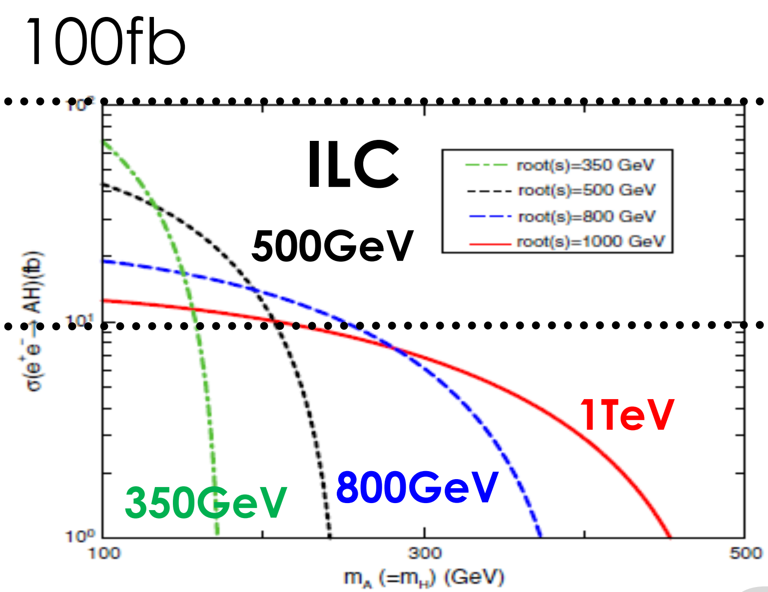
Multi-tau signature

4τ: more than 99%

$2\mu 2\tau$: $\sigma(4\tau)$ x 1/300 x 2!

Cross sections are O(10-100)fb



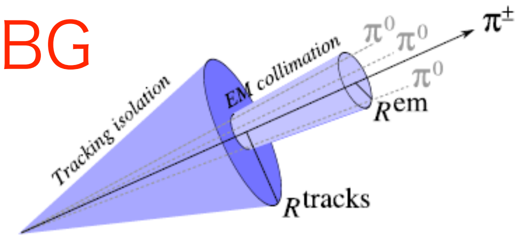


2HDM-X @ LHC

Kanemura, KT, Yokoya (2012)

◻ High multiplicity of tau jet reduces BG

τ ID is important (1 or 3 prong, narrow cone, less QCD activity)



$4\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
Pre-selection	324.	52.8	147.	797.	5105.	0.1	4.7
$p_T^{\tau_h} > 40$ GeV	67.2	4.9	2.0	14.7	21.7	1.9	9.4
$\not{E}_T > 30$ GeV	48.6	4.4	1.1	7.6	10.4	2.8	9.3
$H_T^{\rm jet} < 50$ GeV	34.2	3.4	0.5	0.8	8.2	3.9	8.7
$H_T^{\rm lep} > 350$ GeV	27.6	2.7	0.4	0.5	3.1	7.5	9.3

Simulation results:
An example for 4τ → $4\tau_h$
m_A=130GeV, m_H=170GeV

→ The excess can be seen!!

But, mass reconstruction is difficult due to missing ν's

→"HA→2μ2τ" is reconstructable (w/ collinear approx.)

Huge lumi. is necessary due to $\mathcal{B}^{\mu\mu}/\mathcal{B}^{\tau\tau} \times 2! \simeq 0.7\%$

2HDM-X @ LC

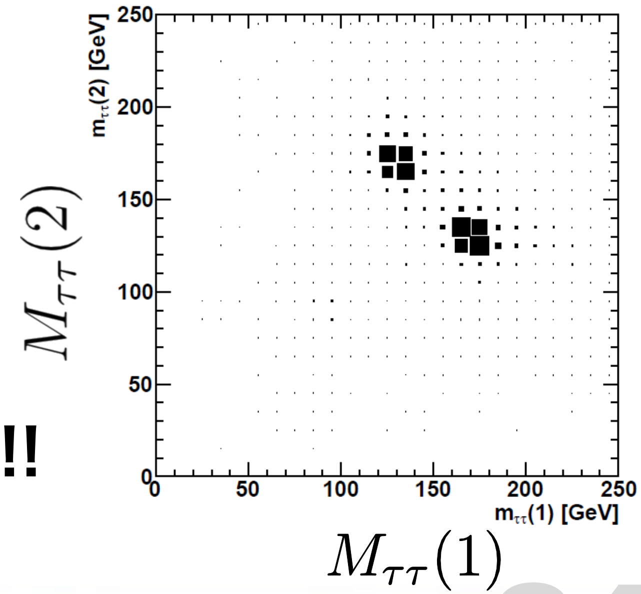
Kanemura, KT, Yokoya (2012)

- 4τ momentum are fully reconstructable from taujets & missing ν's [We know initial 4 momenta @ LC (only p_T @ LHC)]

$4\tau_h$ event analysis	HA	VV	$t\bar{t}$	S (100 fb^{-1})
Pre-selection	300.	10.6	1.2	38.
$0 \leq z_{1-4} \leq 1$	251.	6.2	0.1	38.
$(m_Z)_{\tau\tau} \pm 20$ GeV	238.	1.8	0.	43.

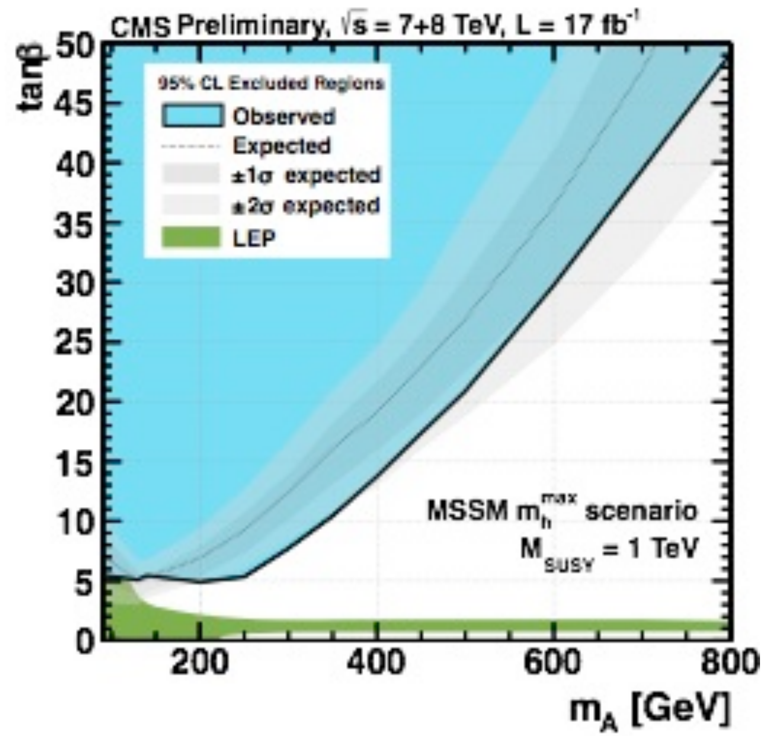
Simulation result:
An example for $4\tau \rightarrow 4\tau_h$
m_A=130GeV, m_H=170GeV

for 5σ ~ 2/fb @ LC



Not only mass reconstruction, but also
direct probe of pair production!!

What Else?

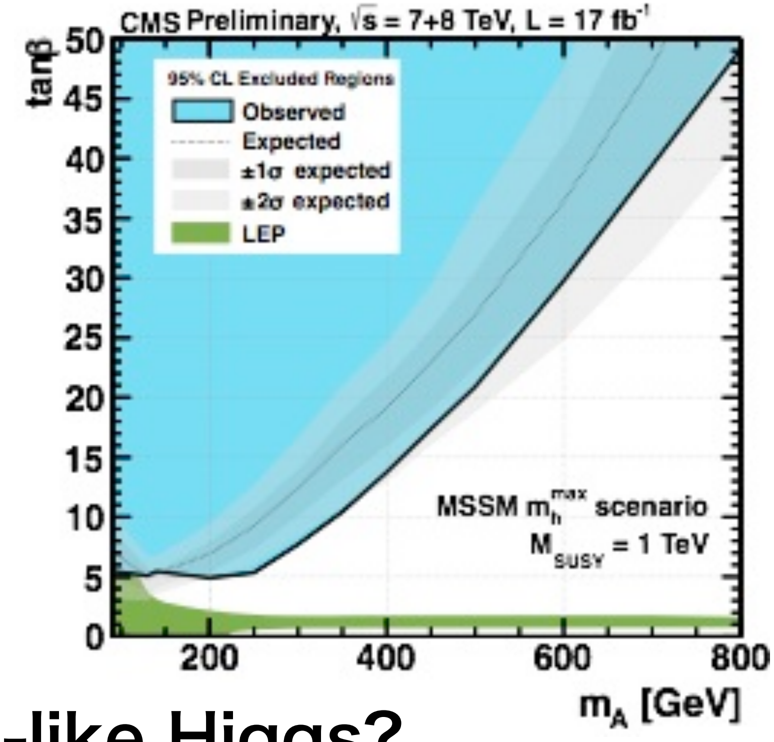


CMS Preliminary, $\sqrt{s}$ = 7+8 TeV, L = 17 fb^{-1}
95% CL Excluded Regions
Observed
Expected
±1σ expected
±2σ expected
LEP
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
tanβ
0
5
10
15
20
25
30
35
40
45
50
200
400
600
800
m_A [GeV]

What Else?

❖ **Precision SM-like Higgs study**

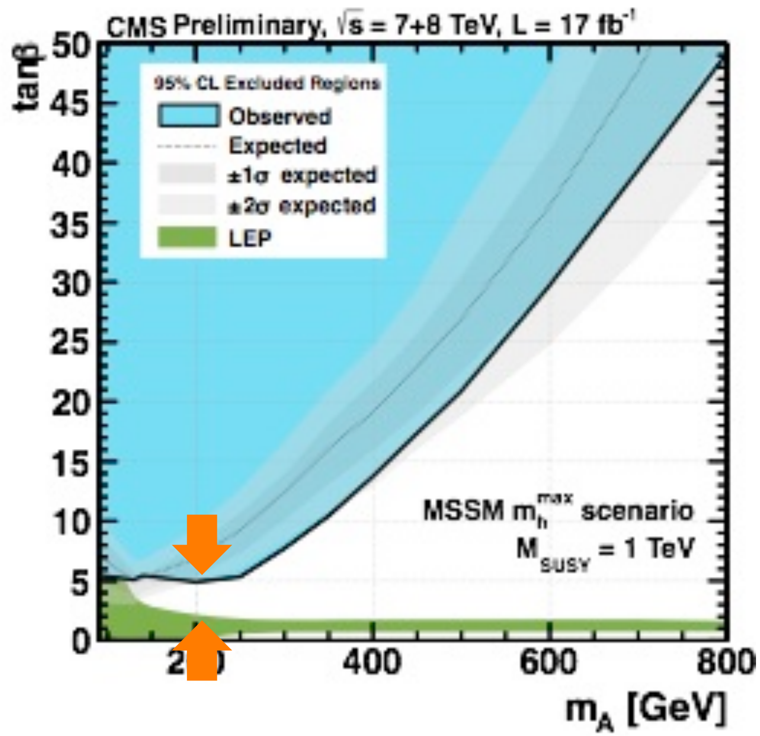
Can we probe 2HDM via SM-like Higgs?



tanβ @ LHC

Once Extra Higgs

is discovered, then…



For example,

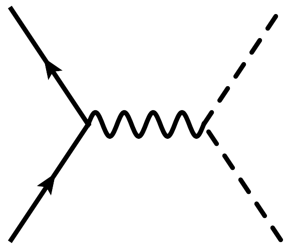
m_A=200GeV → 3 < tanβ < 5

by assuming MSSM(2HDM-II)

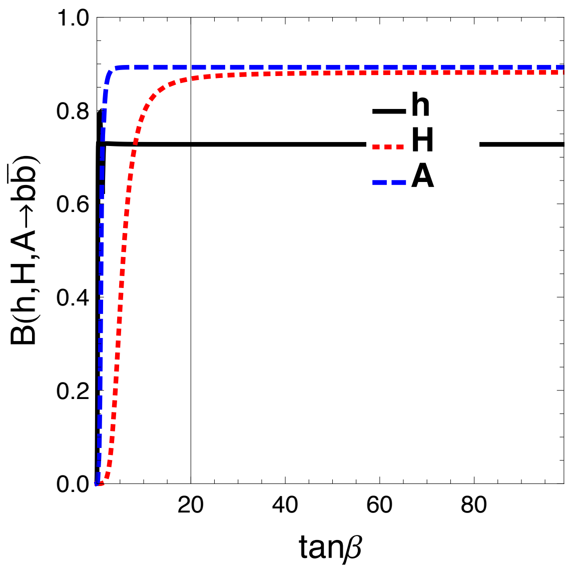
tanβ measurement

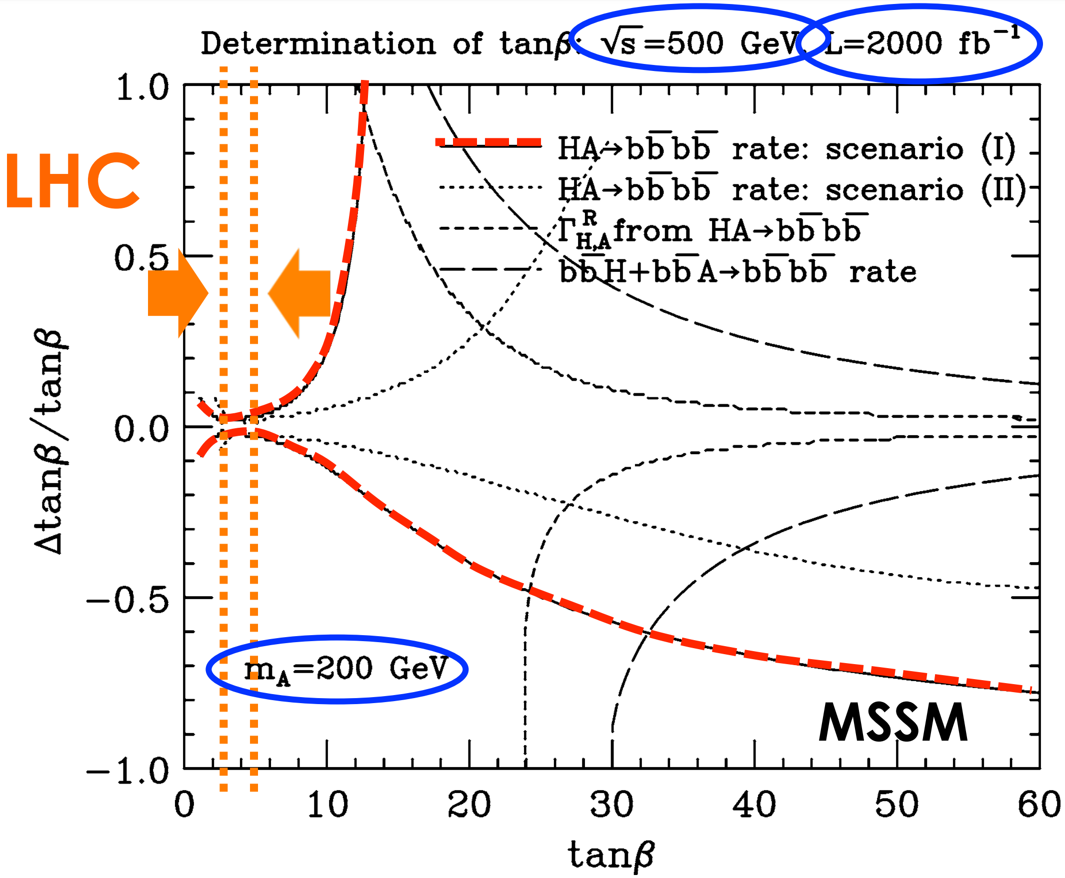
tanβ in MSSM @ LC

Gunion et.al. (2003)



HA production @ LC



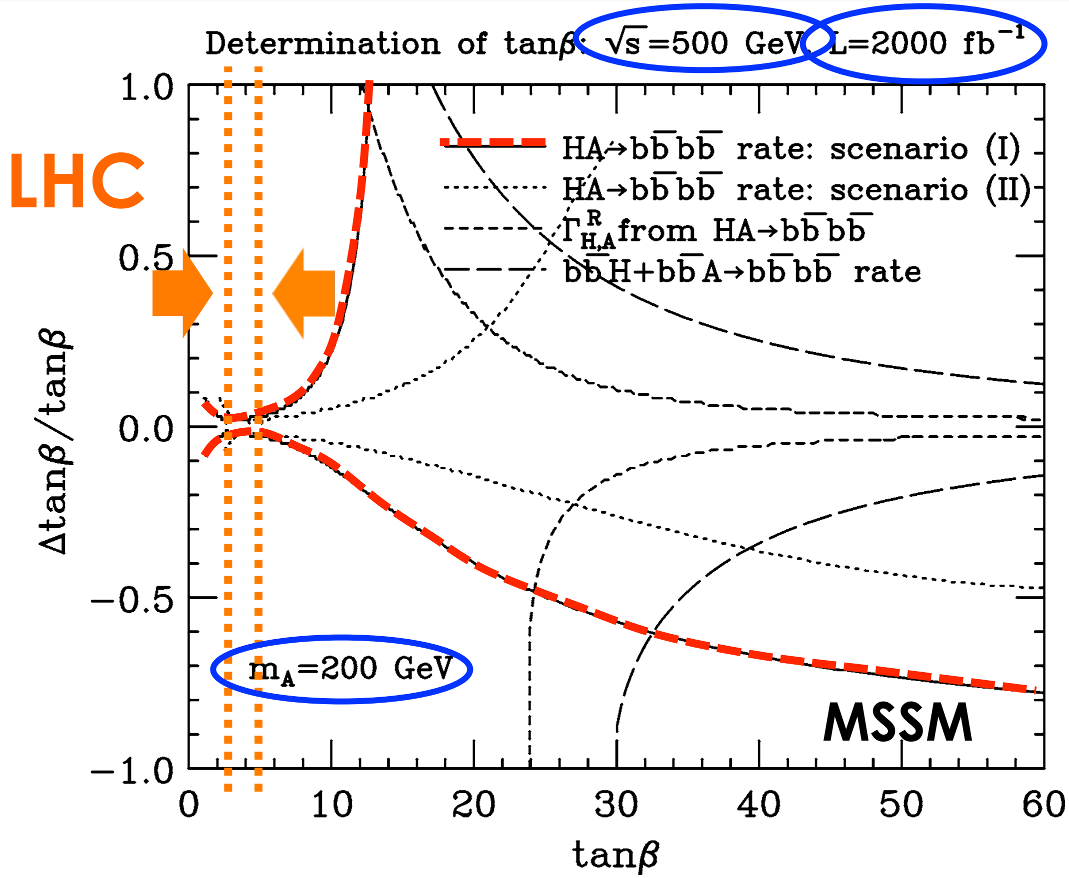


B_H^{bb} rapidly depends on tanβ

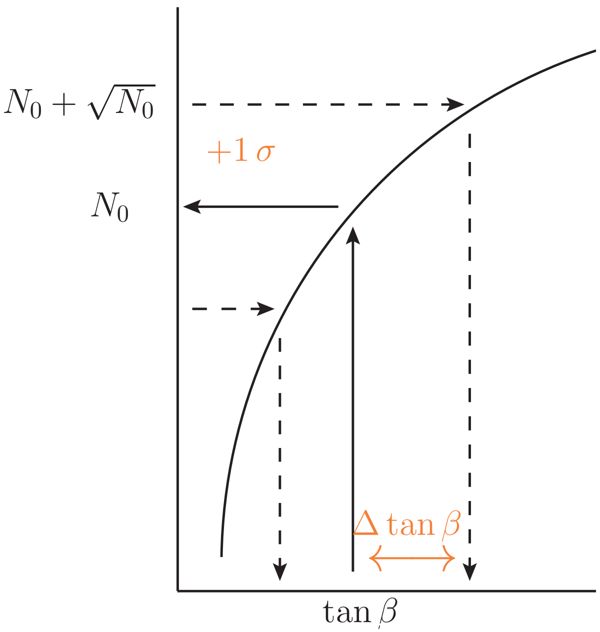
→ BR measurement can probe tanβ very precisely

tanβ in MSSM @ LC

Gunion et.al. (2003)



Definition of 1σ sensitivity



B_H^{bb} rapidly depends on tanβ

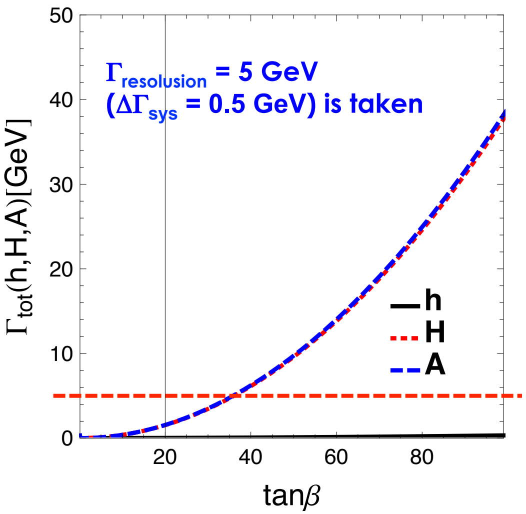
→ BR measurement can probe tanβ very precisely

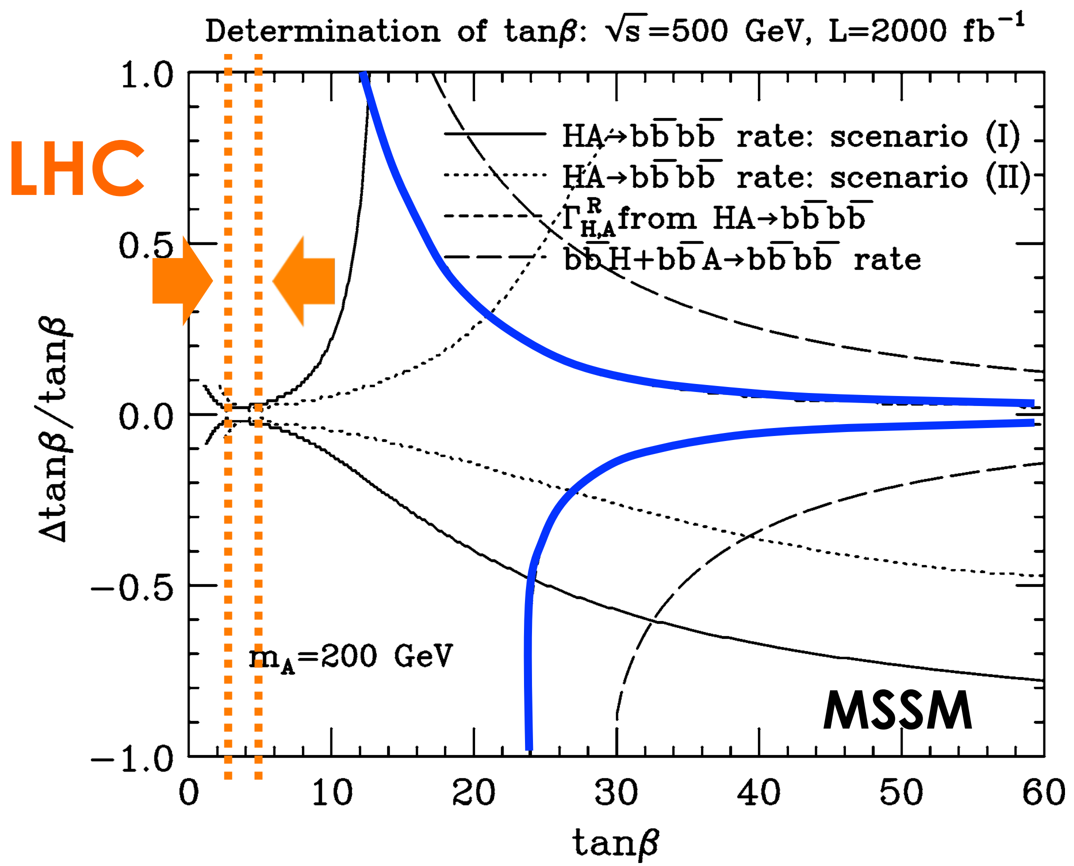
tanβ @ LC

Although, LHC already excluded

Width measurement

$$\Gamma_{\rm tot}^{H,A} \simeq N_C \frac{G_F m_{H,A} m_b^2}{4\sqrt{2}\pi} \tan^2\beta$$



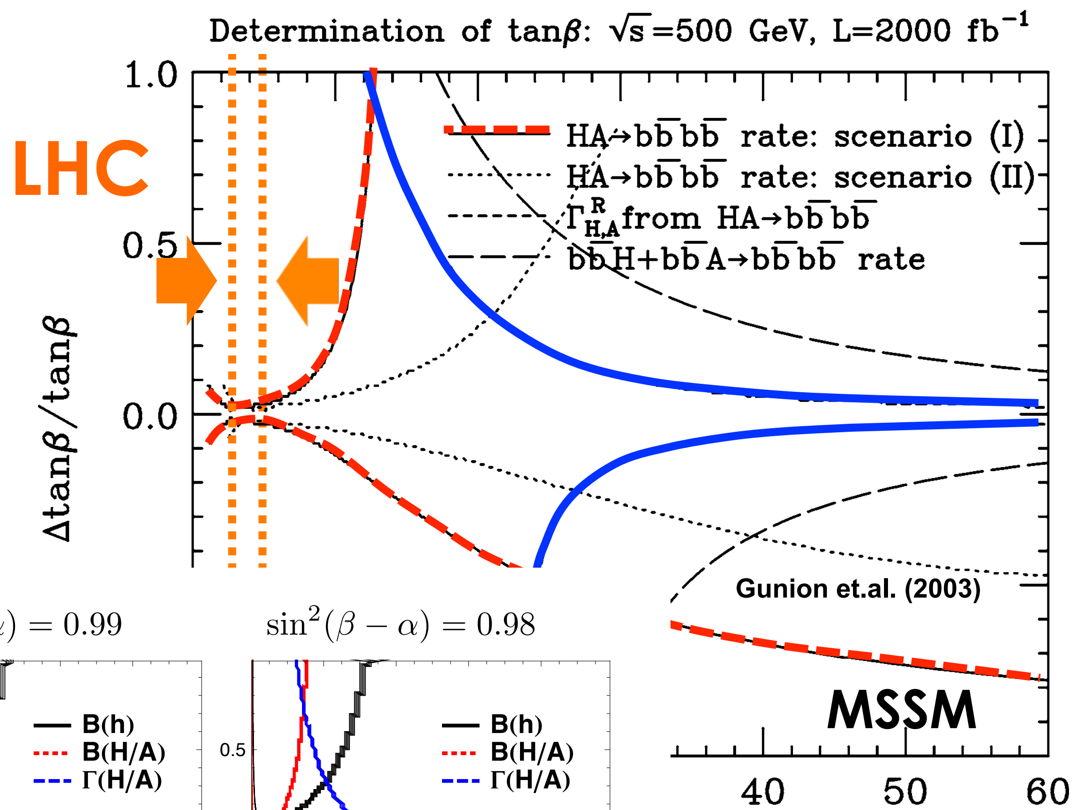


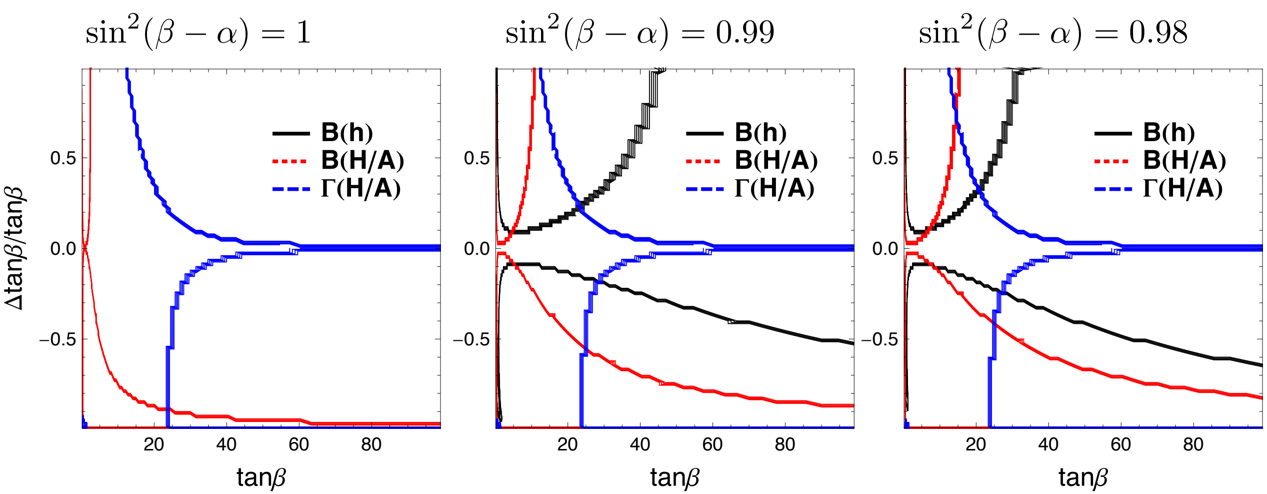
Width measurement is sensitive **for high tanβ**

tanβ in 2HDM-II @ LC

- **Without SUSY relation**

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$





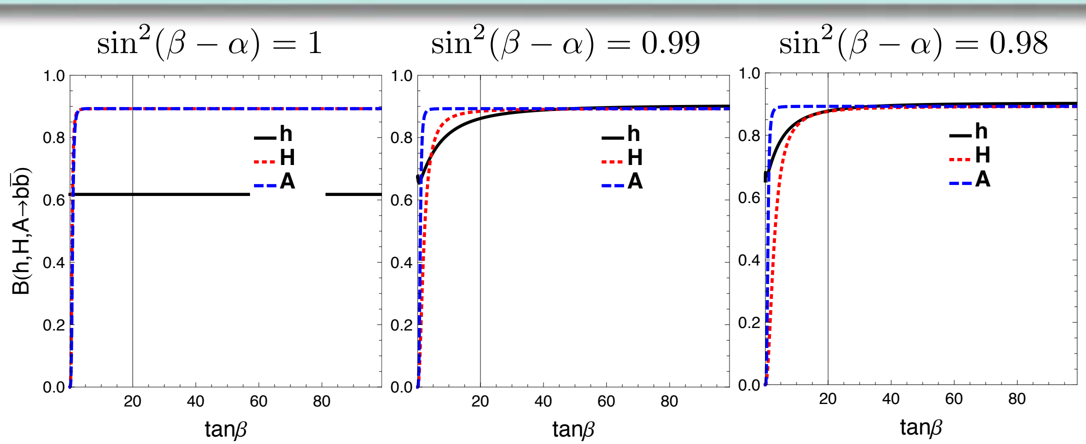
2HDM-II

Kanemura, KT, Yokoya, Yagyu

tanβ in 2HDM-II @ LC

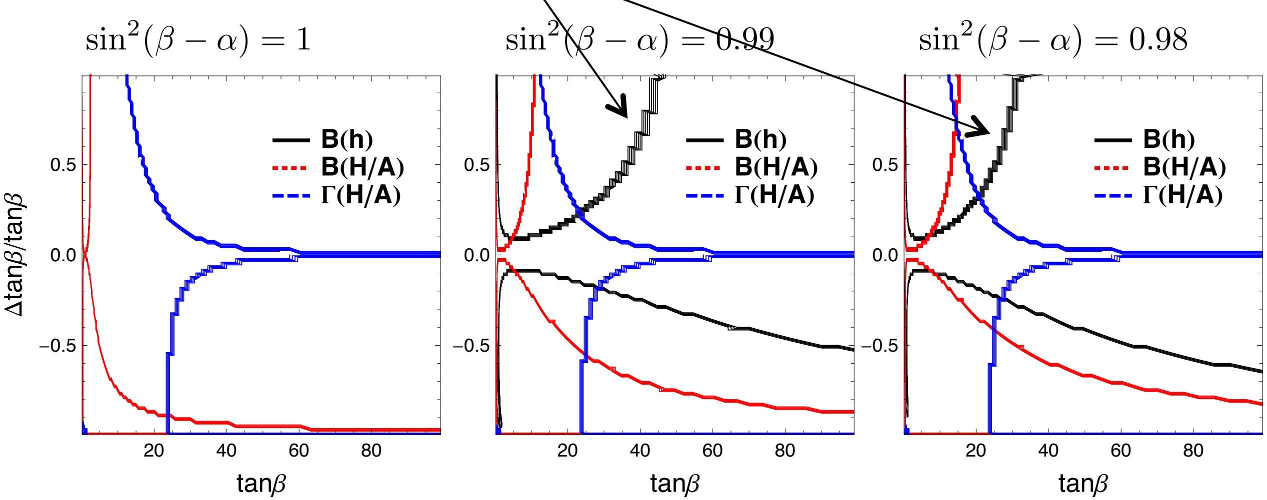
❖ **Without SUSY relation**

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$



SM-like Higgs decay BRs strongly depend on tanβ

You may notice new BLACK curves



Assume Δ(σ x BR)/(σ x BR) = 1%
[Ref: DBD, 250GeV, 250/fb]

For HA [500GeV, 2000/fb]

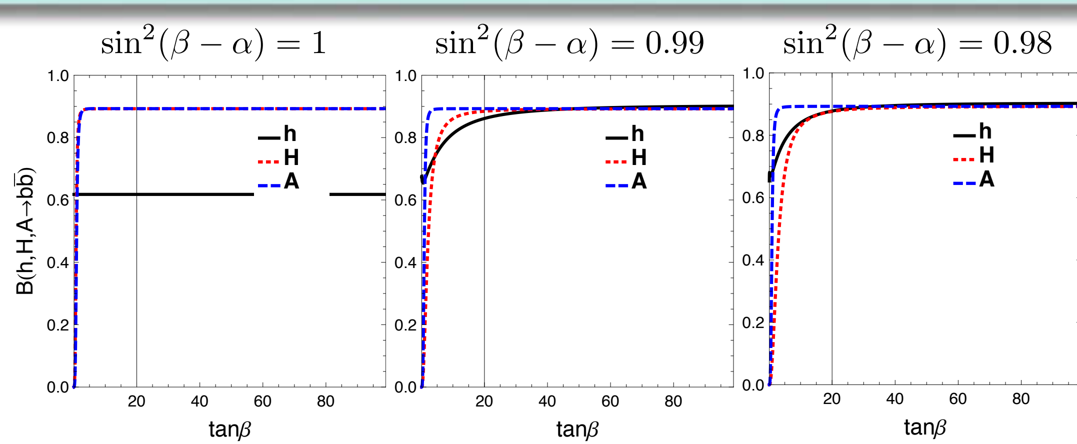
2HDM-II

Kanemura, KT, Yokoya, Yagyu

tanβ in 2HDM-II @ LC

❖ **Without SUSY relation**

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$



SM-like Higgs decay BRs strongly depend on tanβ

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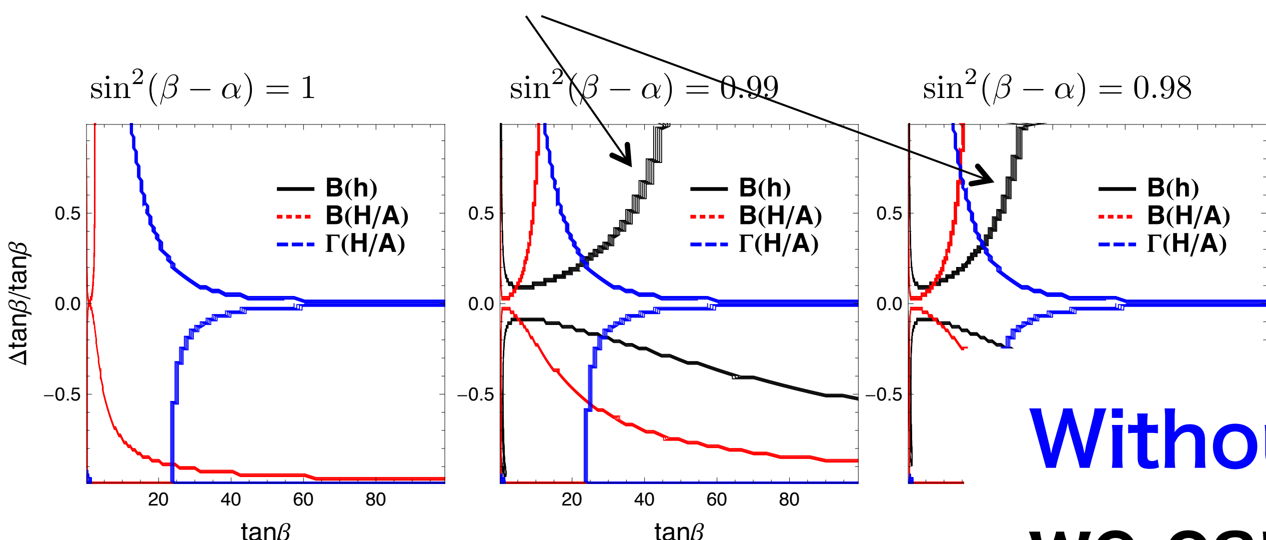


2HDM-II

Kanemura, KT, Yokoya, Yagyu

Initial stage of LC

Assume Δ(σ x BR)/(σ x BR) = 1%
[Ref: DBD, 250GeV, 250/fb]

For HA [500GeV, 2000/fb]

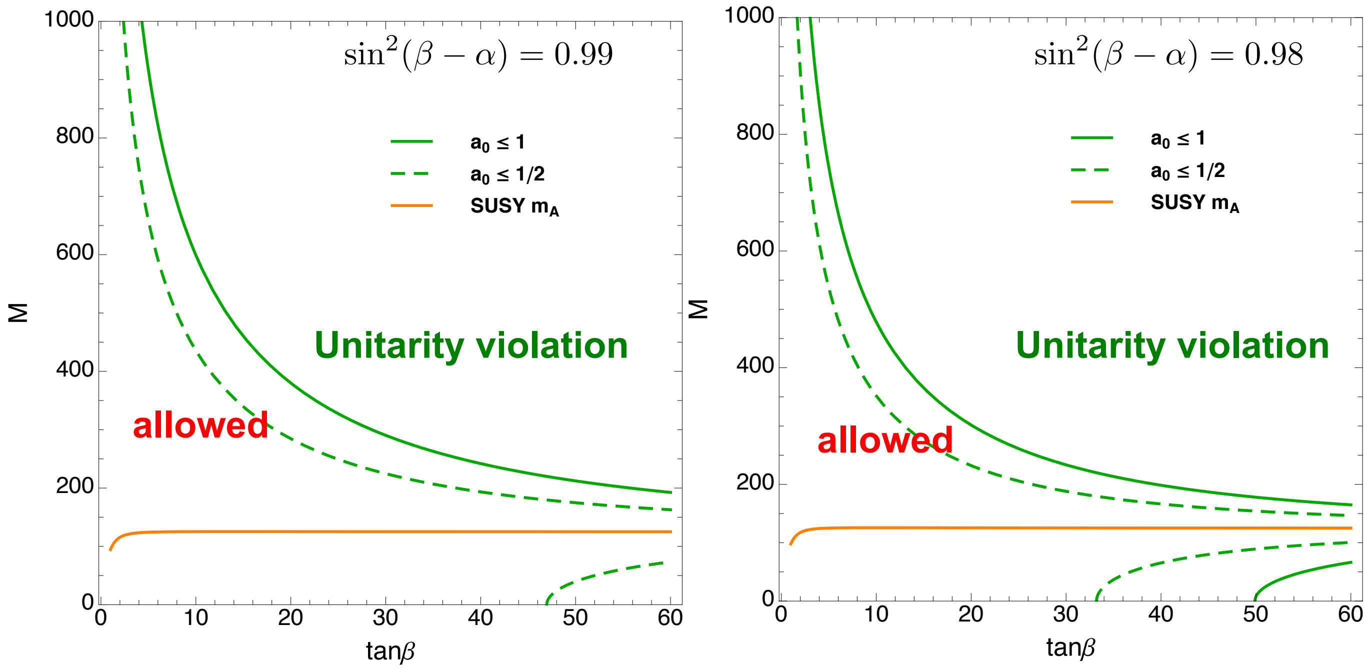
Without H/A,
we can probe tanβ

Unitarity bound

- Potential largest eigenvalue:

Kanemura et,al, (1993)

$$a^{\pm} = -\frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2+4(2\lambda_3+\lambda_4)^2}\right]$$



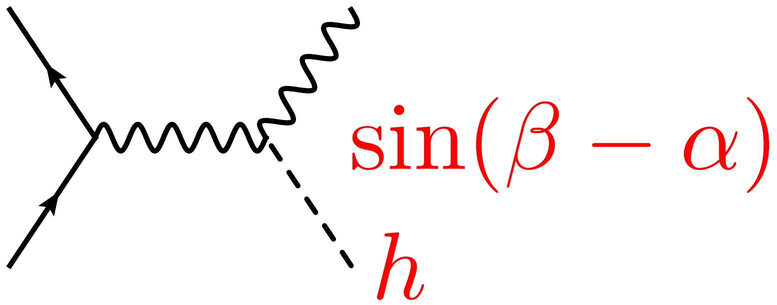
There are implicit upper mass bounds (new no lose theorem?)

[a deviation of sin(β-α) requires large quartic coupling (non-decoupling)]

tanβ @ LC

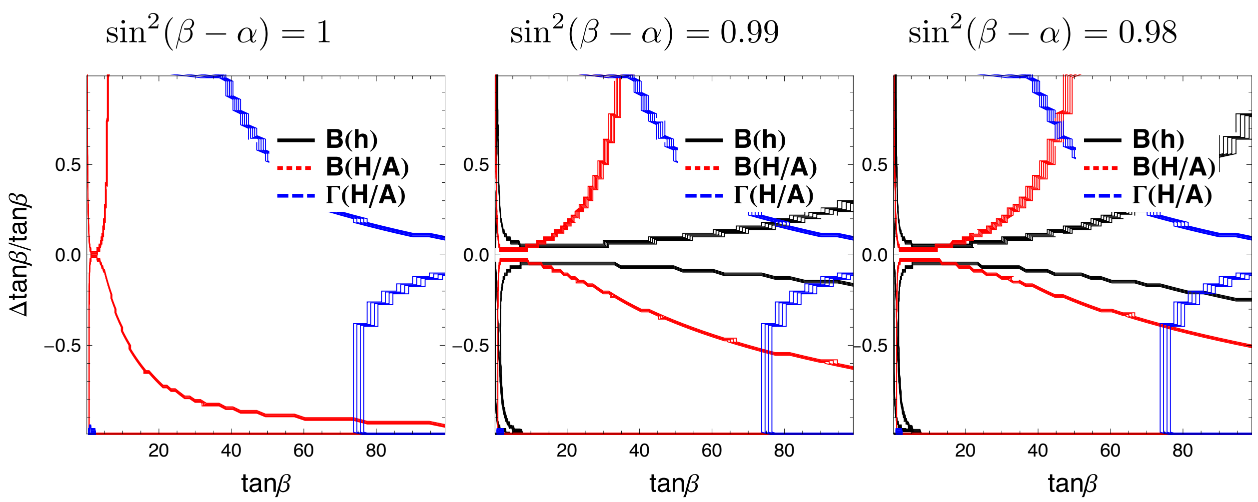
- Precise measurement of sin(β-α) makes BR prediction better in 2HDMs

→ Key observable for determining tanβ

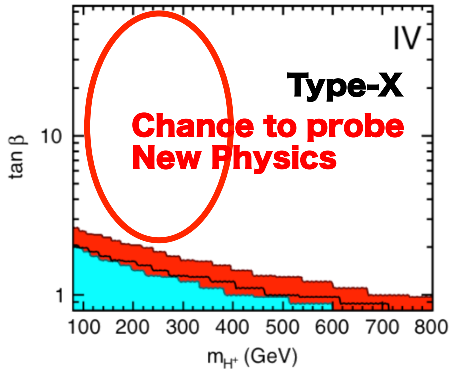


tanβ in 2HDM-X

- SM-like Higgs decay into ττ
- BR measurement w/ 4τ final states
- Width measurement of H/A→ττ



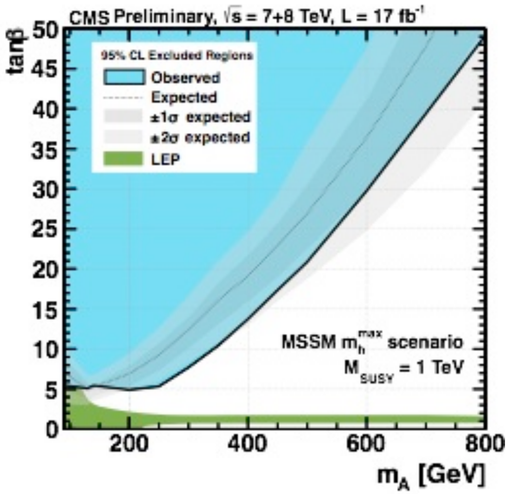
Wider parameter regions
should be examined by LC



Summary

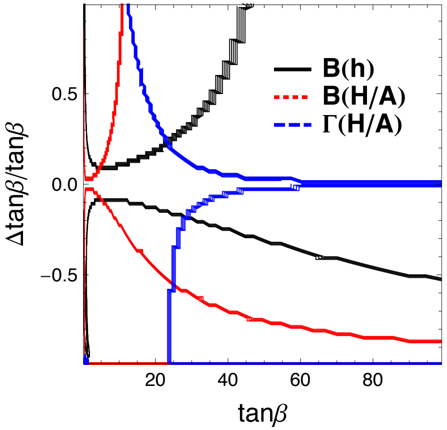
- 2HDM can describe low energy effective theory
  - **Direct search:**
    - ❖ SUSY/2HDM-II Higgs has been searched
    - ❖ Leptophilic Higgs

      (4τ signature @ LHC)
      (4τ signature & tanβ @ LC)



  - **tanβ measurement:**
    - ❖ HA production, width measurement
    - ❖ Precision SM-like Higgs study

      (tanβ from h→bb/ττ @ LC)
      (discriminate types of Yukawa in 2HDMs)



Conclusion


HPNP2013
Toyama International Workshop on
Higgs as a Probe of New Physics 2013
February 13-16, 2013, University of Toyama, Japan

Conclusion

Thank you for your attentions

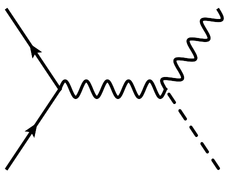
Back up slides

SM-like Higgs in SUSY

- SUSY Higgs sector is the most popular 2HDM
  - Type-II Yukawa interaction w/ SUSY relation

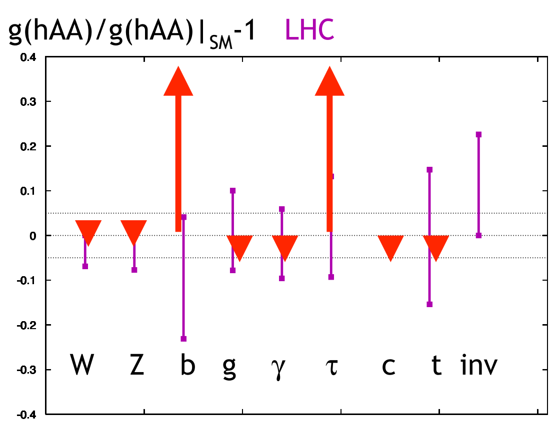
$$\begin{cases} \Phi_u : u, \\ \Phi_d : d, \ell \end{cases}$$

$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta} \approx 1$$

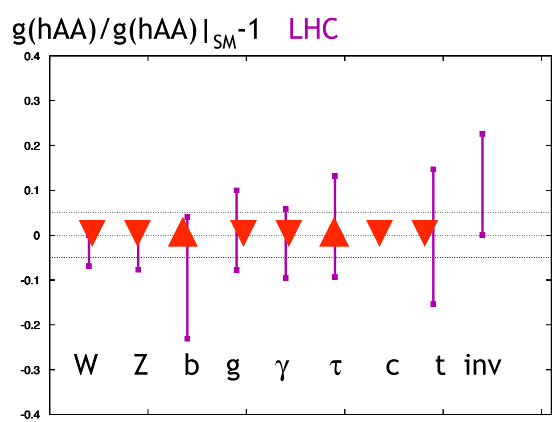


$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \simeq 1 + \frac{2m_Z^2}{m_A^2}$$

$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \simeq 1 - \frac{2m_Z^2}{m_A^2\tan^2\beta}$$



m_A=200GeV
w/ tanβ=5



m_A>>m_Z
w/ tanβ=5

BG figure is taken from 1207.2516 by Peskin

SM-like Higgs in SUSY

- SUSY Higgs sector is the most popular 2HDM
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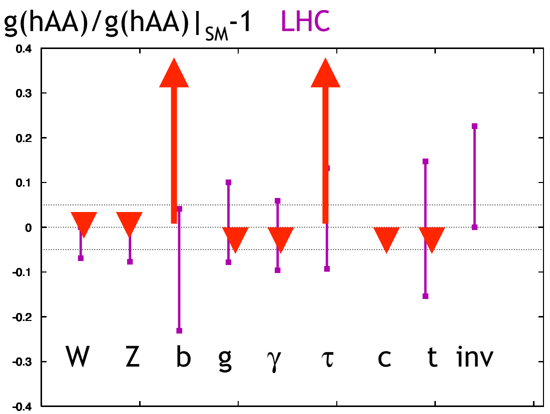
hbb deviation can probe m_A scale



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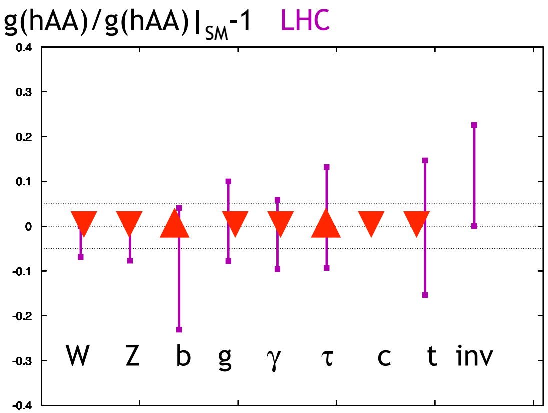

m_A>>m_Z
w/ tanβ=5

SM-like Higgs in 2HDMs

- 2HDM-II

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

  - Type-II Yukawa interaction w/o SUSY relation

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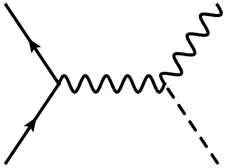
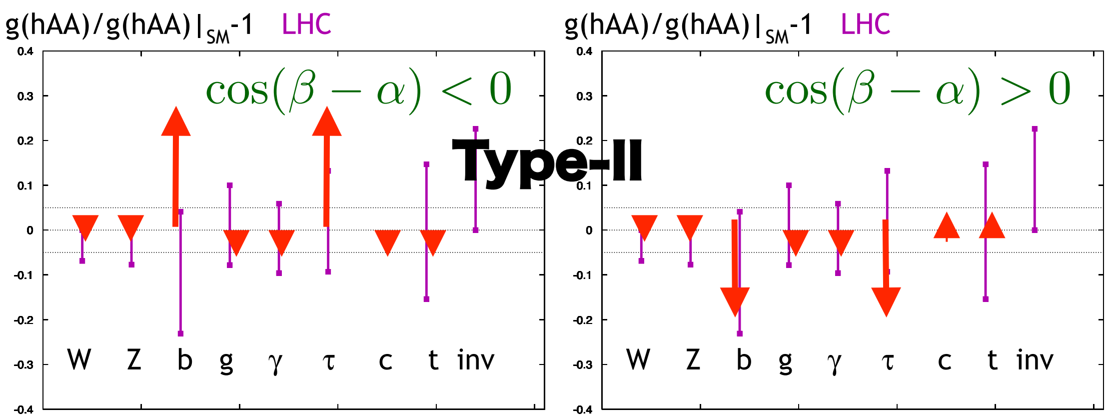
$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

❖ No m_A dependence [$\sin(\beta-\alpha)$ is determined by ]

❖ $\cos(\beta-\alpha)$ can be sizable and positive



SM-like Higgs in 2HDMs

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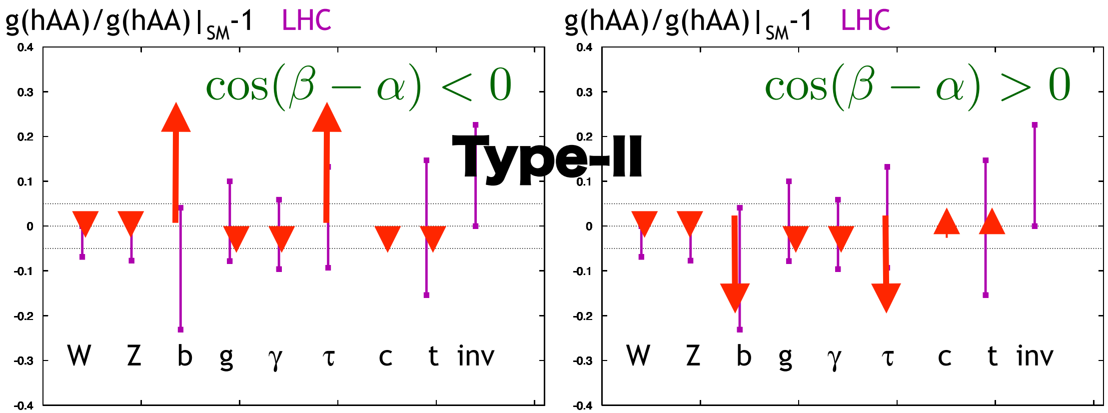
$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

sin(β−α) + hff deviations (w/o m_A)

→ detemination of tanβ



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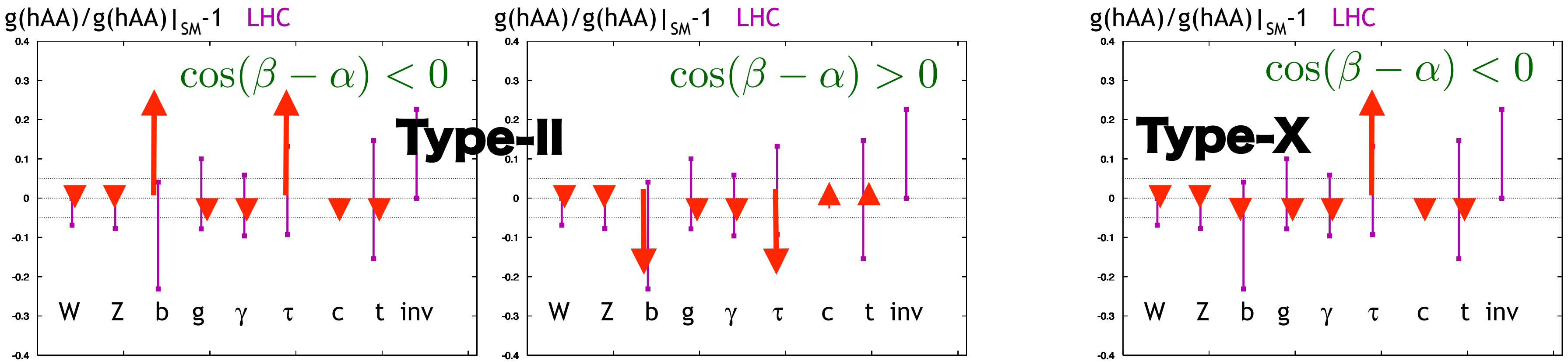
$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

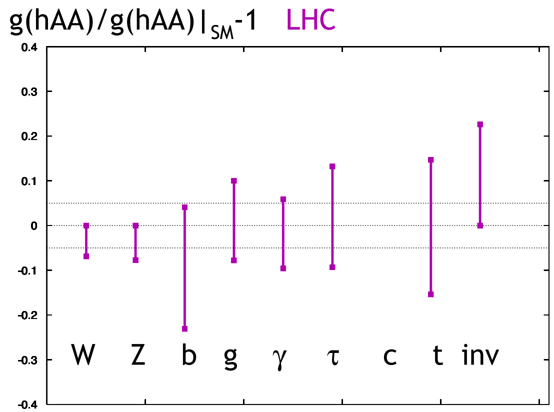
sin(β−α) + hff deviations (w/o m_A)

→ **discrimination of types of Yukawa**



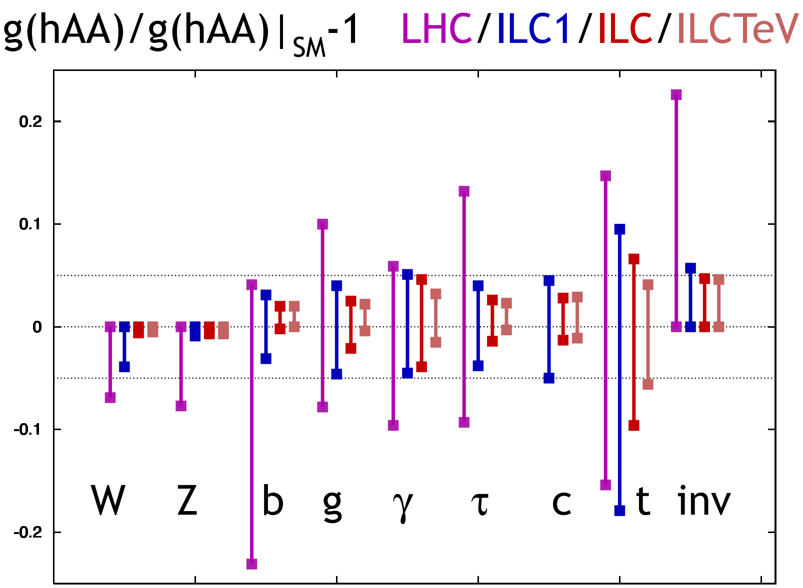
Observable	Expected Error (experiment $\oplus$ theory)
LHC at 14 TeV with 300 fb^{-1}	
$\sigma(gg)\cdot BR(\gamma\gamma)$	$0.06 \oplus 0.13$
$\sigma(WW)\cdot BR(\gamma\gamma)$	$0.15 \oplus 0.10$
$\sigma(gg)\cdot BR(ZZ)$	$0.08 \oplus 0.08$
$\sigma(gg)\cdot BR(WW)$	$0.09 \oplus 0.11$
$\sigma(WW)\cdot BR(WW)$	$0.27 \oplus 0.10$
$\sigma(gg)\cdot BR(\tau^+\tau^-)$	$0.11 \oplus 0.13$
$\sigma(WW)\cdot BR(\tau^+\tau^-)$	$0.15 \oplus 0.10$
$\sigma(Wh)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Wh)\cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(Zh)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Zh)\cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	$0.42 \oplus 0.10$
$\sigma(WW)\cdot BR(\text{invisible})$	$0.2 \oplus 0.24$

Table 1: Input data for the fits to Higgs couplings from LHC measurements.



Observable	Expected Error
ILC at 250 GeV with 250 fb^{-1}	
$\sigma(Zh)$	0.025
$\sigma(Zh) \cdot BR(b\bar{b})$	0.010
$\sigma(Zh) \cdot BR(c\bar{c})$	0.069
$\sigma(Zh) \cdot BR(gg)$	0.085
$\sigma(Zh) \cdot BR(WW)$	0.08
$\sigma(Zh) \cdot BR(ZZ)$	0.28
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.27
$\sigma(Zh) \cdot BR(\text{invisible})$	0.005

Table 2: Input data for the fits to Higgs couplings from ILC measurements.



SUSY Higgs sector

CP even sector

$$\mathcal{M}^2 = \mathcal{M}^2_{\text{tree}} + \begin{pmatrix} 0 & 0 \\ 0 & \epsilon \end{pmatrix}$$

Quantum corrections

$$\epsilon \simeq \frac{3\,\bar{m_t}^4}{2\pi^2 v^2 \sin^2\beta}\left[\ln\frac{M_S^2}{\bar{m_t}^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

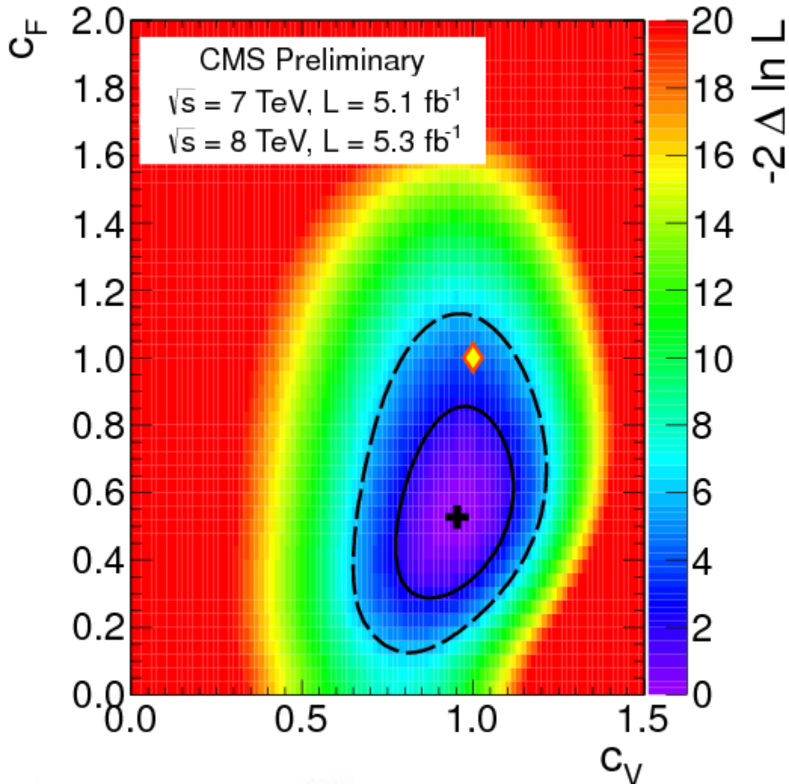
Mass engenvalues & mixing angle

$$m^2_{h,H} = \frac{1}{2}(m_A^2 + m_Z^2 + \epsilon)\left[1 \mp \sqrt{1 - 4\frac{m_Z^2 m_A^2\cos^2 2\beta + \epsilon(m_A^2\sin^2\beta + m_Z^2\cos^\beta)}{(m_A^2 + m_Z^2 + \epsilon)^2}}\right]$$

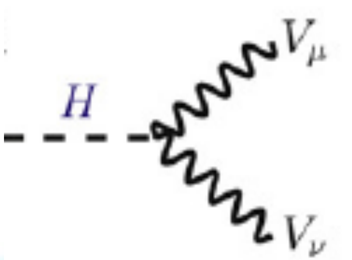
$$\tan 2\alpha = \tan 2\beta\frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2 + \epsilon/\cos 2\beta}$$

SM-like?

- SM-like gauge-gauge-Higgs coupling is favored

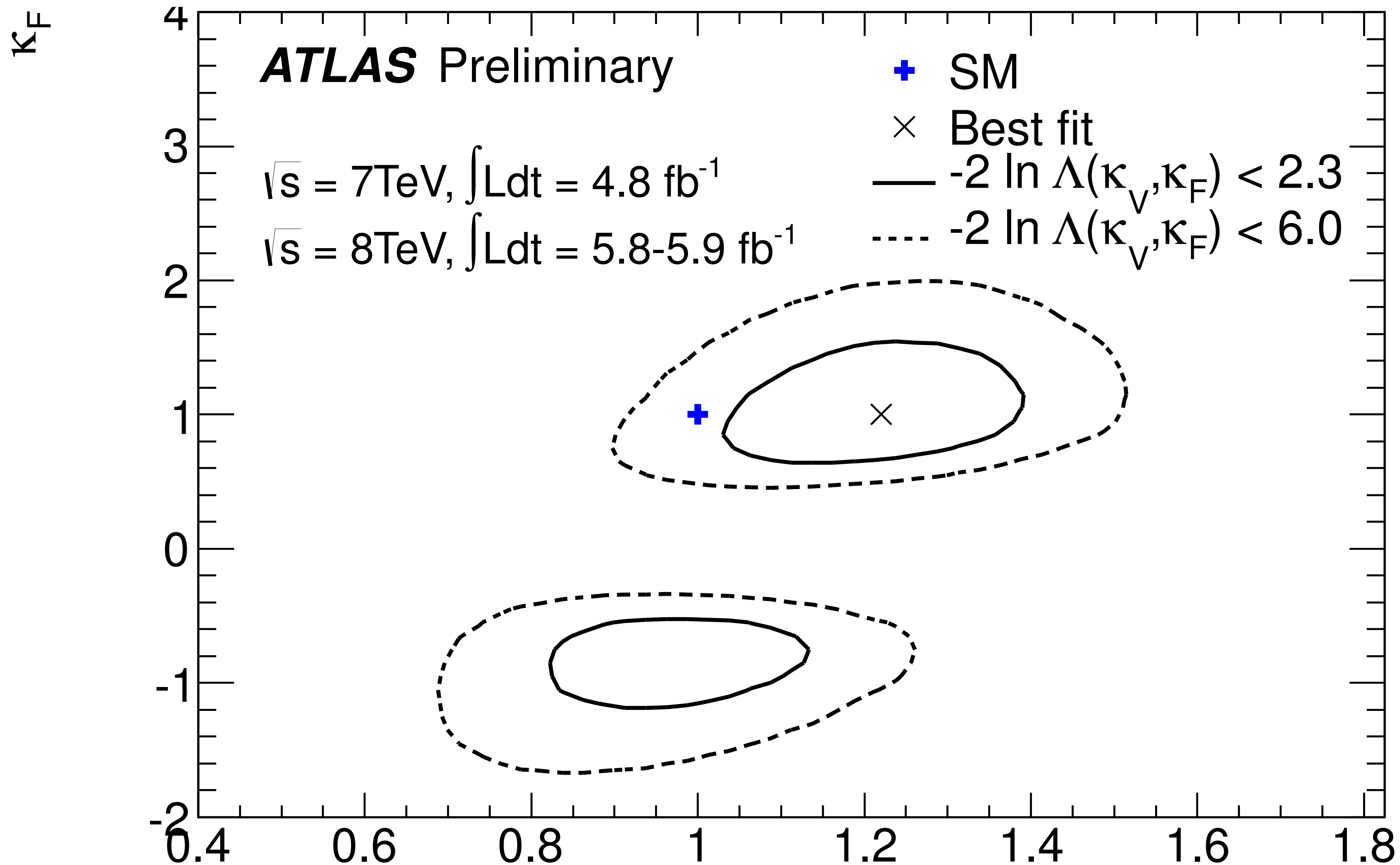


Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF/VH	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF/VH	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$



$$W_\mu^+ W_\nu^+ h : i g_W M_W \sin(\beta - \alpha) g_{\mu\nu}$$

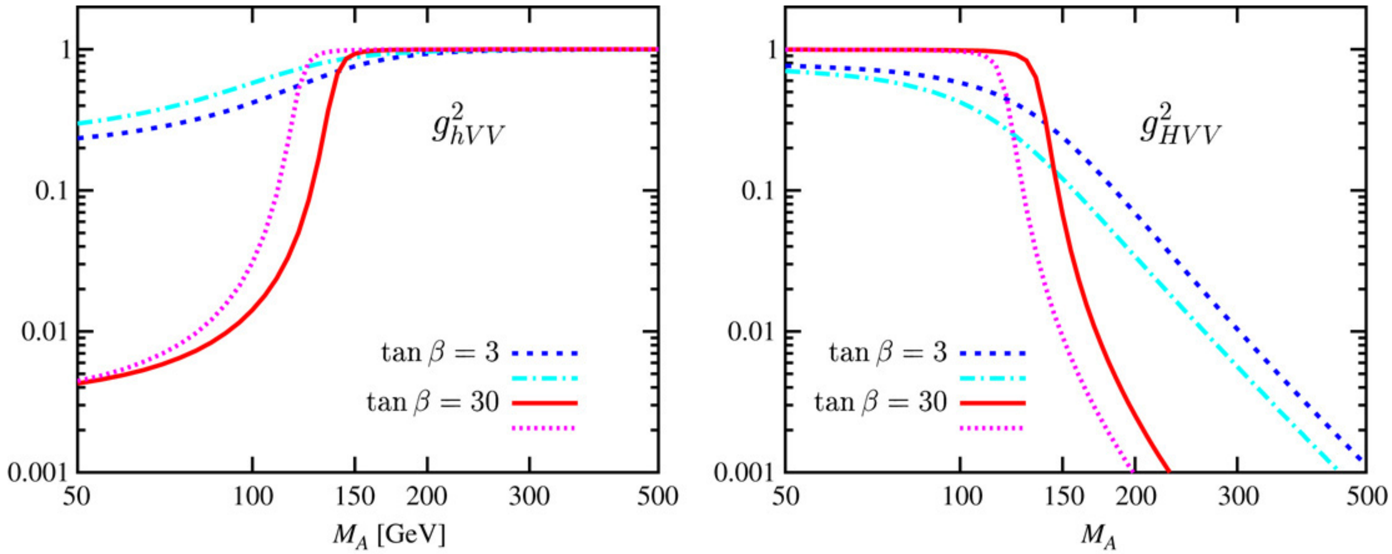
sin(β−α) can be different from unity



ATLAS Preliminary
$\sqrt{s}$ = 7TeV, $\int$Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8TeV, $\int$Ldt = 5.8-5.9 fb^{-1}
SM
Best fit
$-2 \ln \Lambda(\kappa_V,\kappa_F) < 2.3$
$-2 \ln \Lambda(\kappa_V,\kappa_F) < 6.0$
κ_F
4
3
2
1
0
-1
-2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

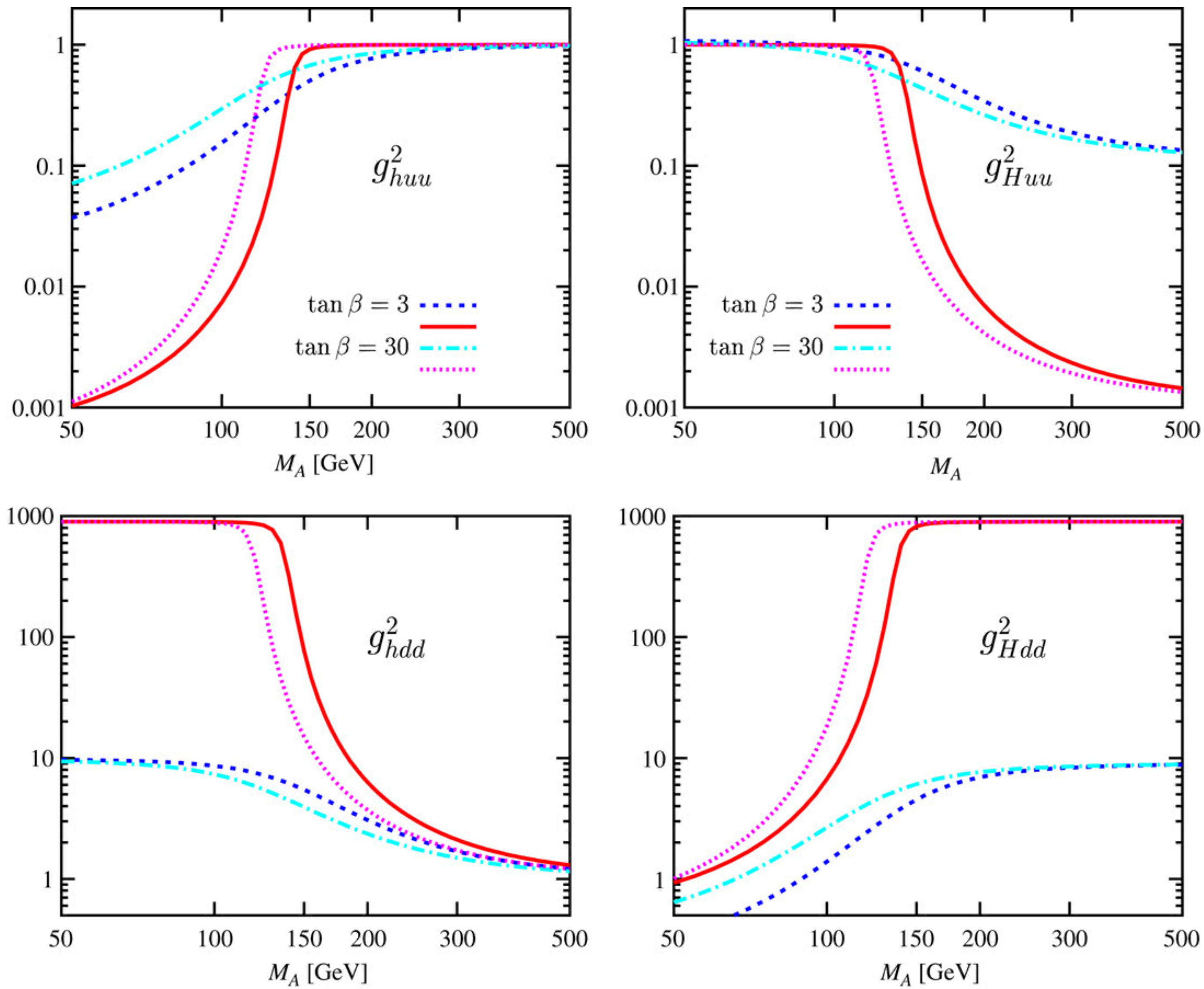
Gauge coupling in MSSM

Djouadi (2008)



Yukawa coupling in MSSM

Djouadi (2008)



Kanemura, KT, Yokoya (2012)

Event analysis details

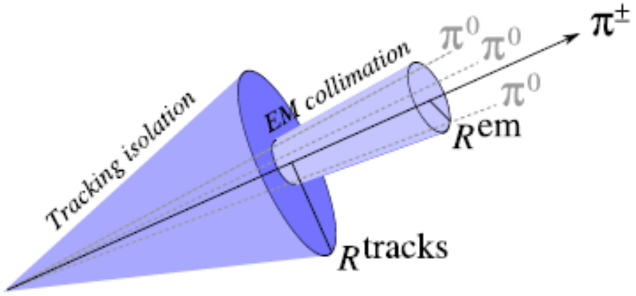
-MadGraph5: event generation, calculate (diff.) σ

-PYTHIA: hadronization (quark, τ → hadron)

w/ TAUOLA (tau polarization)

-FastJet: (construct jets from hadrons)

jet is defined by anti-kT w/ R<0.4



→ Detector simulation
(construct kinematical variables such as invariant mass, etc…)

Unitarity bound

- tanβ enhancement in λ couplings

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left(-M^2\sin^2\beta + m_H^2\cos^2\alpha + m_h^2\sin^2\alpha\right)$$
$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left(-M^2\cos^2\beta + m_H^2\sin^2\alpha + m_h^2\cos^2\alpha\right)$$
$$\lambda_3 = \frac{1}{v^2}\left[-M^2 + (m_H^2 - m_h^2)\frac{\sin 2\alpha}{\sin 2\beta} + 2m_{H^+}^2\right]$$

nearly SM-like ($\beta-\alpha=\pi/2-\delta$), and $M=M_H=M_{H+}$

$$\lambda_1 \to +\frac{m_h^2}{v^2} - \frac{2(M^2-m_h^2)t_\beta}{v^2}\delta - \frac{(M^2-m_h^2)t_\beta^2}{v^2}\delta^2$$
$$\lambda_2 \to +\frac{m_h^2}{v^2} + \frac{2(M^2-m_h^2)/t_\beta}{v^2}\delta + \frac{(M^2-m_h^2)/t_\beta^2}{v^2}\delta^2$$
$$\lambda_3 \to +\frac{m_h^2}{v^2} + \frac{2(M^2-m_h^2)}{v^2}\delta + \frac{(M^2-m_h^2)}{v^2}\delta^2$$

Only λ_1 diverges
@ large tanβ